PREDICTING THE FAILURE TIMES OF GLULAM MEMBERS EXPOSED TO FIRE

By

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Abstract

The methods provided in the National Building Code of Canada (NBCC) for calculating the fire-resistance ratings of glulam beams and columns are shown to be in need of revision. Furthermore, the NBCC gives no guidance for calculating the ratings of glulam members loaded in tension. To correct these shortcomings, detailed models based on current Canadian structural design methods have been developed for calculating the fire-resistance ratings of glulam members loaded in compression, bending or tension. The models account for the development of char and reductions in strength that arise as glulam members are heated during fire exposure. Simpler algebraic models were also developed to calculate the fire-resistance rating of any glulam member. The algebraic models depend only on the factored load, material strength and dimensions prior to fire exposure, all of which are known to the designer. It is recommended that fire tests be performed to verify the models developed.

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Nomenclature

A	mm^2	Area
A_g	mm^2	Gross cross-sectional area
A_n	mm^2	Cross-sectional area at net section
A_r	mm^2	Area of the residual cross section
a	mm	Depth of heat-affected layer
a		Constant found in Table 2
a		Dimensionless exponent used by White
B	mm	Original cross section width
b	mm	Residual cross section width
b		Constant found in Table 2
C_C		Slenderness ratio of compression members
C_B		Slenderness ratio for bending members
C_K		Stiffness ratio
COV_b		Coefficient of variation of the bending strength
COV_c		Coefficient of variation of the compressive strength
COV_E		Coefficient of variation of the modulus of elasticity
COV_t		Coefficient of variation of the tensile strength
c		Constant found in Table 2
c		Hardwood-softwood classification
c		Variability adjustment factor
D	mm	Original cross section depth
D		Dead load
d	mm	Residual cross section depth
d	mm	Depth of penetration of wood preservative CCA
E	MPa	Modulus of elasticity
E_{05}	MPa	Buckling strength
E_{LSD}	MPa	Modulus of elasticity (Limit States Design)
E_{WSD}	MPa	Modulus of elasticity (Working Stress Design)
F_b	MPa	Bending strength
F_c	MPa	Compression strength parallel to the grain
$F_{c,avg}$	MPa	Average ultimate bending strength
$F_{b,WSD}$	MPa	Allowable stress in bending (Working Stress Design)
$F_{c,WSD}$	MPa	Allowable stress in compression parallel to grain (Working Stress Design)
F_t	MPa	Tensile strength
f		Empirical load factor based on the work of Lie
f_b	MPa	Specified strength in bending (fifth percentile ultimate)
$f_{b,LSD}$	MPa	Specified strength in bending (Limit States Design)
$f_{b,avg}$	MPa	Average ultimate strength in bending
f_c		Char contraction factor
f_c	MPa	Specified strength in compression parallel to the grain (fifth percentile ultimate)

$f_{c,avg}$	MPa	Average ultimate strength in compression
$f_{c,LSD}$	MPa	Specified strength in compression parallel to the grain (Limit States Design)
f_{eff}		Effective load factor
f_{tg}	MPa	Specified strength in tension parallel to the grain at the gross section (fifth percentile ultimate)
$f_{tg,avg}$	MPa	Average ultimate tensile strength parallel to the grain
f_{tn}	MPa	Specified strength in tension parallel to the grain at the net section
g		Material property specific factor
h_b		Modification factor for beam equation
h_t		Modification factor for tension equation
I	mm ⁴	Moment of inertia
K		Effective load factor for columns (K_e)
K		Final strength adjustment factor
K_C		Slenderness factor
K_D		Load duration factor
K_e		Effective length factor defined by CSA O86-01
K_H		System factor
K_L		Lateral stability factor
K_{Sb}		Service condition factor for bending
K_{Sc}		Service condition factor for compression parallel to grain
K_{SE}		Service condition factor for the modulus of elasticity
K_{St}		Service condition factor for tension parallel to grain
K_T		Treatment factor
K_x		Curvature factor
K_{Zbg}		Size factor for bending for glue-laminated timber
K_{Zcg}		Size factor for compression for glue-laminated timber
k		Ratio of applied load to ultimate strength
k		Design value adjustment factor
k_f		Material property reduction factor
$k_{fb,fire}$		Bending strength reduction factor due to elevated temperature
$k_{fc,fire}$		Compressive strength reduction factor due to elevated temperature
$k_{ft,fire}$		Tensile strength reduction factor due to elevated temperature
$k_{MOE,fire}$		Modulus of elasticity reduction factor due to elevated temperature
L	mm	Unsupported length of a column
L	mm	Length of a member
L		Live load
L_e	mm	Effective length of a member
l_u		Unsupported length of a bending member
M		Percent moisture content

$M_{allowable}$	Nmm	Allowable bending moment
M_f	Nmm	Maximum factored bending moment
M_r	Nmm	Factored moment resistance
M_{r1}	Nmm	Factored moment resistance
M_{r2}	Nmm	Factored moment resistance
M_s	Nmm	Unfactored moment
m_a	min/mm ^a	Reciprocal char rate
$m_{a=1}$	min/mm	Reciprocal char rate (a=1)
$m_{a=1.23}$	min/mm ^{1.23}	Reciprocal char rate (a=1.23)
n		Number of data points
n_b	min	Calibration term for simplified beam equation
n_c	min	Calibration term for simplified column equation
n_t	min	Calibration term for simplified column equation
P	N	Applied load
P		Percentage of original strength still present
$P_{allowable}$	N	Allowable compressive load
P_f	N	Factored compressive load
P_r	N	Factored compressive resistance
p		Exposed perimeter of the residual cross section
R^2		Coefficient of determination
q		WSD load ratio over LSD load ratio
q_{avg}		Average WSD load ratio over LSD load ratio
r	mm	Radius of arris rounding
r	mm	Radius of gyration
S	mm ³	Section modulus
SG		Dry specific gravity
SSE		Sum square of errors
SST		Sum squares of the total variant of y
T	°C	Temperature
T_f	N	Factored tensile load
T_i	°C	Initial temperature of the wood
T_p	°C	Temperature of the char front
T_r	N	Factored tensile resistance
T_s	N	Unfactored tensile load
T_0	°C	Ambient temperature
t	min	Time
t_{b3}	min	Failure time of a beam exposed to fire on three sides
t_{b4}	min	Failure time of a beam exposed to fire on four sides
t_{c4}	min	Failure time of a column exposed to fire on four sides
t_{t4}	min	Failure time of a tension member exposed to fire on four sides
x	mm	Depth below char front
x	min	Observed time to failure
x_c	mm	Depth of char
$x_{c,t}$	mm	Thickness of the char layer at the end of the fire

		exposure
x_t	mm	Total depth for which strength is lost
Y_j		y-coordinate of the data point
$\hat{Y}_j$		y-coordinate of the trendline
y	mm	Height of centre of gravity of A
y	min	Predicted time to failure
Z_1		Species specific constant
α		Ratio of the material properties at elevated temperatures to material properties at room temperature.
β	mm/min	Charring rate
β_e	mm/min	Effective charring rate
ρ	kg/m ³	Density
σ	MPa	Stress in the cross section
ϕ		Resistance factor
ϕ_1		Unity resistance factor

1.0 Introduction

The National Building Code of Canada (NBCC, 2005) presents equations produced by T. T. Lie (1977) to calculate the fire-resistance ratings (failure times) of exposed glulam beams and columns. Since these equations were developed, additional data has been generated in standard fire tests conducted on glulam beams and on glulam members loaded in tension. Limit States Design has since been adopted by Canadian structural design codes, including CSA O86-01: Engineering Design in Wood. This work employs current Canadian design equations along with models for the charring of wood and for the reduction of strength properties at elevated temperatures to determine the failure times of beams exposed to fire on three sides, and columns and tension members exposed to fire on four sides. First, a detailed model is presented in order to attempt to predict the failure times obtained during testing. The development of a new simplified algebraic approach appropriate for use by design engineers is also presented. The algebraic method has been calibrated to ensure that members are safely designed. It provides a tool for the designer to calculate conservative fire-resistance ratings of glulam members using only the factored load, cross-sectional dimensions prior to fire exposure and specified material strength provided by CSA O86-01.

2.0 Literature Review

In order to calculate the time to failure, the effects of fire on wood must first be considered. A literature review has been undertaken to determine how researchers have modelled the charring rate of wood and the reduction in wood structural properties at elevated temperatures. Particular attention has been paid to models for predicting failure times developed by T. T. Lie (1977) and the American Forest & Paper Association (AF&PA, 2003) as these models are the basis of current codified methods for calculating fire-resistance ratings of glulam members in Canada and the USA.

An attempt was made to develop heat and mass transfer numerical models. However, these models require detailed information on the chemistry of pyrolysis and the parameters that govern both heat and mass transfer. Such data is difficult to come by and the intent of this thesis was to derive simple models that could be used by designers. Consequently, these numerical models are not considered in this thesis.

2.1 *Standard Fires*

The required fire-resistance rating of a member is specified by a building code and is typically expressed as a multiple or fraction of an hour. The fire-resistance rating is the time to failure (failure time) of a member; that is, the time elapsed between when a member is first exposed to a standard fire and failure.

In a standard fire test, a structural member is subjected to a standard fire exposure in a furnace, all the while supporting its design load. Fuel, usually gaseous, is supplied to the furnace at such a rate that the fire gases in the furnace follow a prescribed temperature as a function of time. Around the world there are various standard fire exposures used for fire testing. The Canadian standard fire is defined in CAN/ULC S101-04 (ULC, 2004). The most common standard fires, as mentioned by Buchanan (2002), are ASTM E119 (ASTM, 2005) and ISO 834 (1999). The temperature, T ($^{\circ}\text{C}$) for the ISO 834 fire is defined by the standard time-temperature curve expressed by:

$$T = 345 \log_{10}(8t + 1) + T_0 \quad (1)$$

where T_0 ($^{\circ}\text{C}$) is the ambient temperature, and t (min) is the time. The ASTM E119 time-temperature curve is very similar to the ISO 834 fire, but is defined by a discrete number of points. CAN/ULC S101-04 uses the same time-temperature curve as ASTM E119. Table 1 shows a summary of the temperatures that define the ASTM E119 time-temperature curve at specific times, and the corresponding ISO 834 temperatures calculated using Equation 1.

Table 1: Time-Temperature Curves

Time	ASTM E119	ISO 834
min	Temperature	Temperature
	°C	°C
0	20	20
5	538	576
10	704	678
30	843	842
60	927	945
120	1010	1049
240	1093	1153
480	1260	1257

ASTM E119 and ISO 834 use different methods for measuring temperature. ASTM E119 uses thermocouples located in heavy steel pipes with capped ends, and ISO 834 uses exposed thin wire thermocouples (Buchanan, 2002). The heavy steel pipes take longer to heat up, but as noted by Buchanan (2002), Babrauskas and Williamson (1978) have shown that this temperature difference is most significant only during the first five minutes of the test.

Fire-resistance tests have three types of failure criteria: stability, integrity, and insulation. Because walls and floors can play separation roles in addition to structural roles, they are required to be assessed against all three failure criteria. However, since the members considered in this work are structural elements, they are only required to be assessed against the stability criteria, although when beams and slabs are composite, integrity must be checked. The member must be able to support the applied load and is tested until it can no longer do so. In addition to the structural failure, ISO 834 applies deflection limits such that if a maximum deflection criterion is exceeded, the test is stopped. In either case, the

time of failure is referred to as the fire-resistance. The applied load during a test is typically the maximum permitted load based on the nationally acknowledged design standards. The applied load can vary greatly among countries (Buchanan, 2002).

2.2 Presentation of Results

Throughout this thesis, the calculated time to failure is compared to the observed time to failure from standard fire tests. This is done by plotting a graph of predicted time to failure versus observed time to failure. On the graph a reference line is plotted that has a slope of one to show where a data point would fall if the observed and predicted times were equal. The closer the data points are to the reference line the better the predicted results match experimental values. A trendline, or best fit line, is also plotted on each graph. The closer the slope of the trendline is to one and the closer the intercept is to zero the better is the agreement between predicted and observed results. If the trendline, or best fit line, is below the reference line, the results tend to the conservative side (predicted times are less than observed times) and if it is above the reference line, the results tend to be non-conservative. The coefficient of determination (R^2 value) associated with the trendline is also presented on each graph. Since the R^2 value measures the scatter of the data about the trendline, a measure of fit to the observed data is also required. As a result, the residuals are calculated. The residuals are the sum of the squared errors as seen below in Equation 2:

$$\text{Residuals} = \sum (\text{Observed Failure Time} - \text{Predicted Failure Time})^2 \quad (2)$$

The average residuals per member is also presented. This value is the residuals divided by the total number of test specimens for the member type considered. The number of specimens used is 62 for columns, 7 for beams and 3 for tension members.

Microsoft Excel is used to perform the computations in this thesis. The linear trendline in Microsoft Excel is generated by determining the “least squares fit” (Microsoft, 2003); i.e., minimizing Equation 3.

$$SSE = \sum (Y_j - \hat{Y}_j)^2 \quad (3)$$

where SSE is the sum square of errors, Y_j is the y-coordinate of the data point, $\hat{Y}_j$ is the y-coordinate of the trendline.

The R^2 value is calculated using the following equations (Microsoft, 2003):

$$R^2 = 1 - \frac{SSE}{SST} \quad (4)$$

and:

$$SST = \sum Y_j^2 - \frac{(\sum Y_j)^2}{n} \quad (5)$$

where SST is the sum squares of the total variation of Y and n is the number of data points.

2.3 Effects of Fire on Wood Members

Wood is combustible. When exposed to fire, the temperature of the material becomes elevated and its mechanical properties are reduced. A temperature profile develops through the cross section, with the hottest material at the surfaces exposed to fire. When the temperature of the exposed surfaces climbs sufficiently, charring begins at the surface and progresses inwards. Figure 1 shows a sample cross section.

Figure 1: Sample Cross Section Showing the Char Layer, Pyrolysis Zone and Normal Wood (Schaffer, 1967)

The figure shows the char layer where the wood has been reduced to mainly carbon and is assumed to have no strength. The wood at the char base, the interface between the char layer and zone of active pyrolysis, is at a temperature generally assumed to be 300°C (Buchanan, 2002). In North America however, 288°C (550°F) is the commonly accepted char base temperature (Janssens and

White, 1994). Due to the steep temperature profile in the cross section, the exact temperature is not critical.

Beneath the char layer is a heat-affected layer, which is approximately 35 mm thick (Janssens and White, 1994) as referenced in Buchanan (2002). The portion of the heat-affected layer above 200°C is known as the pyrolysis zone. Pyrolysis, which begins when the wood reaches 200°C, is the thermal decomposition of wood that produces gaseous products or volatiles and char. It causes a reduction in the mass of the member and the final stage of pyrolysis is charring.

Within the heat-affected zone, when the wood approaches 100°C at a given depth the moisture at that depth begins to evaporate, with some of the vapour moving toward the exposed face. At the same time, some of the vapour travels into the wood where it may condense on areas having a lower temperature, causing an increase in moisture content a few centimetres below the interface between the char and the heat-affected layer. By the time wood at a given depth has reached a temperature of 150°C the moisture has been largely driven off at that depth (Fredlund, 1993).

Below the pyrolysis zone base there is heated wood in the heat-affected layer, followed by wood that is assumed to be at the initial temperature (the ambient temperature before fire exposure).

Figure 2 shows cross sections of wood specimens exposed to fire on three and four sides. The depth of char is defined as x_c , with a heat-affected layer of depth a . Dimensions B and D are the original cross-sectional width and depth respectively. The residual cross section dimensions are b and d during fire exposure.

Figure 2: Cross Section of a Wood Member during Fire Exposure

The temperature profile in the heat-affected layer (beneath the char layer) as stated in Eurocode 5 (1995) is given by:

$$T = T_i + (T_p - T_i)(1 - x/a)^2 \quad (6)$$

where T (°C) is the temperature beneath the char layer, T_i (°C) is the initial temperature of the wood, T_p (°C) is the temperature of the char front (300°C), x (mm) is the distance below the char front and a (mm) is the thickness of the heat-affected layer (40 mm based on Eurocode 5, 35 mm based on the work of

Janssens and White). Equation 6 does not account for the plateau in temperature that occurs at 100°C when moisture within the wood begins to evaporate (White, 2002).

As referenced by Janssens and White (1994), during White's PhD studies (White, 1988), he tested eight wood specimens that had a range of moisture contents from 5.2% to 18.1%. Based on those tests, Janssens and White found values for the thickness of the heat-affected layer ranging from 31 to 35 mm suggesting that the thickness, a , could be set equal to 35 mm in Equation 6. Eurocode 5 uses a heat-affected layer thickness of 40 mm.

Roberts (1964) referenced by Drysdale (1999) performed combustion bomb calorimetry on small dry European beech samples. He determined that the yield of char was 16-17% of the original mass of wood, and the mean molecular formulae of dry wood, volatiles and char are as follows:

Dry Wood: $\text{CH}_{1.5}\text{O}_{0.7}$

Volatiles: CH_2O

Char: $\text{CH}_{0.2}\text{O}_{0.02}$

In addition to pyrolysis, an elevated temperature also causes a reduction of member properties, including material strength and modulus of elasticity (MOE). Modelling of this reduction is discussed further in Section 2.3.6.

2.3.1 Constant Charring Rates

The charring rate, β , is defined as the rate of advance of the char base into the wood. The charring rate can depend on the species, density, and moisture content of the wood. A constant charring rate is the simplest form. Using a constant charring rate results in a linear char depth equation defined by:

$$x_c = \beta t \quad (7)$$

where x_c (mm) is the depth of char, β (mm/min) is the constant charring rate, and t (min) is time.

The generally accepted value for the charring rate of wood in North America is 0.635 mm/min (1.5 in/h) (White, 2006). T. T. Lie used a value of 0.6 mm/min (1.42 in/h) in his original research (Lie, 1977).

2.3.1.1 Charring Rates Dependent on Density

Density can greatly affect the charring rate of wood. As stated by Syme (1994), the Australian Code (Standard Association of Australia, 1991) provides a charring rate based on density as follows:

$$\beta = 0.4 + (280/\rho)^2 \quad (8)$$

where β (mm/min) is the charring rate and ρ (kg/m³) is the density. For low densities, Equation 8 tends to predict particularly high charring rates.

As reported in Poon (2003), Gardner and Syme (1991) manufactured and tested glued-laminated beams, exposed to fire on three sides, from eight Australian-grown species; Blackbutt, Blue Gum, Brush Box, Cypress Pine, Jarrah, Radiata Pine, Spotted Gum, and Victorian Ash. With the exception of Radiata Pine, these species are not common in North America. A temperature of 288°C was used to determine the location of the char base. The results presented were only for members that had a central zone that did not exceed 100°C indicating the members could be modelled as a semi-infinite solid (Poon, 2003). For densities from 545 to 1000 kg/m³, the char depth was found to satisfy the following equation as a function of time (Syme, 1994):

$$x_c = 1.61 + 413 \frac{t}{\rho} \quad (9)$$

where x_c (mm) is the char depth, t (min) is the exposure time, ρ (kg/m³) is the air-dried density of the timber. Because the equation was produced based on a regression analysis, the char depth does not equal zero at time equal to zero. Gardner and Syme also found that the difference between the char depths on the sides and base were less than 10%, with the base having the larger char depth most of the time.

2.3.1.2 Charring Rates Depending on Moisture Content and Specific Gravity

Schaffer (1967) published an equation for charring rates as a function of the moisture content and specific gravity. It was developed using regression

analysis on the results of 48 test specimens for several species. Converted into metric units the equation is:

$$\beta = \frac{25.4}{2[(a + bM)SG + c]} \quad (10)$$

where β (mm/min) is the charring rate, M is the percent moisture content, SG is the dry specific gravity, and a , b , and c are constants found in Table 2 for ASTM E-119 exposure conditions.

Table 2: Species Constants for Charring Rate Equation 10 (Schaffer, 1967)

Species	Regression Constants		
	a	b	c
Douglas Fir	28.726	0.578	4.187
Southern Pine	5.832	0.120	12.862
White Oak	20.036	0.403	7.519

2.3.2 Varying Charring Rates

A varying charring rate is not constant over time; rather it changes with the progression of time. Technical Report 10: *Calculating the Fire Resistance of Exposed Wood Members* (TR10) (AF&PA, 2003) uses a time dependent charring rate that is based on the work of Robert White during his PhD research.

2.3.2.1 Charring Rate based on White and Nordheim (1992)

White and Nordheim, (1992) continued White's PhD research (White, 1988). The work began with the equation:

$$t = mx_c^a \quad (11)$$

where t (min) is time, m (min/mm^a) is the reciprocal charring rate, x_c (mm) is the char depth, and the exponent a is a dimensionless parameter. Based on experimental values, little variation was found in the range of the exponent a among test specimens, which varied in species and moisture content. As a result, in order to simplify matters, a species independent and moisture content independent constant of $a = 1.23$ was selected. This indicates that as time progresses, the charring rate begins to slow, possibly due to the char layer acting as an insulating layer.

Regression analysis was used in conjunction with empirical models to determine the relationship between m and the species dependent material properties. The final equation with $R^2 = 0.764$ was as follows:

$$m = 0.162 + 0.809SG + 0.0107M + 0.0689c - 0.00655SGd - 0.00240cd \quad (12)$$

where SG is the oven-dried specific gravity, M is the moisture content expressed as a percentage, c is the hardwood-softwood classification (1 for softwoods, and -1 for hardwoods) and d is the depth of penetration of the wood preservative chromated copper arsenate (CCA) in millimetres, which is used as a measure of permeability.

An alternative equation was also produced using a char contraction factor, f_c . The char contraction factor is the thickness of the char layer at the end of the fire

exposure, $x_{c,t}$, divided by the original thickness of the charred portion of the wood, i.e. the char depth, x_c , (White, 2002), and is defined as:

$$f_c = \frac{x_{c,t}}{x_c} \quad (13)$$

White and Nordheim (1992) developed an equation for char contraction factors with $R^2 = 0.842$ as follows:

$$f_c = 0.732 - 0.00423d + 0.203c - 0.00164cd - 0.270SGc \quad (14)$$

A second equation for m was also presented using species-specific coefficients with $R^2 = 0.906$:

$$m = 0.1526 + 0.5080SG + 0.1475f_c + Z_1M \quad (15)$$

where Z_1 is the species-specific coefficient found in Table 3 below.

Table 3: Species-Specific Coefficients (Z_1)

Species	Z_1
Southern Pine	0.0050
Hard Maple	0.0063
Basswood	0.0080
Yellow Poplar	0.0097
Western red cedar	0.0113
Redwood	0.0156
Red oak	0.0161
Engelmann spruce	0.0205

Calculating the charring rate using the equations presented by White and Nordheim (1992) can become a tedious and time-consuming process. The

charring rate can only be computed if the values of moisture content, oven-dried specific gravity, CCA penetration, char contraction factor, or species-specific coefficient are available.

2.3.2.2 Technical Report 10 Charring Rate Method

To simplify matters, Technical Report 10 (AF&PA, 2003) introduced a simplified version of the equation. The basis of the simplified version is the assumption that the char depth at one hour using a linear char rate must be equal to char depth calculated using the non-linear equation. This method is shown in more detail below.

Using the value of the exponent a recommended by White and Nordheim (1992) Equation 11 became:

$$t = m_{a=1.23} x_c^{1.23} \quad (16)$$

Substituting Equation 7 into Equation 16 and solving at $t = 60 \text{ min}$ Equation 17 is obtained:

$$60 \text{ min} = m_{a=1.23} [(60 \text{ min})(\beta)]^{1.23} \quad (17)$$

which results in:

$$m_{a=1.23} = 0.39\beta^{-1.23} \quad (18)$$

Combining Equations 16 and 18 and solving for the depth of char we obtain a non-linear equation:

$$x_c = 2.15\beta t^{0.813} \quad (19)$$

resulting in an effective varying charring rate β_e equal to:

$$x_c = \beta_e t \quad (20)$$

$$\beta_e = \frac{2.15\beta}{t^{0.187}} \quad (21)$$

In Technical Report 10 (TR10), the char depth as a function of time is calculated using Equations 20 and 21, or effectively Equation 19.

When $a = 1.0$ is used, the model reverts to a constant charring rate model as the following equations are produced:

$$t = m_{a=1} x_c \quad (22)$$

$$\beta = m_{a=1}^{-1} \quad (23)$$

Combining Equations 22 and 23 and solving for the depth of char we obtain:

$$x_c = \beta t \quad (24)$$

2.3.3 Charring Rates Based on White (2006)

White (2006) has recently published results on charring of structural composite lumber products. Laminated strand lumber (LSL), laminated veneer lumber

(LVL), and parallel strand lumber (PSL) were tested. He reported his findings on the reciprocal char rates (m) for both the linear ($a = 1$) and non-linear ($a = 1.23$) configurations of Equation 11. Tests were performed in both a small vertical furnace and an intermediate scale horizontal furnace.

Considering all 58 individual tests performed in the small vertical furnace on the three types of structural composite lumber a mean value for the linear equation $m_{a=1} = 1.54 \text{ min/mm}$ was found, with a standard error of 0.01 min/mm, and a coefficient of variation of 7.1% (White, 2006). This corresponds to an equivalent charring rate of $\beta = 0.649 \text{ mm/min}$. When considering the non-linear equation a mean value of $m_{a=1.23} = 0.653 \text{ min/mm}^{1.23}$, with a standard error of 0.006 min/mm^{1.23}, and a coefficient of variation of 7.1% was found (White, 2006). This is equivalent to a charring rate of $\beta = 0.658 \text{ mm/min}$ using Equation 21.

The exponent a was also investigated. A regression analysis of the test results produced a mean estimate of $a = 1.151$ with a standard error of the estimate of 0.006 (White, 2006). From the small vertical furnace tests, it was concluded that charring rates for composite lumber products were within the range of values previously found for different species of solid-sawn lumber (White, 2006).

A great deal more scatter was present in the horizontal furnace test results. White believed that this was due to the difficulty of placing the thermocouples at a specific location. Even with the scatter when the average m_1 results for 10

specimens that were tested in both the horizontal furnace and small vertical furnace were compared using a regression line with a zero intercept, the slope was found to be 1.001 with $R^2 = 0.5268$. White ascribes the low R^2 value with the high variability in the horizontal furnace results. TR10 uses $m_{a=1.23} = 0.682 \text{ min/mm}^{1.23}$ ($\beta = 0.635 \text{ mm/min}$), which is slightly larger than the value published by White, and results in a slower charring rate. The results are summarized below in Table 4.

Table 4: Summary of the Work of White (2006)

	Reciprocal Char Rate	β (mm/min)	Standard Error (mm/min)	Coefficient of Variation (%)
$m_{a=1}$	1.54 min/mm	0.649	0.01	7.1
$m_{a=1.23}$	0.652 min/mm ^{1.23}	0.658	0.006	7.1

Figure 3 is a plot of the depth of char versus time using equations 22 and 16 with the appropriate charring rates found in Table 4. The varying charring rate method and the constant charring rate method are equal at $t = 64.6 \text{ min}$. This is close to the assumption of 60 minutes used in TR10.

Figure 3: Depth of Char vs. Time Based on Table 4

2.3.4 Comparison of Charring Rates

Based on the material properties of glulam members typically used in Canada (Douglas Fir-Larch and Spruce-Pine) the charring rates presented in Sections 2.3.1 to 2.3.3 have been calculated. From the Wood Design Manual (CWC, 2001) the densities of the members were obtained: Douglas Fir-Larch (D. Fir-Larch) $\rho = 490 \text{ kg/m}^3$ and Spruce-Pine $\rho = 440 \text{ kg/m}^3$. The charring depth models produced are:

- (1) The generally accepted North American constant charring rate equal to 0.635 mm/min was used in conjunction with the linear charring depth (Equation 7).

- (2) The constant charring rate proposed by White (2006) equal to 0.649 mm/min is used in conjunction with the linear charring depth (Equation 7).
- (3) The Australian Code (Equation 8) is used with the linear charring depth (Equation 7) using the two densities listed above.
- (4) The charring depth based on Schaffer (1967) (Equation 9) using the above densities is calculated. To use the data in Table 2, the species are assumed to be Douglas Fir and Southern Pine with a moisture content of 12%.
- (5) The varying charring depth equation (Equation 19) is used in conjunction with the charring rate used in TR10 equal to 0.635 mm/min.
- (6) The varying charring depth equation (Equation 19) is used in conjunction with the charring rate proposed by White in Table 4 equal to 0.658 mm/min.

The work of Syme (1994) (Equation 9) is not presented because the species selected for comparison do not fall in the range of densities for which the equation was developed. The complex equations proposed by White and Nordheim (Equations 11 to 15) are not used due to insufficient information.

Table 5 shows the charring depths at 60 minutes, 90 minutes and 120 minutes.

Table 5: Charring Depths

Method		Charring Depth (mm)		
		60 min	90 min	120 min
Constant - North America	(1)	38.1	57.2	76.2
Constant - White	(2)	38.9	58.4	77.9
Schaffer - D. Fir-Larch	(4)	35.2	52.8	70.4
Australia - D. Fir-Larch	(3)	43.6	65.4	87.2
Schaffer - Spruce-Pine	(4)	47.4	71.2	94.9
Australia - Spruce-Pine	(3)	48.3	72.4	96.6
Varying -TR10	(5)	38.1	53.0	66.9
Varying - White	(6)	39.5	54.9	69.3

The equations from Schaffer and the Australian code produce similar results for Spruce-Pine members. The Australian Code, along with Schaffer Spruce-Pine produce much larger charring depths than the work of White, TR10, and Shaffer D. Fir-Larch. The results of Schaffer differ the most between the two species. This could be due to the usage of improper regression constants from Table 2.

Figure 4 shows a plot of the depth of char versus time. From this graph, it is clear that there is a large variability in the predicted charring rates. At 60 minutes, the spread in the depth of char is approximately 13 millimetres, and at 120 minutes, it is approximately 27 millimetres.

Figure 4: Comparison of Charring Rates vs. Time

2.3.5 Corner Rounding

The result of heat transfer from two exposed surfaces causes high temperatures and greater charring at corners. This causes corner rounding on large glulam members. Figure 5 shows the depth of charring, original and residual cross sections and the rounded corners.

Figure 5: Rounded Corner (Buchanan, 2002)

The radius of arris rounding depicted in Figure 5 is typically defined as the depth of char, which as stated by Buchanan (2002) is supported by Hadvig (1981). Also referenced by Buchanan (2002), Marjamaa (1991) suggests a radius equal to 80% of the char depth, and the Eurocode 5 (1995) suggests a radius similar to the char depth for the first 30 minutes of exposure, and a radius smaller than the char depth afterwards. The area of wood that is removed by corner rounding is equal to:

$$A = 0.215r^2 \quad (25)$$

where A (mm^2) is the area of the lost wood as shown in Figure 5 and r (mm) is the radius of the rounded corner. The area, A , has a centre of gravity located at a height, y (mm), where:

$$y = 0.223r \quad (26)$$

In many models, corner rounding is not accounted for explicitly due to the small effect it typically has on the outcome. Technical Report 10 (AF&PA, 2003) accounts for corner rounding by incorporating it in a 20% increase in the charring

rate. The increase also accounts for the reduction of stiffness and strength of the heated zone as described in the next section.

2.3.6 Reduction of Member Properties

The effects of increased temperature on a cross section can be accounted for in various ways. These include reducing the material properties of the cross section, reducing the dimensions of the cross section, or increasing the charring rate.

Increases in temperature cause reductions in the modulus of elasticity and strength properties. Two common methods that are employed when modelling to account for material property reductions are to consider the entire cross section at a single elevated temperature beneath the char layer, or to consider a heated zone of depth, a , beneath the char layer to be at an elevated temperature as shown in Figure 2.

T. T. Lie (1977) considered a uniform reduction in material properties beneath the char layer. He stated that for various woods exposed to typical fire conditions, the ultimate strength reduces to about 0.85-0.90 of the original strength at room temperature, based on the work of Dorn and Egner (1960), Ödeen (1970) and Tenning (1970). Lie indicated that the reduction for the modulus of elasticity is in the same range. To account for corner rounding Lie selected a slightly greater reduction to 0.80 of the strength at room temperature.

Buchanan (2002) published several graphs summarizing the effects of increased temperature on material properties. Of interest are the modulus of elasticity parallel to the grain, tensile strength parallel to the grain, compression strength parallel to the grain and bending strength. In Figure 6 through Figure 10, a wide variation in the reductions in these properties at elevated temperatures as reported by researchers is observed. Van Zeeland et al. (2004) state that since most strength-reduction models are based on test data, (i.e., they are empirical), the test method used to collect data has a large impact on the results. Tests can involve heating a specimen to the desired exposure temperature then loading it, or loading it then heating it.

2.3.6.1 Relative Modulus of Elasticity Parallel to Grain

For modulus of elasticity of wood parallel to the grain, Figure 6 shows the work of Nyman (1980), Östman (1985), Shaffer (1973) and Preusser (1968) compiled by Gerhards (1982), as reported by Buchanan (2002). Buchanan also included the work of König and Walleij (2000). As the temperature increases, the modulus of elasticity is shown to decrease. Up to 200°C, the relationship between temperature and modulus of elasticity is linear for all reported work, with the exception of that of König and Walleij, and Östman. The work of König and Walleij shows a linear relationship between 0°C and 100°C, and at 100°C, there is a reduction in slope, and the relationship continues to be linear until 300°C.

Östman has a small decrease in slope at 100°C. As the tests approach 300°C the differences in the various results become much more significant.

Figure 6: Relative Modulus of Elasticity Parallel to the Grain Versus Temperature (Buchanan, 2002)

The results presented by König and Walleij may differ from the other test results for several reasons. König and Walleij only exposed one side of the members to fire and used repeat loading during testing. Different loading rates may have been used, and when high loading rates are used in many tests the effect of time dependent creep before the wood dries out is not fully accounted for, or not accounted for at all (König and Walleij, 2000). Moisture was also present in the specimens tested by König and Walleij, whereas others may have been oven dried. A controlled level of moisture is very difficult to maintain. As drying occurs the modulus of elasticity increases.

2.3.6.2 Relative Tensile Strength Parallel to the Grain

The work pertaining to relative tensile strength by Östman (1985), Shaffer (1973), Knudson and Schneiwind (1975), Lau and Barrett (1997) and König and Walleij (2000) is shown in Figure 7 which is adapted from Gerhards (1982). The work of Lau and Barrett shows brittle characteristics over 200°C, and failure typically occurred at the weakest point, which was usually a knot. The moisture content of the specimens was not the same for each researcher.

Figure 7: Relative Tensile Strength Parallel to the Grain Versus Temperature (Buchanan, 2002)

2.3.6.3 Relative Compressive Strength Parallel to the Grain

Figure 8 shows the graph adapted from Lau and Barrett (1977). It contains results referenced by Gerhards (1982) as well as the relationship presented by König and Walleij (2000). The work of König and Walleij follow previous moist wood results until 100°C and then follows a straight line to zero-strength at 300°C. The results of König and Walleij were based on compressive strength in

bending, and as a result may not be appropriate for axial compressive strength (Van Zeeland et al., 2004).

Figure 8: Relative Compressive Strength Versus Temperature (Buchanan, 2002)

Van Zeeland et al. (2004) also published a summary of the work of various researchers, on the percentage-compression-strength reduction models. Table 6 shows the summary table that was developed. P is the percentage of the original strength still present.

Table 6: Percentage-Compressive-Strength Reduction Models (Van Zeeland et. al., 2004)

Authors	Model	Temperature range (°C)	Wood species	Specimen size (mm)	Moisture content	Testing conditions
Kollman(1940)	$P = 105 - 0.25T$	$20 \leq T \leq 220$	Fir and beech	$20 \times 20 \times 30$	Some kiln-dried, some air-dried, some 12% MC	Clear specimens
Schaffier (1971)	$P = 102.8 - 0.1139T$ $P = 126.1 - 0.4509T$ $P = 80.25 - 0.155T$ $P = 119.9 - 0.3502T$	$25 \leq T < 68.9$ $68.9 \leq T < 154.8$ $154.8 \leq T < 203.2$ $203.2 \leq T \leq 342.4$	Douglas-fir	$3 \times 25 \times 95$	Vacuum-dried	Clear specimens; fully heated to exposure temperature, then constant strain-rate applied to failure
Knudson and Schniewind (1975)	$P = 106 - 0.29T$	$20 \leq T \leq 288$	Douglas-fir	$5 \times 5 \times 19$	12% MC	Clear specimens; fully heated to exposure temperature, then ramp-load applied to failure
Rykov(1980)	$P = 122.3 - 1.114T$ $P = 72 - 0.2T$	$20 \leq T < 55$ $55 \leq T \leq 190$	Unknown	Unknown	Unknown	Unknown
Hosser <i>et al.</i> (1994)	$P = 111.4 - 0.57T$	$20 \leq T \leq 160$	Unknown	Unknown	Unknown	Unknown
Young and Clancy (2001)	$P = 115 - 0.75T$ $P = -760 + 8T$ $P = 168.9 - 0.444T$ $P = 240 - 0.8T$	$20 \leq T < 100$ $100 \leq T < 110$ $110 \leq T < 200$ $200 \leq T \leq 250$	<i>Radiata</i> pine	$90 \times 35 \times 300$	~12% MC below 100°C, oven-dry above 100°C	Fully heated to exposure temperature, then constant strain-rate applied to failure
König and Walleij (2000)	$P = 118.8 - 0.9375T$ $P = 37.5 - 0.125T$	$20 \leq T < 100$ $100 \leq T \leq 300$	Spruce	45×195 cross-section	12% – 13%	Relatively clear specimens; bending tests used; exposed to fire on compression side

Van Zeeland compared the predictions of the authors' models to test data obtained by testing 35 mm x 89 mm Spruce-Pine-Fir specimens that were 1.22 m long. Crushing failure was the desired failure mode so short specimens were used to reduce the likelihood of buckling. The members were conditioned indoors for three months, and during this time the moisture content was stabilized between 8% and 12%. The samples were heated by conductive heat transfer from aluminium platens that surrounded the member. The specimens were heated and loaded simultaneously.

A computer program called *HTExposure* was developed to predict the failure times. Initial member properties were assumed uniform throughout the cross section. In the simulations, a temperature gradient was modelled. The cross section was divided into discrete elements instead of layers (Van Zeeland et al., 2004). By checking the five highest temperature and load combinations Van

Zeeland et al. found that the correlations developed by Kollman (1940), Schaffer (1971), Knudson and Schniewind (1975), and Young and Clancy (2001) all over-predicted the actual average percentage of compression strength remaining during exposure and were unable to predict failure using any of the temperature/load combinations. No further analysis was performed with these methods. The König and Walleij (2000) correlation was consistently safe, and predicted higher failure rates and quicker times to failure than what was observed during the tests. As mentioned previously their model was based on compression strength in bending which may not be the best method to predict axial compression strength. In addition, their model between 100°C and 300°C was an approximation because it does not account for the effects of drying, since drying would result in a smaller reduction than presented (König et al., 2000). The Rykov (1980) correlation consistently predicted non-conservative times to failure, and extrapolation was required because the model presented was only valid for temperatures up to 180°C. The model developed by Hosser et al. (1994) also required extrapolation, but predicted the best fit for the failure times when compared to the experimental results.

Van Zeeland et al. (2004) proposed a new model that matches the Young and Clancy model for temperatures up to 100°C and goes to zero relative compressive strength at 300°C.

For temperatures between 0°C and 100°C:

$$P = 115 - 0.75T \quad (27)$$

For temperatures between 100°C and 300°C:

$$P = 60 - 0.20T \quad (28)$$

where P (%) is the percentage of the original strength still present, and T (°C) is the temperature of the wood. Figure 9 below shows the models of Rykov, Hosser et al., König and Walleij as well as the model proposed by Van Zeeland et al.

Figure 9: Compression-Strength Reduction Models (Van Zeeland et al., 2004)

2.3.6.4 Relative Bending Strength

As with all the other member properties, the bending strength decreases with increased temperature. Dry wood retains a larger percentage of the original strength than wood with a moisture content greater than 12%. Buchanan (2002) presents Figure 10 adapted from Gerhards (1982). There have been few tests

assessing bending strength. In bending, the moisture in the wood increases the likelihood of the onset of plastic behaviour, causing large deformations. The work of Glos and Henrici (1991), as well as Kordina and Meyer-Ottens (1983) are shown along with the shaded areas based on the results collected by Gerhards (1982).

Figure 10: Relative Bending Strength Versus Temperature (Buchanan, 2002)

2.3.6.5 Eurocode 5 Zero-Strength Layer

Another method to account for the strength reduction of the elevated temperature section next to the char front is to consider a portion of the cross section to have zero-strength. A zero-strength layer of thickness z surrounding all surfaces directly below the char layer is assumed, with all of the remaining cross section considered to be at ambient temperature. The total depth for which strength is lost, x_t is the sum of the char depth and the zero strength layer.

$$x_t = x_c + z \quad (29)$$

Figure 11 shows the variables on sample cross sections:

Figure 11: Depiction of Zero-Strength Layer

To account for the reduction, the Australian code uses a zero-strength layer of 7.5 mm resulting in a total depth lost x_t of:

$$x_t = \beta t + 7.5 \quad (30)$$

According to Buchanan (2002), Eurocode 5 (1994) offers the option of assuming a zero-strength layer of 7 mm for exposures greater than 20 minutes and a linear relationship between zero and 7 mm for times between zero and 20 minutes:

$$x_t = x_c + \left(\frac{t}{20}\right) 7.0 \quad t \leq 20 \text{ min} \quad (31)$$

$$x_t = x_c + 7.0 \quad t > 20 \text{ min} \quad (32)$$

When this option is employed, a charring rate increased by 10% is to be used along with no corner rounding. The zero-strength layer with full loss of strength for seven millimetres is similar to considering a heat-affected layer with a thickness of 35 millimetres having a 20% reduction in material properties.

2.3.6.6 Eurocode 5 Material Properties Reduction Factors

Eurocode 5 (1994) also offers the option of using a reduced properties method to account for the effects of fire. Beneath the char layer, wood is considered to be at a uniform temperature, with the material properties reduced by a factor k_f . This factor is calculated based on the dimensions of the residual cross section, and applied to the residual cross section. Eurocode 5 also recommends that corner rounding be accounted for explicitly; however, increasing the charring rate by 10% is an acceptable, but less accurate method of accounting for the corner rounding. The equation for k_f is as follows:

$$k_f = 1.0 - \frac{1}{g(A_r \times 10^3 / p)} \quad (33)$$

where A_r (mm²) is the area of the residual cross section, p (mm) is the exposed perimeter of the residual cross section, and g is a factor equal to 200 for bending, 125 for compression and 330 for tension and modulus of elasticity (Buchanan, 2002).

2.3.6.7 Increasing Charring Rate

TR10 recommends increasing the charring rate by 20% to account for the reductions in the material properties, resulting in a smaller ambient cross section. This increase is similar to an equivalent zero-strength thickness of approximately 8 mm per hour of exposure (Buchanan, 2002).

2.3.6.8 Summary

Table 7 shows a summary of the different methods for reducing member properties.

Table 7: Summary of Reduction of Member Properties

	Cross Section	Methods Used	Account for Corner Rounding
T. T. Lie	Reduced Properties Method	<ul style="list-style-type: none"> Reduction factor of $\alpha = 0.8$ was used Constant charring rate $x_c = \beta t$ 	No
Eurocode 5	Reduced Properties Method	<ul style="list-style-type: none"> Reduction factor: $k_t = 1.0 - \frac{1}{g(A_r/p)}$ Constant charring rate $x_c = \beta t$ (increased by 10% if corner rounding is not modelled) 	Yes
Eurocode 5	Effective Cross Section Method	<ul style="list-style-type: none"> Zero-strength layer: $z = (7.0/20)t$ mm for $t \leq 20$ min $z = 7.0$ mm for $t > 20$ min Constant charring rate increased by 10% $x_c = 1.1\beta t$ 	No
Australian Code	Effective Cross Section Method	<ul style="list-style-type: none"> Zero-strength layer: $z = 7.5$ mm Constant charring rate $\beta = 0.4 + (280/\rho)^2$ $x_c = \beta t + 7.5\text{mm}$ 	No
Technical Report 10	Effective Cross Section Method	<ul style="list-style-type: none"> Varying charring rate increased by 20% $x_c = 1.2\beta_e t$ $\beta_e = 2.15\beta_n / t^{0.187}$ 	No

2.4 Review of T. T. Lie's Models

The current Canadian methods for determining the failure time of glulam beams and columns in the National Building Code of Canada (2005) Article D-2.11.2.1 are based on the work of T. T. Lie (1977).

2.4.1 Modelling the Performance of Beams

Lie (1977) began with the basic equation for the bending moment resistance for a beam. As summarized in Table 7, he then assumed that the cross-sectional area was reduced as the char base advanced at a constant rate and that the bending moment resistance of the residual cross section was reduced by a constant value because it was being heated. Finally, he assumed that failure occurred when the bending moment resistance dropped to the level of the applied bending moment.

The following is the derivation of the final equation for a beam exposed to fire on three sides. The ratio of applied load to allowable load is defined by k . As a result, the applied load is equal to:

$$\text{Applied Load} = k (\text{Allowable Load}) \quad (34)$$

The applied load is equated to the strength at elevated temperature resulting in:

$$k F_b \left(\frac{BD^2}{6} \right) = \alpha F_b \left(\frac{bd^2}{6} \right) \quad (35)$$

which reduces to:

$$k BD^2 = \alpha bd^2 \quad (36)$$

where α is the ratio of the material properties (strength and modulus of elasticity) at elevated temperatures to the material properties at room temperature. B and D (mm) are the original cross section width (smaller dimension) and depth at ambient temperature and b and d (mm) are the critical residual cross section

dimensions at failure after having been exposed to fire for a particular length of time.

Considering that time can be calculated by dividing the depth of char by the charring rate, time is defined as:

$$t = \frac{(D-d)}{\beta} = \frac{(B-b)}{2\beta} \quad (37)$$

resulting in:

$$b = B - 2(D-d) \quad (38)$$

where the constant charring rate is represented by β (mm/min).

By substituting Equation 38 into Equation 36 and rearranging Lie arrived at equations that can be used to determine the failure time implicitly. The original equations were expressed using dimensions in metres. The following equations use dimensions in millimetres. For a beam exposed to fire on three sides, the following equations were derived:

$$\frac{k}{\alpha} \left[\frac{B/D}{B/D - 2(1-d/D)} \right] = \left(\frac{d}{D} \right)^2 \quad (39)$$

$$t_{b3} = \frac{(D-d)}{\beta} \quad (40)$$

where t_{b3} (min) is the failure time of a beam exposed on three sides.

Following the same derivation Lie also presents equations for when four sides are exposed to fire:

$$\frac{k}{\alpha} \left[\frac{B/D}{d/D - (1 - B/D)} \right] = \left(\frac{d}{D} \right)^2 \quad (41)$$

$$t_{b4} = \frac{(D - d)}{2\beta} \quad (42)$$

where t_{b4} (min) is the failure time of a beam exposed to fire on four sides.

2.4.2 Modelling the Performance of Columns

For columns exposed on four sides, two situations were considered: the first is that of a short column, and the second is that of a long column. Lie assumed that short columns fail due to material failure:

$$P = \sigma A \quad (43)$$

where P (N) is the applied load, σ (MPa) is the stress in the cross section and A (mm²) is the area of the cross section.

Lie assumed that long columns fail due to buckling following Euler's formula.

$$P = \frac{\pi^2 EA}{(L_e/r)^2} \quad (44)$$

$$L_e = K_e L \quad (45)$$

where P (N) is the applied load, E (MPa) is the modulus of elasticity, A (mm²) is the cross section area, L_e (mm) is the effective length of the column, L (mm) is the member length, K_e is the effective length factor, which is currently defined by CSA O86-01 in Clause A5.5.6.1 (Table A5.5.6.1) and r (mm) is the radius of gyration. In order to predict the critical cross section dimensions for which failure

would occur, the same method as shown in the earlier derivation for beams exposed to fire on three sides was used and the following general equation was derived for a column exposed to fire on four sides:

$$\frac{k}{\alpha} \left[\frac{B/D}{d/D - (1 - B/D)} \right] = \left(\frac{d}{D} \right)^n \quad (46)$$

with:

$$t_{c4} = \frac{(D - d)}{2\beta} \quad (47)$$

where t_{c4} (min) is the failure time of a column exposed on four sides. The exponent n was found to be $n = 1$ for short columns, and $n = 3$ for long columns.

2.4.3 Approximate Relationships

Since the failure times could not be found explicitly, Lie generated approximate relationships by calibrating simplified equations to match the observed experimental failure times and to account for the approximations. To produce these equations, he used an average charring rate of $\beta = 0.6 \text{ mm/min}$. To account for the reduction of strength and modulus of elasticity he assumed $\alpha = 0.8$.

The initial approximate equations produced were:

For a beam exposed on three sides:

$$t_{b3} = 0.033 \frac{B}{k} \left(4 - \frac{B}{D} \right) \quad (48)$$

For a beam exposed on four sides:

$$t_{b4} = 0.033 \frac{B}{k} \left(4 - 2 \frac{B}{D} \right) \quad (49)$$

For a column exposed on four sides:

$$t_{c4} = 0.033 \frac{B}{k} \left(3 - \frac{B}{D} \right) \quad (50)$$

The predictions of these equations matched the predictions of the more complex equations (Equations 39 to 42, 46 and 47) reasonably well for values of k (applied load / ultimate strength) between 0.2 and 0.5. For Working Stress Design, which was used at the time, a k value of 0.33 was typically assumed. However, for over-designed members with $k < 0.2$ the approximate relationships overestimated considerably the fire resistance (Lie, 1977).

Originally for columns, Lie decided that the influence of factors such as timber species, moisture content, type of glue and slenderness were not significant enough to be taken into account, but later included the effects of slenderness. He chose to focus on column size and shape, and the safety factor. When comparing the predictions of the equations to test data, the safety factors were unknown so a safety factor of three ($k = 0.33$) was assumed. For columns, the test data used by Lie is the same as that used in TR10, and is presented in Table A. 1 and Table A. 2 in Appendix A and discussed in Section 2.6.1. Lie also used

$n = 2$, thereby assuming all columns were of intermediate length, which resulted in the underestimation of the fire resistance of short columns, and the overestimation the fire resistance of long columns. In an effort to improve results by accounting for the slenderness of columns and for the potential over-design, an empirical factor, f , was introduced to the design equations. This factor depended on the effective length, as well as the ratio of applied load to allowable load, and is summarized in Table 8.

Table 8: Values of f (Lie, 1977)

Load (as % of allowable load)	Member Type		
	Beam	Column	
		$L/D > 10$	$L/D \leq 10$
Over 75	1.0	1.0	1.2
Between 50 and 75	1.1	1.1	1.3
Under 50	1.3	1.3	1.5

The final equations Lie produced are as follows:

Beams heated on three sides (Lie, 1977):

$$t_{b3} = 0.1fB \left(4 - \frac{B}{D} \right) \quad (51)$$

Beams heated on four sides (Lie, 1977):

$$t_{b4} = 0.1fB \left(4 - 2\frac{B}{D} \right) \quad (52)$$

Columns heated on three sides (ASCE, 1992):

$$t_{c4} = 0.1fB\left(3 - \frac{B}{2D}\right) \quad (53)$$

Columns heated on four sides (ASCE, 1992):

$$t_{c4} = 0.1fB\left(3 - \frac{B}{D}\right) \quad (54)$$

Due to a lack of experimental results for glulam beams, Lie was unable to compare the beam equations to test data.

A difference of 35% to 40% (Lie, 1977) between calculated and experimental results were still present even after the factor f was implemented. Stanke (1970) and Stanke et al. (1973), as referenced by Lie, state that differences between repeat fire tests of 30% are not uncommon, indicating the fire resistance predictions produced by his equations were reasonably accurate.

2.5 Review of the Current Canadian Method

The method in the current National Building Code of Canada provides equations for calculating the fire-resistance rating of exposed glulam beams and columns when subjected to a standard fire test. As mentioned previously the method is based on the work of T. T. Lie, 1977.

The equations from Article D-2.11.2.1 (NBCC, 2005) are precisely those derived by T. T. Lie as follows:

For beams that may be exposed to fire on three sides:

$$t = 0.1fB\left(4 - \frac{B}{D}\right) \quad (55)$$

For beams that may be exposed to fire on four sides:

$$t = 0.1fB\left(4 - 2\frac{B}{D}\right) \quad (56)$$

For columns that may be exposed to fire on three sides

$$t = 0.1fB\left(3 - \frac{B}{2D}\right) \quad (57)$$

For columns that may be exposed to fire on four sides:

$$t = 0.1fB\left(3 - \frac{B}{D}\right) \quad (58)$$

where f is the load factor shown in Figure 12 (Figure D-2.11.2.-A (NBCC, 2005)), and B and D (mm) are the full dimensions of the smaller and larger side respectively of the original cross section as depicted in Figure 13 (Figure D-2.11.2.-B (NBCC, 2005)). Equations 56 to 57 are only valid for the member orientations shown in Figure 13. When three sides are exposed to fire, the smaller of the two faces must be the unexposed face.

Figure 12 shows the load factor f , and how it varies with the load ratio defined as factored load over factored resistance. Beams and long columns with $KL/B \geq 12$ where K is the effective length factor (K_e) from CSA-O86-01 Clause A5.5.6.1 (Table A5.5.6.1) and L (mm) is the unsupported length of the column are characterised by the same curve for f . Short columns, with $KL/B < 12$ are characterised by a separate curve with larger load factors resulting in longer failure times.

Figure 12: Load factor, f (Figure D-2.11.2.-A (NBCC, 2005))

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Figure 13: Member Orientation (Figure D-2.11.2.-B (NBCC, 2005))

2.6 Review of Technical Report 10

The American Forest & Paper Association (AF&PA) prepared Technical Report 10 (AF&PA, 2003) to provide a method for calculating failure times based on American standards and methods.

A charring depth based on the non-linear model developed by White was used as previously described in Section 2.3.2.2. To account for the reduction of material properties in the heated zone and for rounding of the corners the

charring rate produced by White was increased by 20%. Removing species and moisture content from the equation and including the 20% increase, the resulting effective varying charring rate converted to metric units is:

$$\beta_e = 1.2 \left(\frac{2.15\beta}{t^{0.187}} \right) = \frac{2.58\beta}{t^{0.187}} \quad (59)$$

where the charring rate β equal to 0.635 mm/min (1.50 in/h) was used in the calculations.

Table 9 provides the equations used to define the cross-sectional properties of the members. This table shows equations for members exposed on four sides; however, similar equations could be produced for three-sided exposure.

Table 9: Cross-Sectional Properties for Four-Sided Exposure (AF&PA, 2003)

Cross-sectional Property	Four-Sided Example
Area of the cross-section (mm ²)	$A(t) = (B - 2\beta_e t)(D - 2\beta_e t)$
Section Modulus about the major-axis direction (mm ³)	$S(t) = (B - 2\beta_e t)(D - 2\beta_e t)^2 / 6$
Section Modulus about the minor-axis direction (mm ³)	$S(t) = (B - 2\beta_e t)^2 (D - 2\beta_e t) / 6$
Moment of Inertia about the major-axis direction (mm ⁴)	$I(t) = (D_{\min} - 2\beta_e t)(D_{\max} - 2\beta_e t)^3 / 12$
Moment of Inertia about the minor-axis direction (mm ⁴)	$I(t) = (D_{\min} - 2\beta_e t)^3 (D_{\max} - 2\beta_e t) / 12$

Average ultimate member strengths were used to calculate member resistances and subsequent failure times. These values were obtained by modifying fifth percentile allowable design values typically used in design using the method

described below. The following table taken from TR10 summarizes the values used in order to obtain the average ultimate member properties.

Table 10: Allowable Design Stress to Average Ultimate Strength Adjustment Factors (AF&PA, 2003)

	F	$1/k$	c	Assumed Coefficient of Variation	K
Bending Strength (MPa)	F_b	2.1^1	$1-1.645COV_b$	0.16^2	2.85
Tensile Strength (MPa)	F_t	2.1^1	$1-1.645COV_t$	0.16^2	2.85
Compression Strength (MPa)	F_c	1.9^1	$1-1.645COV_c$	0.16^2	2.58
Buckling Strength (MPa)	E_{05}	1.66^3	$1-1.645COV_E$	0.11^4	2.03

¹ taken from Table 10 of ASTM D 245 Standard Practice for Establishing Structural Grades and Relates Allowable Properties for Visually Graded Lumber

² taken from Table 4-6 of 1999 Wood Handbook

³ taken from Appendices D and H of 1997 National Design Specifications for Wood Construction.

⁴ taken from Sections 3.3.3.8 and 3.7.1.5 of 1997 National Design Specification for Wood Construction.

In Table 10, $1/k$ is the inverse of the applicable design value adjustment factor, c is the variability adjustment factor where COV_b , COV_t , COV_c and COV_E , are the coefficients of variation of the bending strength, tensile strength, compressive strength and buckling strength respectively., and K is the final adjustment factor where,

$$K = \frac{1/k}{c} \quad (60)$$

and:

$$\text{Average Ultimate Stress} = K(\text{Allowable Design Stress}) \quad (61)$$

Using *National Design Specifications for Wood Construction (NDS)* (AF&PA, 1997) the member resistances of seven beams, 63 columns, and three tension members were calculated at incremental time steps as charring progressed until

the applied load was larger than the member resistances. At this time, the member was assumed to have failed. NDS calculations are still based on working stress design.

The material properties of the members were not always readily available. The authors of TR10 used Table 10 and Equation 61 to modify strength values when necessary to obtain $F_{c,avg}$ values. Also, when the ultimate strength or modulus of elasticity values were not provided, but specific gravity was available the following relationships were used:

$$F_{c,avg} = 39922 D^{-0.185} SG^{1.609} \quad (R^2 = 0.76) \quad (62)$$

$$E = 15.1 \times 10^6 D^{-0.390} SG^{1.490} \quad (R^2 = 0.84) \quad (63)$$

The strength values presented in TR10 (AF&PA, 2003) are also used in this thesis since modifying the models for member properties is beyond the scope of this research. End support conditions for the test specimens were assumed to be pin-pin.

2.6.1 Columns

The results of 63 fire tests conducted on columns by various researchers around the world are reported in TR10 and are used to validate the TR10 methodology. The column data is based on the same tests as the work of Lie. Two of the columns were tested by the Centre Scientifique et Technique du Bâtiment

(CSTB) in France on French Maritime Pine, Frackler (1961) and presented by TR10 (AF&PA, 2003). An effective length $L_e = 2286.0$ mm was used in resistance calculations. These columns were the same except for the glue used, but failed at the same time. As a result, only one of the columns is used in this study.

As reported by TR10 (AF&PA, 2003), Stanke et al. (1970) tested many columns in Germany. The species of the members was not recorded, only the specific gravity of the laminations. Load ratios of 1.00, 0.75, and 0.50 were reported by Stanke et al. Two types of adhesive were used; resorcinol (R) and urea based (H). An effective length $L_e = 3658$ mm was used in resistance calculations.

TR10 (AF&PA, 2003) presents 16 glulam column tests by Malhotra and Rogowski (1970) (Stanke et al., 1973) that were performed at the Fire Research Station in the UK. The tests were performed to assess the effect of four factors; species, adhesive, shape and test load. These factors were also used to name the tests. The species is the first letter in the test designation; Douglas Fir (F), western hemlock (H), European redwood (R), and western red cedar (C). The second letter in the designation is the adhesive; urea (U), casein (C), resorcinol (R), and phenolic (P). Three cross-sectional shapes were considered; 229 mm x 229 mm, 305 mm x 175 mm, and 381 mm x 142 mm. Loads of 100%, 50% and 25% of the design load were tested. An effective length $L_e = 2083$ mm was used in resistance calculations.

The member dimensions, properties and observed failure times are reported in Table A. 1 and Table A. 2, which are located in Appendix A of this thesis.

2.6.2 Beams

The seven beams reported in TR10 were tested by four different organizations. The effective lengths shown were calculated in accordance with CSA O86-01.

In 1968 the Timber Research and Development Association (TRADA) in the UK tested one glulam beam which was described by Hall (1968) as reported in TR10 (AF&PA, 2003). The species of this beam was not reported. The beam was tested at an applied load to design load ratio of 80%. At the supports, the beam was braced to resist lateral rotation and translation. The beam was loaded by 11 evenly spaced bearing blocks, which results in an effective length, L_e , equal to:

$$L_e = 1.92 \times l_u = 7008 \text{ mm} \quad (64)$$

where l_u is the unsupported length and is equal to the full span of the beam.

As reported by TR10 (AF&PA, 2003) The National Forest Products Association (NFoPA) which is now the American Forest & Paper Association tested a Douglas Fir glulam beam in 1986. The beam was tested at an applied load to design load ratio of 72% (King & Glowinski, 1988). The load was applied to the beam by three hydraulic cylinders at the quarter points without bracing. Restraint

against lateral rotation and translation was provided at the supports resulting in an effective length, L_e , equal to:

$$L_e = 1.92 \times l_u = 9930 \text{ mm} \quad (65)$$

where l_u is equal to the full span of the beam.

The AF&PA tested four glulam beams in 1997 (SwRI, 1997) as reported by TR10 (AF&PA, 2003), however one of the four was not loaded. The three beams that were loaded were tested at applied load to design load ratios of 27%, 44% and 91%. The species of these members are unknown. Lateral rotation and translation was resisted at the supports. Bracing was provided at the two load points that were evenly spaced along the beam. This resulted in an effective length, L_e , equal to:

$$L_e = 1.68 \times l_u = 2650 \text{ mm} \quad (66)$$

where l_u is equal to one-third the full span of the beam.

The final two beams were tested by the Forestry Commission of New South Wales (FCNSW) (Syme 1994, and Dayeh and Syme 1993) as reported by TR10 (AF&PA, 2003). The beams were made of Brush Box and Radiata Pine and were tested to design load ratios of 46% and 18% respectively. The beams were loaded and braced against rotation at the third points along the beam, and were restrained against lateral translation and rotation resulting in an effective length, L_e , equal to:

$$L_e = 1.68 \times l_u = 2246 \text{ mm} \quad (67)$$

where l_u is equal to one-third the full span of the beam.

The member dimensions, properties and observed failure times are found in Table A. 3, which is located in Appendix A of this thesis.

2.6.3 Tension Members

The tension members were tested by AF&PA in 2000. The results from the tests on three members were presented in TR10 (AF&PA, 2003), and were taken from the work of White (2001). The tension members were made from Douglas Fir and were 2972 mm long. The third tension member presented (Test 4) with the largest failure time was loaded with 26.7 kN for the first 120 minutes of the test. Since failure did not occur, the load was gradually increased until failure took place. The member dimensions, properties and observed failure times are found in Table A. 4, which is located in Appendix A of this thesis.

2.6.4 Predictions – TR10

Summary Tables in Appendix B of this thesis compare the observed times to failure (from experiments) and the predicted times to failure (from TR10 calculations). Figure 14 to Figure 16 show the results of predicted time to failure versus observed time to failure for columns, beams and tension members. A

trendline has been added to the data presented by TR10 to provide a measure of fit for the TR10 predictions.

Figure 14: Predicted Time (TR10) versus Observed Time to Failure of Columns

Figure 15: Predicted Time (TR10) versus Observed Time to Failure of Beams

Figure 16: Predicted Time (TR10) versus Observed Time to Failure of Tension Members

Applying linear trendlines to the data the following equations and R^2 values were determined:

Table 11: Trendline Equations

Member	Trendline Equation	R^2	Residuals	Average Residuals per Member
Columns	$y = 1.020x - 5.690$	0.679	9999	161
Beams	$y = 0.992x - 0.867$	0.907	693	99
Tension	$y = x + 2.000$	1.000	12	4

where y (min) is the predicted time to failure and x (min) is the observed time to failure. TR10 produces acceptable results so therefore they are used as points of reference for measuring the fit of the methods analyzed in this thesis. However, since they are based on the American NDS Working Stress Design method, it was decided to undertake a similar modelling exercise using Canadian standards and design methods and to employ the wealth of experimental data available in TR10 to validate (or calibrate) the Canadian approach. The low R^2 values for beams could be caused by the uncertainty or variability in the material properties and the different test setups used. For beams and tension members, statistically there are not many data points, however the tests presented are all that is available.

2.6.5 Predictions of T. T. Lie Models as Cited in TR10

TR10 presents the predicted failure times of the tested beams and columns based on the work of T. T. Lie (Equations 56 to 57 and Figure 12) with a small

modification to the load factor, f . The division between short and long columns was used as $KL/D=11$, not $KL/D=12$ as is used in the NBCC (2005). The specified load ratios used were those presented by the respective authors of the tests. They were based on the standards in the countries of origin, not those calculated using the resistance based on the NDS (AF&PA, 1997) equations and the specified applied load. As a result, the predictions by Lie's method presented in TR10 differed from those presented later in this report where efforts are made to apply the Canadian methods in a more systematic manner.

3.0 Assessment of the Current NBCC Method

In the following sections the results produced using the current NBCC method are examined. In addition, the effect of the change from Working Stress Design (WSD) to Limit States Design (LSD) on Figure 12 (NBCC Figure D-2.11.2.-A) is evaluated.

3.1 Results from Current Method

In order to assess the predictions of the NBCC method, an effective load factor is introduced for beams exposed to fire on three sides and columns exposed to fire on four sides. This effective load factor, f_{eff} , is the load factor that in conjunction with Equations 56 to 57 is required to produce the observed failure times of glulam members. The observed failure times, member dimensions, and material properties were obtained from the test results presented in TR10 (Appendix A). If the effective load factor for a member is less than the values currently used in the NBCC, this indicates that the current method predicts larger than observed failure times, indicating non-conservative results. When the effective load factor is greater than the currently used values, the current method produces a shorter time to failure, which is conservative.

The factored resistances were calculated in accordance with CSA O86-01 using the ambient temperature equations defined later in Section 4.1.3. Fifth percentile ultimate strength values used were calculated from average ultimate strengths as described later in Section 4.3.2, and the factored load was calculated using an

equivalent load factor as described later in Section 4.3.1. Since the coefficient of variation (COV) of material properties was selected on the low side of the acceptable range, the strength values of the members are on the high side, resulting in larger factored resistances and therefore smaller load ratios. This produces a shift along the abscissa of Figure 12 to the left and indicates that the actual load factor specified by the code may be larger than if a larger COV was used. As a result, the results are somewhat non-conservative; however, the following graphs are for illustrative purposes only.

Figure 17, Figure 18 and Figure 19 are graphs showing the effective load factor, as well as the load factor used currently in the NBCC for glulam members. Figure 17 shows that for beams, the dependency of the effective load factor as a function of the load ratio is quite different than the dependency of the load factor values that are currently used. Four of the seven beams require effective load factors less than those currently employed by the NBCC (2005). For these four beams, the current method is not conservative.

Figure 17: Effective Load Factor Based on Test Results for Beams

For short columns, 30% of the members have effective load factor values less than those presented by NBCC 2005, and 30% are greater, as seen in Figure 18. However, for short columns 40% are very heavily loaded and as a result when using factored loads and factored resistances the columns have load ratios greater than one. Although these members would not be designed or built under Canadian standards, these members are retained in the analysis herein.

Figure 18: Effective Load Factor Based on Test Results for Short Columns

Figure 19 shows that 61% of long columns considered have calculated f_{eff} values below the values provided in the NBCC. Consequently, for those columns the NBCC produces non-conservative results. For long columns, there is also one test point that has a load ratio greater than one.

Figure 19: Effective Load Factor Based on Test Results for Long Columns

The majority of the column tests tend to group between a load ratio of 0.55 and 0.75. This may be because many of the specimens were originally tested at a load ratio of 0.75 using the design codes of the countries where the tests were performed to evaluate the factored resistance. However, when the factored loads and resistances are calculated in accordance with CSA O86-01, some scatter is produced.

Figure 20 and Figure 21 show the predicted times to failure following the NBCC method plotted versus the observed times to failure. When the design load ratio is greater than one, the load factor value at a load ratio equal to one is used in calculating the failure time. If the trendline slope is close to one, the trend of the results closely matches the observed results. The value of the residuals for the

columns is good; however, for the beams the value is large. The results are summarized in Table 12.

Table 12: NBCC Method Results

Member	Trendline Equation	R ²	Residuals	Average Residuals per Member	
Column	$y=0.629x+19.072$	0.749	4778	77	Figure 20
Beam	$y=0.480x+41.199$	0.658	2735	391	Figure 21

The main concern is that for 38 of the 62 columns, the NBCC method over predicts the failure time of the member producing non-conservative results.

Figure 20: Predicted Time to Failure of Columns Using NBCC Method

For beams, four of the seven members have predicted failure times larger than those observed. The method presented in the NBCC does not accurately predict the failure times for beams. The trendline has a slope significantly less than one, and value of the residuals is very high.

Figure 21: Predicted Time to Failure of Beams Using NBCC Method

From Figure 20 and Figure 21 it is evident that a new method for predicting fire resistance ratings of glulam beams and columns is required.

3.2 Effects of Changing from WSD to LSD

When the CSA O86 design philosophy shifted from Working Stress Design (WSD) to Limit States Design (LSD), the label of the abscissa of Figure 12

(NBCC Figure D-2.11.2-A) was changed from a ratio of Applied Load divided by Allowable Load in WSD, to a ratio of Factored Load divided by Factored Resistance in LSD. No other changes were made to the graph or to the scale of the axis. The following discussion examines the validity of this direct change.

A variable q is introduced in Equation 68 to determine the difference between the WSD load ratio compared to the LSD load ratio. If $q = 1$ then a direct change is justified. When $q < 1$ the location on the abscissa of Figure 12 shifts to the right resulting in potentially smaller f values, and shorter failure times, therefore more conservative results. When $q > 1$ less conservative results are produced due to shifting the location on the abscissa in Figure 12 to the left resulting in potentially larger f values.

$$\left(\frac{\text{Applied Load}}{\text{Allowable Load}} \right)_{WSD} = q \left(\frac{\text{Factored Load}}{\text{Factored Resistance}} \right)_{LSD} \quad (68)$$

Under WSD, the applied load was defined as:

$$\text{Applied Load} = D + L \quad (69)$$

and under LSD the factored load is defined as:

$$\text{Factored Load} = 1.25D + 1.5L \quad (70)$$

where D is the dead load, and L is the live load. A live load to dead load ratio $L/D = 4$ is assumed. This is typical for wood construction (ULC, 2004) because typical residential and light industrial structural applications for wood have dead loads ranging from 0.5 kPa to 1.0 kPa with live loads (occupancy and/or snow

loads) ranging from 1.5 to 2.5 kPa. Therefore, a L/D ratio of four is a reasonable assumption. The sensitivity of conclusions in this section to the choice of this ratio is investigated in Section 3.2.3. The WSD allowable load is defined in accordance with CAN3-O86-M80 in the following sections. The LSD factored resistance is defined in accordance with CSA O86-01.

In order to simplify the equations, typical ratios of strength to modulus of elasticity are used. These values are found by comparing the values in CSA O86-01 (LSD) and CAN3-O86-M80 (WSD). Table 13 and Table 14 summarize the ratios used. The allowable stress in compression parallel to the grain is defined by $F_{C,WSD}$, $F_{b,WSD}$ is the allowable stress in bending and E_{WSD} is the modulus of elasticity all in accordance with CAN3-O86-M80 (WSD). The specified fifth percentile strength in compression parallel to the grain is referred to as $f_{c,LSD}$, $f_{b,LSD}$ is the specified fifth percentile strength in bending, and E_{LSD} is the modulus of elasticity, all in accordance with CSA O86-01 (LSD).

Table 13: Compression Ratios Comparing WSD and LSD Values

	D. Fir-Larch	Lodgepole Pine and/or Spruce	Ratios
	Compression	Compression	Compression
Grade	16c-E	12c-E	
$F_{c,WSD}$ (MPa)	11		
$f_{c,LSD}$ (MPa)	30.2	25.2	
$f_{c,LSD} / F_{c,WSD}$	2.745		2.75
E_{WSD} (MPa)	12400		
E_{LSD} (MPa)	12400	10300	
E_{LSD} / E_{WSD}	1		1
$E_{WSD} / F_{c,WSD}$	1127		1127
$f_{c,LSD} / E_{LSD}$	0.0024	0.0024	0.0024
$f_{c,LSD} / E_{WSD}$	0.0024		0.0024

Table 14: Bending Ratio Comparing WSD and LSD Values

	Douglas Fir - Larch		Hemlock- Fir Douglas Fir - Larch	Lodgepole Pine and/or Spruce	Ratio
	Bending		Bending	Bending	
Grade	24f-E 24f-EX	20f-E 20f-EX	24f-E 24f-EX	20f-E 20f-EX	
$F_{b,WSD}$ (MPa)	16.5	13.8	16.5	13.8	
$f_{b,LSD}$ (MPa)	30.6	25.6	30.6	25.6	
$f_{b,LSD} / F_{b,WSD}$	1.855	1.855	1.855	1.855	1.855

3.2.1 Columns

For the factored compressive resistance, P_r (N), based on LSD:

$$P_r = (\phi F_c K_{Zcg} K_C A)_{LSD} \quad (71)$$

$$F_c = (f_c K_D K_H K_{Sc} K_T)_{LSD} \quad (72)$$

where the resistance factor ϕ is 0.8, f_c (MPa) is the specified strength in compression parallel to the grain and A (mm²) is the cross-sectional area. K_D is the load duration factor, K_H is the system factor, K_{Sc} is the service condition factor

for compression parallel to the grain, K_T is the treatment factor, and K_{Zcg} is the size factor. Assuming standard duration loading, no system factor, dry service conditions, and untreated wood, $K_D K_H K_{SC} K_T = 1$.

For column dimensions in millimetres, the size factor, K_{Zcg} , is defined by the equation:

$$K_{Zcg} = 0.68(AL \times 10^{-9})^{-0.13} \quad (73)$$

where A (mm²) is the cross-sectional area and L (mm) is the member length. In Equation 71 K_C is the slenderness factor defined by:

$$K_C = \left[1 + \frac{F_C K_{Zcg} C_C^3}{35 E_{05} K_{SE} K_T} \right]_{LSD}^{-1} \quad (74)$$

with:

$$E_{05} = 0.87E \quad (75)$$

$$C_C = L_e / B \quad (76)$$

where E_{05} (MPa) is the modulus of elasticity for the design of compression members and E (MPa) is the specified modulus of elasticity. Also, C_C is the slenderness ratio, L_e (mm) is the unsupported length, and B (mm) is the smaller cross-sectional dimension. K_{SE} is the service condition factor for the modulus of elasticity. Due to the dry service conditions and untreated wood, it is assumed that $K_{SE} K_T = 1.0$.

The ratio $f_{c,LSD}/E_{LSD} = 0.0024$ from Table 13 is applied and K_C reduces to:

$$K_C = \left[1 + 0.68(AL \times 10^{-9})^{-0.13} \frac{0.0024 \left(\frac{L_e}{B} \right)^3}{30.45} \right]_{LSD}^{-1} \quad (77)$$

When calculating the allowable load using Working Stress Design, it is necessary to consider three different conditions, corresponding to short, medium and long columns. Although CSA O86-01 has only one equation for column strength, as a function of slenderness, CAN3-O86-M80 separates the columns into three divisions based on their slenderness. For all three types of columns, the following equation is applied with the slenderness factor, K_C , varying depending on the slenderness ratio.

$$P_{allowable} = (F_c K_T K_D K_C A)_{WSD} \quad (78)$$

where F_c (MPa) is the allowable stress in compression parallel to the grain at normal duration of load and A (mm²) is the net area. The member is assumed to be untreated therefore, the treatment factor, $K_T = 1.0$ and is assumed to undergo normal duration loading therefore, the load duration factor, $K_D = 1.0$.

3.2.1.1 Short Columns

For a short column in WSD $L_e/B < 10$ where L_e is the effective length, and B is the width of the column, $K_C = 1$, therefore Equation 78 reduces to:

$$P_{allowable} = F_c A \quad (79)$$

Substituting Equations 69 to 72, 77 and 79 into Equation 68 the following equation is obtained:

$$\left(\frac{D+L}{F_c A}\right)_{WSD} = q \left\{ \frac{1.25D + 1.5L}{\phi f_c 0.68(AL \times 10^{-9})^{-0.13} \left[1 + 0.68(AL)^{-0.13} \frac{0.0024}{30.45} \left(\frac{L_e}{B}\right)^3 \right]^{-1} A} \right\}_{LSD} \quad (80)$$

Dividing both numerators by D and applying the live to dead load ratio $L/D = 4$ the numerator can be simplified. The area terms (A) on each side cancel. The ratio $f_{c,LSD}/F_{c,WSD} = 2.75$ from Table 13 is applied. Combining all these factors the variables D, L, A, and F_c on the WSD side of the equation cancel with those on the LSD side resulting in a value of one. The final equation reduces to:

$$\left(\frac{1}{1}\right)_{WSD} = q \left\{ \frac{1.45}{1.493(AL \times 10^{-9})^{-0.13} \left[1 + 5.360 \times 10^{-5} (AL)^{-0.13} \left(\frac{L_e}{B}\right)^3 \right]^{-1} } \right\}_{LSD} \quad (81)$$

3.2.1.2 Intermediate Columns

In WSD, an intermediate column ranges from $10 < L_e/B < C_K$. Where the stiffness ratio of a compression member C_K is defined as:

$$C_K = \left(0.641 \sqrt{\frac{E}{F_c}} \right)_{WSD} \quad (82)$$

From Table 13 the ratio of $E_{WSD}/F_{C,WSD} = 1127$ is applied. This results in $C_K = 21.5$. For an intermediate column, K_C is defined as follows:

$$K_C = 1 - \frac{1}{3} \left(\frac{C_C}{C_K} \right)^4 \quad (83)$$

where C_C is the slenderness ratio previously defined by Equation 76.

Substituting equations 82 and 83 into Equation 79 the allowable load reduces to

$$P_{allowable} = \left\{ F_c \left[1 - \frac{1}{3} \left(\frac{L_e/B}{21.5} \right)^4 \right] A \right\}_{WSD} \quad (84)$$

When Equation 84 along with Equations 69 to 72 is substituted into Equation 68 the following equation is obtained:

$$\left\{ \frac{D+L}{F_c \left[1 - \frac{1}{3} \left(\frac{L_e/B}{21.5} \right)^4 \right] A} \right\}_{WSD} = \left\{ \frac{1.25D + 1.5L}{\phi f_c 0.68 (AL \times 10^{-9})^{-0.13} \left[1 + 0.68 (AL \times 10^{-9})^{-0.13} \frac{0.0024}{30.45} \left(\frac{L_e}{B} \right)^3 \right]^{-1} A} \right\}_{LSD} \quad (85)$$

Which, following similar arguments as invoked for short columns, simplifies to:

$$\left\{ \frac{1}{\left[1 - 1.560 \times 10^{-6} \left(\frac{L_e}{B} \right)^4 \right]} \right\}_{WSD} = q \left\{ \frac{1.45}{1.493 (AL \times 10^{-9})^{-0.13} \left[1 + 5.360 \times 10^{-5} (AL \times 10^{-9})^{-0.13} \left(\frac{L_e}{B} \right)^3 \right]^{-1}} \right\}_{LSD} \quad (86)$$

3.2.1.3 Long Columns

Using WSD a long column, for which $C_k < \frac{L_e}{B} < 50$, has a slenderness factor of:

$$K_c = \left(\frac{0.274E}{C_e^2 F_c K_D} \right)_{WSD} \quad (87)$$

which results in:

$$P_{allowable} = \left[\frac{0.274EA}{(L_e/B)^2} \right]_{WSD} \quad (88)$$

A ratio $f_{c,LSD}/E_{WSD} = 0.0024$ based on code value comparisons shown in Table 13 is also applied. Substituting Equations 69 to 72, 77 and 88 into Equation 68 the following results:

$$\left\{ \frac{D+L}{\left[\frac{0.274EA}{(L_e/B)^2} \right]_{WSD}} \right\} = \left\{ \frac{1.25D + 1.5L}{\phi_c f_c 0.68 (AL \times 10^{-9})^{-0.13} \left[1 + 0.68 (AL \times 10^{-9})^{-0.13} \frac{0.0024}{30.45} \left(\frac{L_e}{B} \right)^3 \right]^{-1} A}_{LSD}} \right\} \quad (89)$$

The equation reduces to:

$$\left\{ \frac{1}{\left[\frac{0.274}{(L_e/B)^2} \right]_{WSD}} \right\} = \left\{ \frac{1.45}{1.327 \times 10^{-3} (AL \times 10^{-9})^{-0.13} \left[1 + 5.360 \times 10^{-5} (AL \times 10^{-9})^{-0.13} \left(\frac{L_e}{B} \right)^3 \right]^{-1}} \right\}_{LSD} \quad (90)$$

3.2.1.4 Summary

Short Columns: $L_e/B < 10$

$$\left(\frac{1}{1} \right)_{WSD} = q \left\{ \frac{1.45}{1.493 (AL \times 10^{-9})^{-0.13} \left[1 + 5.360 \times 10^{-5} (AL \times 10^{-9})^{-0.13} \left(\frac{L_e}{B} \right)^3 \right]^{-1}} \right\}_{LSD} \quad (91)$$

Intermediate Columns: $10 < L_e/B < C_k$

$$\left\{ \frac{1}{\left[1 - 1.560 \times 10^{-6} \left(\frac{L_e}{B} \right)^4 \right] } \right\}_{WSD} = q \left\{ \frac{1.45}{1.493 (AL \times 10^{-9})^{-0.13} \left[1 + 5.360 \times 10^{-5} (AL \times 10^{-9})^{-0.13} \left(\frac{L_e}{B} \right)^3 \right]^{-1}} \right\}_{LSD} \quad (92)$$

Long Columns: $C_k < L_e/B < 50$

$$\left\{ \frac{1}{\left[\frac{0.274}{(L_e/B)^2} \right] } \right\}_{WSD} = q \left\{ \frac{1.45}{1.327 \times 10^{-3} (AL \times 10^{-9})^{-0.13} \left[1 + 5.360 \times 10^{-5} (AL \times 10^{-9})^{-0.13} \left(\frac{L_e}{B} \right)^3 \right]^{-1}} \right\}_{LSD} \quad (93)$$

Values for the factor q are determined using actual dimensions from test specimens. Originally, column cross-sectional dimensions and lengths of test specimens listed in TR10 were used. However, since many of the columns had the same dimensions, few distinct data points were found. Additional column

lengths were added, while still using the same column cross sections from test specimens to create additional data points that would make the trends more visible.

Figure 22 shows the calculated q values plotted versus the slenderness ratio L_e/B . It can be seen that the factor q for the members considered is always greater than one. A value greater than one creates a shift along the abscissa of Figure 12 (NBCC Figure D-2.11.2-A) to the left. A shift left potentially creates non-conservative results because the ordinate value, f , may become larger for a given column, producing a larger time to failure. This indicates that the current LSD NBCC results are less conservative than those originally published under WSD.

Figure 22: q values for comparison of WSD Abscissa to LSD Abscissa of Figure 12

3.2.1.5 Example

If a particular long column designed under working stress design has a ratio

$$\left(\frac{\text{Applied Load}}{\text{Allowable Load}} \right)_{\text{WSD}} = 0.75, \text{ using Figure 23, the column would have an } f \text{ value}$$

of 1.10. When considering the same column designed under LSD and by inspection of Figure 22 assuming an average q value of 1.24 the new ratio is:

$$\left(\frac{\text{Factored Load}}{\text{Factored Resistance}} \right)_{\text{LSD}} = \frac{1}{q} \left(\frac{\text{Applied Load}}{\text{Allowable Load}} \right)_{\text{WSD}} = \frac{1}{1.24} (0.75) = 0.61 \quad (94)$$

A ratio of 0.61 corresponds to an f value of 1.19. As a result, the larger f value produces a larger time to failure, indicating that the shift is not conservative.

Figure 23 shows the shift graphically.

Figure 23: Effects of Changing from WSD to LSD on Load Factor, f

3.2.2 Beams

Based on CSA O86-M80 (WSD) the allowable bending capacity for a beam is given by:

$$M_{allowable} = (SF_b K_T K_D K_L K_x)_{WSD} \quad (95)$$

where S (mm^3) is the section modulus of the beam. F_b (MPa) is the allowable stress in bending. The wood is assumed to be untreated and sustain normal duration loads therefore $K_T = 1.0$ and $K_D = 1.0$ respectively. A straight member is being assumed therefore the curvature factor, $K_x = 1.0$. This reduces the allowable moment, $M_{allowable}$ (MPa) to:

$$M_{allowable} = (SF_b K_L)_{WSD} \quad (96)$$

The factored resistance based on CSA O86-01(LSD) is calculated using the lesser of the following two equations:

$$M_{r1} = (\phi F_b S K_X K_{Zbg})_{LSD} \quad (97)$$

$$M_{r2} = (\phi F_b S K_X K_L)_{LSD} \quad (98)$$

with:

$$F_b = (f_b K_D K_H K_{Sb} K_T)_{LSD} \quad (99)$$

where the resistance factor $\phi=0.9$, f_b (MPa) is the specified strength in bending K_{Sb} is the service condition factor for bending at the extreme fibre, K_{Zbg} is the size factor, and K_L is the lateral stability factor. K_{Sb} is the service condition factor for bending. Also, since the member is assumed straight the curvature factor $K_X = 1.0$. Assuming typical conditions $K_D K_H K_{Sb} K_T = 1.0$

Combining Equations 68 to 70 and 96 to 99 the following is obtained:

$$\left(\frac{D+L}{SF_b k_L} \right)_{WSD} = q \left(\frac{1.25D+1.5L}{\phi f_b S (k_{zbg} \text{ or } k_L)} \right)_{LSD} \quad (100)$$

The section modulus cancels from both sides of the equation. The unsupported length is assumed to fit with typical experimental setup resulting in an unsupported length of $I_u = 400$ mm being used. Based on Table 6.5.6.4.3 from CSA O86-01 the effective length for a bending member with any loading, results in an effective length of:

$$L_e = 1.92 \times I_u = 1.92 \times 400 \text{ mm} = 768 \text{ mm} \quad (101)$$

Since the unsupported length is so small, the slenderness factor is defined by:

$$C_B = \sqrt{\frac{L_e d}{b^2}} \quad (102)$$

and is typically less than 10. This results in $K_L=1.0$ for both WSD and LSD. K_{zbg} is defined by:

$$K_{zbg} = 1.03(BL \times 10^{-6})^{-0.18} \leq 1.0 \quad (103)$$

From Table 2.11 in the Wood Design Manual (CWC, 2001) showing typical sizes K_{zbg} is found to range from 0.75 to 1.0, where B (mm) is the smaller cross section dimension and L (mm) is the member length.

The numerators are divided by D, and a live load to dead load ratio of $L/D = 4$ is once again assumed. Comparing bending strength values from WSD and LSD the ratio was found to be $f_{b,LSD}/F_{b,WSD} = 1.855$ as shown in Table 14. Dividing both sides by $F_{b,WSD}$ the following equation is obtained:

$$\left(\frac{1+4}{1}\right)_{WSD} = q \left(\frac{1.25(1)+1.5(4)}{0.9(1.855)(0.75 \text{ to } 1)}\right)_{LSD} \quad (104)$$

Recall that:

$$LSD = \frac{1}{q} WSD \quad (105)$$

Using $K_{zbg} = 0.75$;

$$5 = q(5.790) \quad (106)$$

$$q = 0.864 \quad (107)$$

resulting in:

$$LSD = \frac{1}{0.864} WSD = 1.157 WSD \quad (108)$$

This results in a shift to the right along the abscissa of Figure 12 (Figure D-2.11.2.-A (NBCC, 2005)) producing more conservative results.

Using $K_{zbg} = 1.0$;

$$5 = q(4.343) \quad (109)$$

$$q = 1.151 \quad (110)$$

resulting in:

$$LSD = \frac{1}{1.151} WSD = 0.869 WSD \quad (111)$$

This results in a shift to the left along the abscissa of Figure 12 (Figure D-2.11.2.-A (NBCC, 2005)) producing less conservative results.

The average of the two q values is $q_{avg} = 1.007$ which indicates that the direct shift for beams appears to be appropriate, however for test situations where the length would typically be 3660mm it is reasonable to assume that $K_{zbg} = 1.0$ would apply. This would result in $q = 1.151$, which indicates less conservative results.

For potential actual beam sizes that have a size factor $K_{Zbg} < 1.0$ results that are more conservative would be expected.

3.2.3 Sensitivity of the Conclusions to the Live to Dead Load Ratio

For conventional light-frame construction, a live to dead load ratio of four is typically assumed. However, since glulam members are significantly larger than light frame members, it is possible that the live to dead load ratio could decrease. Table 15 shows the results from considering live to dead load ratios between one and five to assess its impact on q for beams. This is also shown graphically in Figure 24. The size factor $K_{Zbg} = 1.0$ is used for this comparison as it produces a non-conservative shift along the abscissa of Figure 12 (Figure D-2.11.2.-A (NBCC, 2005)), however a similar reduction occurs when $K_{Zbg} = 0.75$ as shown in Figure 24.

3.2.3.1 Sample Calculation

Consider $L/D = 3$:

$$\left(\frac{1+3}{1} \right)_{WSD} = q \left(\frac{1.25(1) + 1.5(3)}{0.9(1.855)(1)} \right)_{LSD} \quad (112)$$

which results in:

$$q = 1.161 \quad (113)$$

Table 15: Effects of the Load Ratio on q

L/D	q
1	1.214
2	1.178
3	1.161
4	1.151
5	1.145

Figure 24: q vs. L/D

From these values, it can be concluded that the live to dead load ratio does not have a significant effect on q , particularly when a ratio of live to dead load equal to one is unlikely.

4.0 Determining Failure Time

In the following sections, two basic methods are developed for determining the failure times of glulam members exposed to standard fire tests. The first method to accurately predict failure times is based directly on the design equations provided in CSA O86-01, and is found to give very good predictions. The second is a simplified algebraic method that provides conservative, easy to calculate results for designers.

4.1 Detailed Prediction Method

The detailed prediction method uses the structural design equations provided by CSA O86-01. This method has been formulated to predict the failure times of glulam members from a strictly experimental standpoint. It uses unfactored loads and average ultimate strength values, and resistance factors, ϕ , of unity. These values are utilized to try to better match the experimental data, by removing all of the applied safety factors. When the resistance factor, ϕ , is less than one and the applied loads are multiplied by a factor greater than one, an inherent level of safety is implied. In addition, average ultimate strength values better represent the actual strength of the member, whereas the fifth percentile values provide conservative strength values appropriate for design. The applied loads are obtained directly from TR10 and can be found in Appendix A. All values have been converted to SI units.

4.1.1 Ultimate Strength and Modulus of Elasticity

The average ultimate strength and modulus of elasticity values are obtained directly from TR10 since sufficient test data is not available to make independent judgements. Table 10 and Equation 61 in Section 2.6 provide an explanation of how the values are obtained from fifth percentile allowable ultimate strength values by assuming a normal distribution. For members that had unknown strength values, Equations 62 and 63 were used in TR10 to calculate the average ultimate strength and modulus of elasticity of the members, based on their specific gravities.

4.1.2 Modelling Approach

Microsoft Excel is used as the primary computational engine in conjunction with Microsoft Visual Basic for Applications (VBA) to program the various required spreadsheets. The member resistance is calculated at room temperature as well as at incremental time steps specified by the user during fire exposure. A time step equal to 0.1 minutes is used in all calculations. Since convergence of the results does not depend on time step selected, 0.1 minutes was sufficiently small especially since the observed failure times were only reported in full minutes. At each time step, the member properties (strength and modulus of elasticity) are reduced depending on the method selected, and the cross-sectional dimensions are reduced based on the selected charring rate. The reduced resistance of the member is calculated and compared with the applied load. Failure is deemed to have occurred when the applied load is greater than the member resistance.

The time to failure is noted as the final time step at which there is sufficient resistance to resist the applied load. Using this time is conservative because it results in a slightly smaller time to failure being reported. In reality the actual predicted failure time is sometime between the final time step that has ample strength to resist the load, and the first time step when the applied load is greater than the resistance. Using sufficiently small time steps, this error is negligible. The goal is to find a single method that accurately predicts results for all three member types (columns, beams and tension members) that requires little or no calibration to match test data.

The VBA source code used for the columns, beams and tension members, when Eurocode 5 zero strength layer method, constant property reductions, and Eurocode 5 material property reductions are implemented is found in Appendix C. Both constant and varying charring rates are shown.

4.1.3 Member Resistance Equations

The strength of columns, beams and tension members considered in this study are calculated in accordance with CSA O86-01. While originally the method of using a heated layer of thickness, a , as shown in Figure 6 was considered, this method proved to produce results of varying accuracy, and did not generate consistent results between beams and columns. Furthermore, the reduction factors required to obtain a good fit did not match what was expected based on previously published literature. Finally, the geometric equations required were

more complex, particularly for beams due to the shift in the neutral axis caused by the heated layer. Since better results are obtained by considering the cross section to have uniform properties, the original method of considering a heated perimeter layer was abandoned. Rounded corners have been ignored to simplify the final equations for the end user.

4.1.3.1 Columns

As stated in Section 3.2.1, for LSD the member resistance is given by:

$$P_r = \phi F_c K_{Zcg} K_C A \quad (114)$$

$$F_c = f_{c,avg} (K_D K_H K_{Sc} K_T) \quad (115)$$

with $\phi = 1.0$ and $K_D K_H K_{Sc} K_T = 1$ as mentioned in Section 4.1 based on assumed standard conditions and load duration. The average ultimate compressive strength is defined by $f_{c,avg}$. In some prediction models considered below, the compressive strength of the entire cross section is reduced to account for the effects of increased temperature, and in other prediction models a zero strength layer is implemented. As a result, Equation 114 becomes:

$$P_f = \phi k_{f_{c,fire}} F_c K_{Zcg} K_C A \quad (116)$$

where $k_{f_{c,fire}}$ is the compressive strength reduction factor due to increased temperature.

The cross-sectional area decreases with time due to the charring of the member cross section. As a result, the area of the member is given by:

$$A = (B - 2x_c - 2z)(D - 2x_c - 2z) = (b - 2z)(d - 2z) \quad (117)$$

where B and D (mm) are the original cross section dimensions, b and d (mm) are the residual cross section dimensions during fire exposure, x_c (mm) is the char depth, and z (mm) is the depth of the zero-strength layer if used in the modelling method.

With member dimensions expressed in millimetres the size factor K_{Zcg} is given by the equation:

$$K_{Zcg} = 0.68(AL \times 10^{-9})^{-0.13} \quad (118)$$

Although the zero-strength layer is used to account for a reduction in member properties, it is not applied to K_{Zcg} , because the reduction of F_c is already accounted for due to the reduction of the cross-sectional area in Equation 114. If the cross-sectional area in Equation 118 is decreased further to account for the zero-strength layer, the size factor would increase. The effects of charring are still considered, resulting in:

$$K_{Zcg} = 0.68((B - 2x_c)(D - 2x_c)L \times 10^{-9})^{-0.13} = 0.68(b d L \times 10^{-9})^{-0.13} \quad (119)$$

K_C is the slenderness factor defined by Equation 120:

$$K_C = \left[1 + \frac{F_C K_{Zcg} C_C^3}{35E_{05} K_{SE} K_T} \right]^{-1} \quad (120)$$

with:

$$E_{05} = 0.87E \quad (121)$$

$$C_C = L_e / B \quad (122)$$

where $K_{SE}K_T = 1.0$ is assumed as mentioned previously. When the effects of elevated material temperatures and charring are considered Equations 120, 121 and 122 become:

$$K_C = \left[1 + \frac{k_{f_c, fire} F_C K_{Zcg} C_C^3}{35 k_{MOE, fire} E_{05} K_{SE} K_T} \right]^{-1} \quad (123)$$

$$E_{05} = 0.87 k_{MOE, fire} E \quad (124)$$

$$C_C = L_e / (B - 2x_c) = L_e / b \quad (125)$$

where $k_{MOE, fire}$ is the reduction factor to account for the effects of increased temperature on the modulus of elasticity. The depth of the zero-strength layer is not subtracted from the column width in Equation 125 because if it is assumed that $k_{MOE, fire}$ and $k_{f_c, fire}$ are similar or equal the reductions cancel out in Equation 123. If the zero-strength layer cross section reduction was applied in Equation 125 for C_C , the additional depth would increase the factor. Although this would cause K_C to decrease, it would not have the same effect as reducing the compressive strength and modulus of elasticity, which the zero-strength layer method was intended to achieve.

4.1.3.2 Beams

The bending moment equations used for beams are those from CSA O86-01 given in Section 3.2.2. As stated in Section 3.2.2 $K_X = 1.0$ and $K_D K_H K_{Sb} K_T = 1.0$.

$$M_{r1} = \phi F_b S K_X K_{Zbg} \quad (126)$$

$$M_{r2} = \phi F_b S K_X K_L \quad (127)$$

$$F_b = f_{b,avg} K_D K_H K_{Sb} K_T \quad (128)$$

with the member resistance factor $\phi = 1.0$, $K_X = 1.0$ and $f_{b,avg}$ is the average ultimate bending strength. Shear has not been taken into consideration.

To account for the increased temperature, a reduction factor $k_{f_b,fire}$ is applied to the modified bending strength, F_b (MPa), resulting in:

$$M_{r1} = \phi k_{f_b,fire} F_b S K_X (K_{Zbg} \text{ or } K_L) \quad (129)$$

The section modulus of the charred cross section exposed to fire on three sides is defined by:

$$S = \frac{(B - 2x_c - 2z)(D - x_c - z)^2}{6} = \frac{(b - 2z)(d - z)^2}{6} \quad (130)$$

The slenderness ratio is defined by:

$$C_B = \sqrt{\frac{L_e D}{B^2}} \quad (131)$$

When the effects of fire are considered on the cross section, the following is obtained:

$$C_B = \sqrt{\frac{L_e(D - x_c)}{(B - 2x_c)^2}} = \sqrt{\frac{L_e d}{b^2}} \quad (132)$$

The zero-strength layer is not subtracted from the original cross section dimensions because it would not properly reduce the modulus of elasticity or bending strength.

The lateral stability factor, K_L , in Equation 127 depends on the slenderness ratio:

If $C_B \leq 10$:

$$K_L = 1.0 \quad (133)$$

If $10 < C_B \leq C_K$:

$$C_K = \sqrt{\frac{0.97 k_{MOE, fire} E K_{SE} K_T}{k_{fb, fire} F_b}} \quad (134)$$

with the added reduction factor, $k_{MOE, fire}$, applied to the modulus of elasticity, E (MPa), to account for the increased temperature. This results in a lateral stability factor equal to:

$$K_L = 1 - \frac{1}{3} \left(\frac{C_B}{C_K} \right)^4 \quad (135)$$

If $C_k < C_B \leq 50$

$$K_L = \frac{0.65k_{MOE,fire}EK_{SE}K_T}{C_B^2k_{fb,fire}F_bK_x} \quad (136)$$

The size factor, K_{Zbg} , of a glulam beam is as follows:

$$K_{Zbg} = 1.03(BL \times 10^{-6})^{-0.18} \leq 1.0 \quad (137)$$

when charring is accounted for the following equation is produced:

$$K_{Zbg} = 1.03((B - 2x_c)L \times 10^{-6})^{-0.18} \leq 1.0 \quad (138)$$

Once again, the depth of the zero-strength layer is not applied because it would only increase the factor, and the strength reduction has already been accounted for by reducing the section modulus.

4.1.3.3 Tension Members

The resistance of tension members is defined by the follow equations:

$$T_r = \phi F_{tn} A_n \quad (139)$$

$$F_{tn} = f_{tn}(K_D K_H K_{St} K_T) \quad (140)$$

or

$$T_r = \phi F_{tg} A_g \quad (141)$$

$$F_{tg} = f_{tg,avg}(K_D K_H K_{St} K_T) \quad (142)$$

where the resistance factor ϕ is 1.0, $f_{tg,avg}$ is the average ultimate gross tensile strength parallel to grain, A_n (mm²) is the net area of the cross-section, and A_g (mm²) is the gross area of the cross section. The net area is the gross area of the cross section minus the area lost due to the drilling or bolting for connections. The specified strength of a glulam member in tension parallel to the grain at the net section is defined as f_{tn} (MPa) and at the gross section as f_{tg} (MPa). K_D is the load duration factor, K_H is the system factor, K_{St} is the service condition factor for tension parallel to the grain, and K_T is the treatment factor, all of which are assumed to equal one due to the assumptions of standard load duration and service conditions, along with no applied treatment, or system present.

Only Equations 141 and 142 are used in this work because only gross member properties are known from test data.

When considering the effects of fire, the tensile strength of the member is reduced by a factor, $k_{f,fire}$, and $(K_D K_H K_{St} K_T) = 1.0$ as previously mentioned resulting in Equation 143 becoming:

$$T_r = \phi k_{f,fire} F_{tg} A_g \quad (143)$$

As mentioned previously, the cross-sectional area also reduces due to charring and the zero-strength layer when applicable, which results in:

$$A = (B - 2x_c - 2z)(D - 2x_c - 2z) = (b - 2z)(d - 2z) \quad (144)$$

4.1.4 Charring Rate and Charring Depth Equations

The Australian charring rate equation (Equation 8) and the charring depth equation proposed by Gardner and Syme (Equation 9) were investigated, but the charring rates and depths produced were too severe. Although the equations produced conservative results, they did not closely predict the observed results. The results for beams were the most drastically under predicted, particularly those with large failure times. Also, no specific gravity or density information was provided for the tested tension members, and although the species is known, the actual specific gravity of the members is required.

The charring rate equation produced by Schaffer (Equation 10) was not applied due to lack of information. The regression constants, a , b , and c are not known for all the identified species tested, and for many of the members tested the species are unknown. Additionally, moisture content data is not provided, and could be assumed, however additional error would be introduced.

The detailed reciprocal charring rate, m , proposed by White and Nordheim (1992) which is shown previously in Equations 12 to 15 was also not used due to a lack of information needed to complete the calculations.

As a result the two charring depth models used are the linear charring depth equation with constant charring rate (Equation 7) and the non-linear charring depth based on the method proposed in TR10 (Equation 19). The charring rates

selected are those based on the results of White (2006). As referenced above in Section 2.3.2, for the linear char depth model, $\beta = 0.649$ mm/min is used and for the non-linear char depth model, $\beta = 0.658$ mm/min in Equation 21 is used. Even though these charring rates were determined for composite lumber products, they were found to fall within the range of charring rates for solid sawn lumber (White, 2006). Hence, they are used as acceptable starting values, and can be modified if necessary.

In order to explore the failure time results using the assumptions of Lie in conjunction with Canadian O86-01 structural design equations, a charring rate of 0.6 mm/min with the linear char depth model was also used in conjunction with the appropriate material property reductions mentioned below in Section 4.1.5. Also, a charring rate of 0.635 mm/min is used in calculating the failure times based on the work of TR10 with the non-linear char depth model.

4.1.5 Material Property Reductions

Three methods of reducing the material properties of the members are considered in this work, along with the two methods using the assumptions from Lie and TR10. The first is the use of the zero-strength layer presented in Eurocode 5 to calculate an effective cross section. The Australian code also presents a zero-strength layer, but is not used in favour of the slightly smaller zero-strength layer from Eurocode 5. The next method, Eurocode 5 material property reductions, uses the specified reduction factor, k_f , found in Equation 33

is applied to the member properties. The final method is applying a constant reduction factor to the specified bending, compressive and tensile strengths.

To show the failure time results if the assumptions employed by Lie are applied, a constant reduction factor of 0.8 is used. To produce failure times based on the assumptions implemented in TR10 to account for material reductions and corner rounding, the charring rate is increased by 20%.

4.2 Detailed Prediction Method Results

The predictions of the detailed method for several choices of the charring and strength reduction models are presented in this section. To be specific, detailed results are presented when the assumptions made by Lie and TR10 are implemented, as well as the Eurocode 5 zero-strength layer method and material property reductions method.

Summary tables containing the numerical results of each of the four methods presented below can be found in Appendix D. Column results are located in

Table D. 1 and

Table D. 2. Table D. 3 and Table D. 4 contain the results for beams and tension members respectively.

4.2.1 Implementation of Assumptions Made by Lie

Applying the above mentioned method of using a linear charring depth in Equations 114 to 144, and applying a charring rate of 0.6 mm/min, along with $k_{t_c,fire} = k_{t_p,fire} = k_{t_c,fire} = k_{MOE} = 0.8$ and no zero-strength layer ($z = 0$) the results in Table 16 are produced.

Table 16: Lie Method Results

Member	Trendline Equation	R²	Residuals	Average Residuals per Member	
Column	$y=1.047x-1.221$	0.665	9836	159	Figure 25
Beam	$y=0.949x+4.408$	0.869	923	132	Figure 26
Tension	$y=0.954x+15.568$	1.000	453	151	Figure 27

Figure 25 and Figure 26 show the results graphically for columns and beams respectively. The results for both are acceptable. The trendline equation slopes are close to one, and the trendline is close to the reference line.

Figure 25: Predicting Column Failure Times by Implementing Assumptions Made by Lie

Figure 26: Predicting Beam Failure Times by Implementing Assumptions Made by Lie

Figure 27 shows the results for tension members. Lie's assumptions do not accurately predict the failure time of the tension members. Although the slope of the trendline is close to one, there is an offset of between 10 and 14 minutes for the members, which is unacceptable, in part because predictions are not conservative.

Figure 27: Predicting Tension Member Failure Times by Implementing Assumptions Made by Lie

4.2.2 Implementation of Assumptions Made in TR10

As mentioned previously in Section 4.1.4, the authors of TR10 used a non-linear char depth equation. The charring rate (0.635 mm/min) was increased by 20 percent to account for material property losses and corner rounding, which resulted in a charring rate of 0.762 mm/min. No material property reductions

were applied ($k_{t,fire} = k_{f,fire} = k_{t,fire} = k_{MOE} = 1.0$) and no zero-strength layer was used ($z = 0$). Table 17 summarizes the results found when these assumptions were applied to the Canadian code equations from CSA O86-01.

Table 17: TR10 Method Results

Member	Trendline Equation	R²	Residuals	Average Residuals per Member	
Column	$y=1.052x-8.807$	0.674	11864	191	Figure 28
Beam	$y=0.964x-5.261$	0.896	1246	178	Figure 29
Tension	$y=1.004x+1.508$	1.000	10	3	Figure 30

The results produced using the Canadian design equations, do not produce results as good as when the TR10 method is used in conjunction with the NDS equations.

For columns, as seen in Figure 28, the trendline is under the reference line, indicating conservative results; however, the offset is larger than desired. Due to the misalignment of the trendline and the reference line, the value of the residuals is larger. The Average Residuals per Member is 30 larger than when the NDS method is applied as presented in Section 2.6.1.

Figure 28: Predicting Column Failure Times of by Implementing Assumptions Made in TR10

Figure 29 shows the results for beams. Like columns, the trendline for the beams is below the reference line. These results indicate that the strength is reducing too fast, and that a smaller increase applied to the charring rate may better suit the test data.

Figure 29: Predicting Beam Failure Times of by Implementing Assumptions Made in TR10

The results for tension members as shown in Figure 30 are the same as calculated in TR10 because the tensile resistance equations are the same. The charring rate that varies with time as proposed by White predicts the times to failure of the tension members very well. The results are non-conservative by only 1.5 minutes.

Figure 30: Predicting Tension Member Failure Times of by Implementing Assumptions Made in TR10

4.2.3 Implementation of Eurocode 5 Zero-Strength Layer Method

The Eurocode 5 zero-strength layer method used in conjunction with a constant charring rate turns out to be the preferred method when used in conjunction with the Canadian strength equations. The thickness of the Eurocode 5 zero strength layer, z , is as defined in Section 2.3.6.5. A constant charring rate of 0.649 mm/min as proposed by White suited this method. Since there is no strength reduction applied due to increased temperature the factors are simply

$k_{f_b, fire} = k_{f_o, fire} = k_{f_t, fire} = k_{f_{MOE}, fire} = 1.0$. The results are shown in Table 18.

Table 18: Eurocode 5 Zero-Strength Layer Method Results

Member	Trendline Equation	R²	Residuals	Average Residuals per Member	β (mm/min)
Column	$y=1.027x-3.338$	0.695	8372	135	0.649
Beam	$y=0.886x+3.886$	0.886	1019	146	0.649
Tension	$y=0.901x+4.841$	1.000	57.81	19	0.649

Decreasing the charring rate to 0.635 mm/min, which is the generally accepted value in North America (White, 2006) produces better results. The results are shown in Table 19 and Figure 31 to Figure 33.

Table 19: Eurocode 5 Zero Strength Method Results ($\beta = 0.635$ mm/min)

Member	Trendline Equation	R²	Residuals	Average Residuals per Member	
Column	$y=1.050x-3.414$	0.696	8569	138	Figure 31
Beam	$y=0.906x+3.907$	0.887	887	127	Figure 32
Tension	$y=0.921x+6.515$	1.000	26	9	Figure 33

The results for columns are very good, with both a good slope and an acceptable residual value.

Figure 31: Predicting Column Failure Times by Applying Eurocode 5 Zero Strength Layer Method and Using a Constant Charring Rate

The beam results are also very good as seen in Figure 32. The slope is low, but satisfactory residual values are produced, although not as good as those produced by TR10, which are shown in Table 10.

Figure 32: Predicting Beam Failure Times by Applying Eurocode 5 Zero Strength Layer Method and Using a Constant Charring Rate

The tension results are also good for the three members as seen in Figure 33, with the failure time of the third specimen being under predicted. The observed time to failure of the third point (Test 4), is less reliable because as mentioned previously a small load was placed on the test specimen first, and when the member still had not failed at 120 minutes the load was increased to over three times the original load, until failure occurred.

Figure 33: Predicting Tension Member Failure Times by Applying Eurocode 5 Zero Strength Layer Method and Using a Constant Charring Rate

4.2.4 Implementation of Eurocode 5 Material Property Reduction Method

The method that worked second best was the method that used the Eurocode 5 strength reduction factor k_f . A constant charring rate of $\beta = 0.649$ mm/min was used. No zero strength layer was used ($z = 0$). This method is described in Section 2.3.6.6. The results are summarized in Table 20.

Table 20: Eurocode 5 Zero Strength Method Results

Member	Trendline Equation	R ²	Residuals	Average Residuals per Member	
Column	$y=1.012x-1.312$	0.701	7714	124	Figure 34
Beam	$y=0.876x+6.824$	0.872	961	137	Figure 35
Tension	$y=0.901x+12.209$	1.000	108	36	Figure 36

This method produces the best result for columns, with a trendline slope close to one, an intercept very close to zero, a good R² value, and a residuals value lower than all other methods. Figure 34 below shows these results.

Figure 34: Predicting Column Failure Times by Applying Eurocode 5 Material Property Reductions and Using a Constant Charring Rate

The results for beams were acceptable. They are shown in Figure 35. The value of the residuals is very good; however, the slope is further from one than desired.

Better results for beams would be found by using a smaller charring rate as shown in Table 21.

Figure 35: Predicting Beam Failure Times by Applying Eurocode 5 Material Property Reductions and Using a Constant Charring Rate

The results for tension members are shown in Figure 36. The residuals values are large compared to other results. Better results for tension members are produced using a larger charring rate, which is presented in Table 21.

Figure 36: Predicting Tension Member Failure Times by Applying Eurocode 5 Material Property Reductions and Using a Constant Charring Rate

Table 21: Additional Results Using Eurocode 5 Material Property Reduction Factors

Member	Charring Rate β (mm/min)	Trendline Equation	R^2	Residuals	Average Residuals per Member
Beam	0.610	$y=0.933x+7.253$	0.873	890	127
Tension	0.68	$y=0.849x+11.371$	1.000	87	29

4.2.5 Additional Methods

The following tables present summary results for other methods that are investigated. These methods may produce acceptable results for one type of member, but not all three types, or acceptable results for all members, using different charring rates and/or reduction factors for each member type.

4.2.5.1 Constant Charring Rate and Constant Material Property Reductions

Table 22 and Table 23 show the results for when a constant charring rate and constant material property reductions are applied. The table shows the reduction factors and charring rates applied, as well as the trendline equations, R^2 values, and residual values. No zero-strength layer was used ($z = 0$). Good results have been found for both beams and columns, however, the slope on the trendline for beams is low when $\beta = 0.635$ mm/min. For beams and columns acceptable residual values are obtained. This method does not produce good results for tension members. The slopes of the trendlines are low, and the residual values are higher than for other methods.

Table 22: Results Using Constant Charring Rate and Constant Material Property Reduction Factors

Member	Charring Rate β (mm/min)	$k_{fc,fire}$	$k_{fb,fire}$	$k_{ftg,fire}$	$k_{MOE,fire}$	Trendline Equation	R^2
Column	0.635	0.85			0.85	$y=1.014x-0.571$	0.669
Column	0.649	0.90			0.90	$y=1.014x-0.010$	0.672
Beam	0.635		0.85		0.85	$y=0.866x+6.892$	0.866
Beam	0.649		0.90		0.90	$y=0.895x+4.138$	0.878
Tension	0.635			0.60		$y=0.876x+10.291$	0.994
Tension	0.649			0.72		$y=0.873x+12.900$	0.998

Table 23: Results Using Constant Charring Rate and Constant Material Property Reduction Factors Continued

Member	Charring Rate β (mm/min)	Residuals	Average Residuals per Member
Column	0.635	8933	144
Column	0.649	8844	143
Beam	0.635	963	138
Beam	0.649	996	142
Tension	0.635	80	27
Tension	0.649	101	34

4.2.5.2 Varying Charring Rate and Eurocode 5 Zero-Strength Layer Method

Using a varying charring rate in conjunction with the Eurocode 5 zero-strength layer method does not produce good results for columns or beams. No material property reductions were applied ($k_{fc,fire} = k_{fb,fire} = k_{ftg,fire} = k_{MOE,fire} = 1.0$). The trendline slopes are higher than desired, and the residual values particularly for columns are higher than desired. Good results are predicted for tension members. The varying charring rate models the tension members very well. Table 24 and Table 25 present the best results for each member obtained by selecting various charring rates.

Table 24: Results Using Varying Charring Rate and Eurocode 5 Zero-Strength Layer Method

Member	Charring Rate β (mm/min)	$k_{fc,fire}$	$k_{fb,fire}$	$k_{ftg,fire}$	$k_{MOE,fire}$	Trendline Equation	R ²
Column	0.67	1			1	$y=1.170x-13.395$	0.693
Beam	0.68		1		1	$y=1.113x-13.450$	0.900
Tension	0.710			1		$y=1.064x-8.508$	1.000

Table 25: Results Using Varying Charring Rate and Eurocode 5 Zero-Strength Layer Method Continued

Member	Charring Rate β (mm/min)	Residuals	Average Residuals per Member
Column	0.67	12684	205
Beam	0.68	1090	156
Tension	0.710	58	19

4.2.5.3 Varying Charring Rate and Constant Material Property Reductions

Table 26 and Table 27 present the results when a varying charring rate is used along with constant material property reductions. No zero-strength layer was used ($z = 0$). Acceptable values are found for beams columns and tension members, but the residual value for columns is high. Tension member results are acceptable; however, there is no consistency for charring rates or resistance factors that produced good results for all member types.

Table 26: Results Using Varying Charring Rate and Constant Material Property Reduction Factors

Member	Charring Rate β (mm/min)	$k_{fc,fire}$	$k_{fb,fire}$	$k_{ftg,fire}$	$k_{MOE,fire}$	Trendline Equation	R ²
Column	0.659	0.7			0.95	$y=1.067x-7.534$	0.667
Beam	0.700		0.85		0.9	$y=1.058x-9.097$	0.884
Tension	0.720			0.72		$y=1.027x-2.034$	0.997

Table 27: Results Using Varying Charring Rate and Constant Material Property Reduction Factors Continued

Member	Charring Rate β (mm/min)	Residuals	Average Residuals per Member
Column	0.659	11153	180
Beam	0.700	1117	160
Tension	0.720	14	5

4.2.5.4 Varying Charring Rate and Eurocode 5 Material Property Reductions

The Eurocode 5 material property reduction factor method in conjunction with the varying charring rate did not produce good results for columns. No zero-strength layer was used ($z = 0$). The slope of the trendline is high and the residual value is also high. Good results are obtained for beams and excellent results are found for tension members. This method produced the lowest residual value for tension member compared to all other methods investigated. Table 28 shows a summary of the results.

Table 28: Results Using Varying Charring Rate and Eurocode 5 Material Property Reduction Method

Member	Charring Rate β (mm/min)	Trendline Equation	R²	Residuals	Average Residuals per Member
Column	0.700	$y=1.102x-11.148$	0.700	11624	187
Beam	0.700	$y=1.068x-9.905$	0.886	1124	161
Tension	0.740	$y=1.028x-2.944$	1.000	5	2

4.3 Simplified Design Method

A simplified method to calculate failure times that is easy for a designer to use, and only uses variables that are readily available in CSA O86-01 is desired. The use of factored loads is required as well as the fifth percentile ultimate strength values that are found in the code, instead of the average ultimate strength values used in the detailed prediction method. Summary tables of the results in the

following section can be found in Appendix E. The equations are calibrated such that a maximum of approximately 10% of the members are not conservative.

4.3.1 Equivalent Load Factor

To find an equivalent load factor to apply to the applied load in order to change it to a factored load a live to dead load ratio $L/D = 4$ is once again assumed. Using Equations 145 to 147, an equivalent load factor equal to 1.45 is calculated. The factored load combination for dead and live load as specified in the NBCC is used, however since fire is an extreme event it is possible that a reduced load factor would be more appropriate. The NBCC does not specify a load combination for fire, therefore the basic dead and live load combination from Article 4.1.3.2. in Division B of Volume 1 (NBCC, 2005) will be used.

$$\text{Factored Load} = 1.25D + 1.5L \quad (145)$$

$$\text{Equivalent Load Factor} = \frac{\text{Factored Load}}{\text{Unfactored Load}} \quad (146)$$

$$\text{Equivalent Load Factor} = \frac{1.25D + 1.5L}{D + L} = \frac{1.25D + 1.5(4D)}{D + 4D} = 1.45 \quad (147)$$

Varying the live to dead load ratio does not produce large changes in the equivalent load factor, particularly when a ratio between three and four is most

commonly found in design. Table 29 shows a summary of the effect of the live to dead load ratio on the equivalent load factor.

Table 29: Effects of L/D on the Equivalent Load Factor

L/D	Equivalent Load Factor
1	1.375
2	1.417
3	1.438
4	1.450
5	1.458

4.3.2 Converting Average Ultimate to Fifth Percentile Ultimate Strengths

TR10 provides average ultimate strength values. However, since CSA O86-01 uses fifth percentile ultimate values the strength values must be modified. A normal distribution is not used because it does not accurately predict the distribution of material strengths particularly because it extends to negative infinity, and negative strengths are not possible (Madsen, 1993). A lognormal distribution is used instead because it better predicts the material strengths. A coefficient of variation (COV) equal to 0.14 is assumed for all member properties. This value is based on results published in Foschi et. al. (1989) which states that for bending strengths based on a lognormal distribution a COV of 0.144 for Douglas Fir is appropriate, and 0.194 for Spruce-Pine. Also, TR10 cites a COV equal to 0.16 as shown in Table 10. Since the species of wood is not always known, a conservative value of 0.14 has been chosen. The smaller COV is selected because it results in stronger members hence larger failure times. As a

result, once the model predicting larger failure times is calibrated to produce conservative results, if the strength is lower than calculated, the failure time will be less, ensuring conservative results.

The following steps were taken to convert the values from average ultimate to fifth percentile ultimate:

Standard Deviation, σ :

$$\sigma = \sqrt{\ln(\text{COV}^2 + 1)} \quad (148)$$

Mean, μ :

$$\mu = \ln(\text{Average Ultimate}) - \frac{\sigma^2}{2} \quad (149)$$

where *Average Ultimate* is the average ultimate strength property.

This results in the fifth percentile ultimate strength value equal to:

$$\text{5th Percentile Ultimate} = e^{\mu - 1.645\sigma} \quad (150)$$

and:

$$\frac{\text{5th Percentile Ultimate}}{\text{Average Ultimate}} = 0.7875 \quad (151)$$

The Eurocode 5 zero-strength layer method that proves to be the most effective for the detailed method is also used in the simplified method. Although the zero-strength depth varies from zero to seven millimetres for the first 20 minutes, it is assumed that all members have a failure time greater than 20 minutes, which for

design is typical, so the zero-strength layer thickness is set equal to 7 mm for all times.

4.3.3 Tension Members

The member is deemed to have failed when the factored tensile load, T_f (N) is equal to the member resistance, T_r (N).

$$T_f = T_r = \phi A F_{tg} \quad (152)$$

$$F_{tg} = f_{tg} K_D K_H K_{ST} K_T \quad (153)$$

Once again, it is assumed that $K_D K_H K_{ST} K_T = 1.0$. This results in:

$$T_f = T_r = \phi A f_{tg} \quad (154)$$

where $\phi = 0.8$ and, and f_{tg} is the specified strength in tension parallel to the grain at the gross section, and A is as defined below in Equation 155 since the member resistance reduces with time due to the reduction in the cross-sectional area.

$$A = (B - 2x_t)(D - 2x_t) \quad (155)$$

where x_t (mm) is the sum of the total depth of material lost due to charring and the thickness of the zero-strength layer (7 mm) as shown in Equation 156:

$$x_t = x_c + 7 \quad (156)$$

$$T_f = \phi (B - 2x_t)(D - 2x_t) f_{tg} \quad (157)$$

A modification factor, h_t , is required to compensate for the shift from average ultimate strength values to fifth percentile strength values, and from unfactored loads and resistances to factored loads and resistances. The calculation of h_t is shown in Equations 158 to 160.

$$(B - 2x_t)(D - 2x_t) = \frac{T_f}{\phi h_t f_{tg}} \quad (158)$$

$$T_r = T_f = \phi A h_t f_{tg} \quad (159)$$

$$T_s = T_{r,s} = \phi_1 A f_{tg,avg} \quad (160)$$

where T_s is the applied (service) load, ϕ_1 is the member resistance factor (equal to one in the detailed method) and $f_{tg,avg}$ is the average ultimate tensile strength parallel to the grain at the gross section.

Solving Equations 159 and 160 for A and equating them yields Equation 161:

$$\frac{T_s}{\phi_1 f_{tg,avg}} = \frac{T_f}{\phi h_t f_{tg}} \quad (161)$$

At failure:

from Equation 147:

$$T_s = \frac{T_f}{1.45} \quad (162)$$

from Equation 151:

$$f_{tg,avg} = \frac{f_{tg}}{0.7875} \quad (163)$$

For tension members the resistance factor $\phi = 0.8$ therefore:

$$\phi_1 = \frac{\phi}{0.8} \quad (164)$$

Substituting Equations 162 to 163 into 161, the following is obtained:

$$\frac{T_s}{\phi_1 f_{tg,avg}} = \frac{\frac{T_f}{1.45}}{\left(\frac{\phi}{0.8}\right)\left(\frac{f_{tg}}{0.7875}\right)} = \frac{T_f}{\phi h_t f_{tg}} \quad (165)$$

resulting in:

$$h_t = 2.30 \quad (166)$$

Applying the modification factor of 2.30 to Equation 158, Equation 167 is obtained.

$$(B - 2x_t)(D - 2x_t) - \frac{T_f}{1.84f_{tg}} = 0 \quad (167)$$

Solving the quadratic equation for x_t :

$$x_t = \frac{(B + D) \pm \sqrt{(B + D)^2 - 4\left(BD - \frac{T_f}{1.84f_{tg}}\right)}}{4} \quad (168)$$

The smallest positive root is desired, which will always result in the use of the negative sign.

The time to failure is as follows:

$$t_{t4} = \frac{x_c}{\beta} - n_t = \frac{x_t - 7}{\beta} - n_t \quad (169)$$

where n_t is a constant calibration term used to reduce the failure time to ensure that the predicted failure times of the members are less than the observed failure times.

The same constant charring rate that produced good results in the detailed method is also applied in the simplified method, therefore $\beta = 0.635$ mm/min.

$$t_{t4} = \frac{(B+D) - \sqrt{(B+D)^2 - 4\left(BD - \frac{T_f}{1.84f_{tg}}\right)}}{2.54} - (11 + n_t) \quad (170)$$

Simplifying the equation a final time and rounding to obtain an attractive user-friendly equation with $n_t = 4.0$ the final equation for the failure time of a tension member exposed to fire on four sides is:

$$t_{t4} = 0.4 \left[(B+D) - \sqrt{(B-D)^2 + \frac{T_f}{1.84f_{tg}}} \right] - 15 \quad (171)$$

Figure 37 shows the predicted failure times using Equation 171 plotted versus the observed failure times, with all the members being conservatively predicted.

Figure 37: Predicted Failure Times for Tension Members Using Equation 171 vs. Observed Failure Times

Equation 171 could provide the much-needed guidance to calculate failure times of tension members for designers as currently none is provided in the NBCC.

4.3.4 Beams

The proposed solution for beams is not as straightforward as that of tension members because a cubic equation must be solved.

$$M_f = M_r = \phi S F_b K_x K_{zbg} \quad (172)$$

with:

$$F_b = f_b K_D K_H K_{Sb} K_T \quad (173)$$

where $\phi = 0.9$, M_f (Nmm) is the maximum factored bending moment on the member, M_r (Nmm) is the member resistance, S is the section modulus (mm^3), f_b (MPa) is the specified bending strength and $K_D K_H K_{Sb} K_T = 1.0$. The section modulus for a member exposed to fire on three sides is determined as follows:

$$S = \frac{(B - 2x_t)(D - x_t)^2}{6} \quad (174)$$

The size factor, K_{Zbg} , and the lateral stability factor, K_L , are assumed equal to one. A calibration term will be incorporated to account for this assumption.

Because of these assumptions, Equation 172 reduces to:

$$M_f = M_r = \phi S f_b \quad (175)$$

The time to failure for a beam exposed on three sides is defined by:

$$t_{b3} = \frac{x_c}{\beta} - n_b = \frac{x_t - 7}{\beta} - n_b \quad (176)$$

As performed for tension members, to account for factored loads, factored resistances and fifth percentile ultimate values, a modification factor h_b must be calculated.

$$\frac{(B-2x_t)(D-x_t)^2}{6} = \frac{M_f}{\phi h_b f_b} \quad (177)$$

$$M_r = M_f = \phi S h_b f_b \quad (178)$$

$$M_s = M_{r,s} = \phi_1 S f_{b,avg} \quad (179)$$

where M_s is the unfactored (service) moment, ϕ_1 is the member resistance factor equal to one, and $f_{b,avg}$ is the average ultimate bending strength. Solving Equations 178 and 179 for S and equating the following is obtained:

$$\frac{M_s}{\phi_1 f_{b,avg}} = \frac{M_f}{\phi h_b f_b} \quad (180)$$

At failure:

from Equation 147:

$$M_s = \frac{M_f}{1.45} \quad (181)$$

from Equation 151:

$$f_{b,avg} = \frac{f_b}{0.7875} \quad (182)$$

For beams the resistance factor $\phi = 0.9$ therefore:

$$\phi_1 = \frac{\phi}{0.9} \quad (183)$$

Substituting Equations 181 to 182 into 180, the following is obtained:

$$\frac{M_s}{\phi_1 f_{b,avg}} = \frac{\frac{M_f}{1.45}}{\left(\frac{\phi}{0.9}\right)\left(\frac{f_b}{0.7875}\right)} = \frac{M_f}{\phi h_b f_b} \quad (184)$$

Resulting in:

$$h_b = 2.05 \quad (185)$$

$$(B - 2x_t)(D - x_t)^2 = \frac{6M_f}{\phi 2.05 f_b} \quad (186)$$

Setting the equation equal to zero and applying $\phi = 0.9$ the following is obtained:

$$(B - 2x_t)(D - x_t)^2 - \frac{3.3M_f}{f_b} = 0 \quad (187)$$

The cubic equation above is solved for the smallest real root, x_t . This can be done using available computer software or by using equations 188 to 193.

$$x_t = \frac{1}{6w} (w^2 + w(4D + B) - 4BD + 4D^2 + B^2) \quad (188)$$

where:

$$w = \left(B^3 + v - 54u + 6\sqrt{3}\sqrt{-u(B^3 + v - 27u)} \right)^{1/3} \quad (189)$$

$$v = 2D(-4D^2 + 6BD - 3B^2) \quad (190)$$

$$u = \frac{2.93 \times M_f}{f_b} \quad (191)$$

Once x_t is obtained the time to failure can be solved using Equation 176 and applying a charring rate of 0.635 mm/min. To ensure that the time to failure predicted for the majority of members is less than the observed and account for rounding n_b has been set equal to 12.

$$t_{b3} = \frac{x_c}{0.635} - 12 = \frac{x_t - 7}{0.635} - 12 = \frac{x_t}{0.635} - 23 \quad (192)$$

If equations 188 to 191 were used to calculate x_t the time to failure can be simplified to:

$$t_{b3} = \frac{0.26}{w} (w^2 + w(4D + B) - 4BD + 4D^2 + B^2) - 23 \quad (193)$$

with Equations 189 to 191 remaining the same. Figure 38 shows the results for beams.

Figure 38: Predicted Failure Times for Beams Using Equation 193 vs. Observed Failure Times

4.3.5 Columns

While developing the detailed method to predict failure times it became apparent that the failure time depended strongly on the unfactored applied load, cross-sectional area and average ultimate compressive strength. The time to failure is the time when the factored compressive load, P_f (N) is equal to the member resistance, P_r (N).

$$P_f = P_r = \phi F_c K_{Zcg} K_C A \quad (194)$$

$$F_c = f_c (K_D K_H K_{SC} K_T) \quad (195)$$

with $\phi = 0.8$, and $K_D K_H K_{SC} K_T = 1$ and f_c (MPa) is the specified compressive strength. Once again, to simplify the equations the size factor, K_{Zcg} , and the slenderness factor, K_C are assumed to equal one. A calibration term n_c is applied to account for slenderness and to ensure the majority of failure times are conservative. Without the calibration term, the times predicted are much larger than the observed times to failure because buckling has not been taken into account. Equation 194 reduces to:

$$P_f = P_r = \phi A f_c \quad (196)$$

where A (mm²) is as defined in Equation 155.

The failure time of columns follows the same equations as used in tension members. Where the total depth is as follows:

$$x_t = \frac{(B+D) - \sqrt{(B+D)^2 - 4\left(BD - \frac{P_f}{1.84f_c}\right)}}{4} \quad (197)$$

The time to failure is defined by:

$$t_{c4} = \frac{x_c}{\beta} - n_c = \frac{x_t - 7}{\beta} - n_c \quad (198)$$

where the same charring rate as tension members and beams, $\beta = 0.635 \text{ mm/min}$, is used.

To ensure safe failure times, an appropriate n_c value is selected:

$$t_{c4} = \frac{(B+D) \pm \sqrt{(B+D)^2 - 4\left(BD - \frac{P_f}{1.84f_c}\right)}}{2.54} - (11 + n_c) \quad (199)$$

Simplifying the equation a final time and rounding to provide the user with an appealing equation the following is obtained:

$$t_{c4} = 0.4 \left[(B+D) - \sqrt{(B-D)^2 + \frac{P_f}{1.84f_c}} \right] - 64 \quad (200)$$

Figure 39: Predicted Failure Times for Beams Using Equation 200 vs. Observed Failure Times

The members circled are the columns that have load ratios greater than one as calculated in Section 3.1. These members would not be used in Canadian design. The other member surrounded by a diamond is the member tested by CSTB, which has a particularly low compressive strength.

4.3.6 Summary

Tension members exposed to fire on four sides:

$$t_{t4} = 0.4 \left[(B + D) - \sqrt{(B - D)^2 + \frac{T_f}{1.84f_{tg}}} \right] - 15 \quad (201)$$

Beams exposed to fire on three sides:

$$t_{b3} = \frac{0.26}{w} (w^2 + w(4D + B) - 4BD + 4D^2 + B^2) - 23 \quad (202)$$

where:

$$w = \left(B^3 + v - 54u + 6\sqrt{3}\sqrt{-u(B^3 + v - 27u)} \right)^{1/3} \quad (203)$$

$$v = 2D(-4D^2 + 6BD - 3B^2) \quad (204)$$

$$u = \frac{2.93 \times M_f}{f_b} \quad (205)$$

Columns exposed to fire on four sides:

$$t_{c4} = 0.4 \left[(B + D) - \sqrt{(B - D)^2 + \frac{P_f}{1.84f_c}} \right] - 64 \quad (206)$$

4.4 Uncertainty

Wood is a natural material with variable mechanical properties and fire is a complex phenomenon involving marked uncertainties. The structural behaviour of wood under fire is an inherently uncertain, variable, and complex phenomenon that is extremely difficult to characterize. The deterministic analytical and numerical models in this investigation are only the first step towards a more involved stochastic or reliability-based formulation.

Throughout this thesis there have been a number of uncertainties resulting from unknown information and assumptions. As mentioned in Section 2.4.3

differences among repeat fire tests of 30% are not uncommon. Table 30 shows examples of column test data from TR10 and the differences between repeat tests. These pairs of columns are expected to have the same or very similar observed failure times, however differences of up to 40% are observed. All columns have a length of 3658 mm and the percent difference is calculated as the percent increase based on the smaller observed failure time.

Table 30: Comparison of Column Test Data from Technical Report 10 (AF&PA, 2003)

Designation	B	D	$f_{c,avg}$	MOE, E	Specific Gravity	Applied Load	Observed Failure Time	% Difference
	mm	mm	MPa	MPa		kN	min	
R14D	139.7	139.7	51.3	15168.5	0.43	63.4	26	34.6
H14D	139.7	139.7	51.3	15168.5	0.43	63.4	35	
H14/24A	139.7	241.3	43.0	11721.1	0.41	145.1	32	21.8
H14/24B	139.7	241.3	42.5	11031.6	0.41	145.1	39	
R15A	149.2	149.2	41.3	12410.6	0.38	106.9	27	14.8
R15B	149.2	146.9	41.2	12410.6	0.38	106.9	31	
R16/30	158.8	298.5	41.0	10342.1	0.41	122.6	40	17.6
H16/30D	158.8	298.5	39.4	10342.1	0.4	122.6	34	
H20A	200.0	200.0	40.7	11721.1	0.38	251.0	43	39.5
H20B	200.0	200.0	41.6	12410.6	0.39	251.0	60	
R27C	269.9	269.9	42.9	11031.6	0.41	538.4	59	0
H27C	269.9	269.9	42.6	11031.6	0.41	538.4	59	

There is also uncertainty in the material properties reported and used. For many of the column test specimens the strength and modulus of elasticity was based on the density. Also, since the members were tested in different labs in different countries, there is would be variation in the test setup, moisture content as well as the way the material properties are measured. The mode of failure of the test specimens is unknown, but was assumed to be structural failure due to

insufficient resistance. Since a constant charring rate was assumed, no account was taken for the variation in charring based on the density of the species.

Assumptions were made by TR10 to convert the allowable design stresses to average ultimate design stresses. In this report, the average ultimate design stresses were then converted to fifth percentile ultimate design stresses for use in the simplified design method creating additional uncertainty. The live to dead load ratio equal to four is also an assumption that adds to the uncertainty of the results

Columns and tension members have added uncertainty due to the small number of test results available. Few data points are better than none, however as a result the results may not be as reliable.

5.0 Conclusions

The objective of this thesis was to determine whether the current equations provided by the NBCC correctly predicted the failure times of glulam test specimens exposed to fire. It was found that for 57% of the beams and 61% of the columns, the NBCC equations for calculating fire resistance overestimates the failure times, producing unsafe results. Therefore, improved equations to aid the designer in better predicting the failure times of glulam beams and columns as well as a new equation to provide much need guidance for the fire resistance of members loaded in tension were required.

To predict failure times as measured in tests, the detailed method using the Eurocode 5 zero-strength layer method as presented in Section 4.2.3 produces the best results. Ultimate strength values and unfactored loads, in conjunction with the commonly accepted charring rate of $\beta = 0.635 \text{ mm/min}$ are used.

The simplified method provides algebraic equations to conservatively predict the fire-resistance rating (time to failure) of glulam columns, beams and tension members exposed to fire. Once again, the Eurocode 5 zero-strength layer method is used and upon setting the slenderness factors for beams and columns equal to one, and applying a calibration term to account for rounding and slenderness, acceptable results are obtained. The final equations are conservative and easy for a designer with little knowledge of the science of burning wood to use. The equations depend only on the specified material

strength, cross-sectional dimensions prior to fire exposure and the factored load, all of which are known to the designer. The simplified method presented in this work provides better results than those currently provided by the NBCC and provides the much needed guidance for glulam members loaded in tension.

6.0 Recommendations

It is recommended that additional fire tests be performed to verify the equations presented and to add to the database for beams and tension members. The fifth percentile strength values of the new test specimens should be determined in accordance with Canadian standards. Testing should also be performed using load ratios similar to those typically found in design. A standard methodology for obtaining material properties of test specimens at ambient and elevated temperatures is recommended to ensure that future test results from different labs in different countries can be compared. These results could be compiled into a database that is updated regularly and available to researchers and designers. An in-depth analysis of the charring rate of species used in Canadian glulam members would be beneficial to verify values used in this work. In future research, shear failure and deflection should also be investigated for beams.

Following verification of the presented equations, it is recommended that the simplified method equations be submitted to the Committees responsible for writing the National Building Code of Canada for review.

A reliability-based formulation of the structural behaviour of wood under fire is a major undertaking but its consideration by the research establishment is necessary to bring this topic under the same level of academic and professional rigour present in our current codes of practice.

7.0 References

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Appendix A: Test Data from Technical Report 10

Table A. 1: Column Test Data from Technical Report 10 (AF&PA, 2003)

Designation	B	D	Length	$f_{c,avg}$	Modulus of Elasticity, E	Specific Gravity	Applied Load	Observed Failure Time
	mm	mm	mm	MPa	MPa		kN	min
CSTB	177.8	200.0	2286	17.7	11031.6	0.56	177.0	29
R14A	139.7	139.7	3657.6	50.8	17236.9	0.44	84.6	21
R14B	139.7	139.7	3657.6	54.7	15857.9	0.45	84.6	36
R14C	139.7	139.7	3657.6	56.1	16547.4	0.45	42.4	29
R14D	139.7	139.7	3657.6	51.3	15168.5	0.43	63.4	26
H14A	139.7	139.7	3657.6	55.5	13789.5	0.44	84.6	27
H14B	139.7	139.7	3657.6	52.8	16547.4	0.48	84.6	43
H14C	139.7	139.7	3657.6	56.1	16547.4	0.45	42.4	34
H14D	139.7	139.7	3657.6	51.3	15168.5	0.43	63.4	35
H14/24A	139.7	241.3	3657.6	43.0	11721.1	0.41	145.1	32
H14/24B	139.7	241.3	3657.6	42.5	11031.6	0.41	145.1	39
H14/30A	139.7	298.5	3657.6	47.7	11721.1	0.45	181.4	59
H14/30B	139.7	298.5	3657.6	59.9	18615.8	0.47	90.7	53
H14/30C	139.7	298.5	3657.6	49.4	12410.6	0.46	90.7	43
H14/40	139.7	400.1	3657.6	46.0	11031.6	0.45	241.2	26
R15A	149.2	149.2	3657.6	41.3	12410.6	0.38	106.9	27
R15B	149.2	146.9	3657.6	41.2	12410.6	0.38	106.9	31
H15A	149.2	149.2	3657.6	44.9	13100.0	0.4	106.9	30
H15B	149.2	149.2	3657.6	40.5	11721.1	0.37	106.9	30
R16	149.2	149.2	3657.6	29.7	8963.2	0.31	130.9	31
H16A	158.8	158.8	3657.6	39.5	11721.1	0.37	130.9	37
H16B	158.8	158.8	3657.6	45.5	13100.0	0.4	130.9	58
R16/30	158.8	298.5	3657.6	41.0	10342.1	0.41	122.6	40
H16/30A	158.8	298.5	3657.6	42.9	11031.6	0.42	245.2	52
H16/30B	158.8	298.5	3657.6	46.0	11721.1	0.44	245.2	45
H16/30C	158.8	298.5	3657.6	44.6	11031.6	0.43	245.2	57
H16/30D	158.8	298.5	3657.6	39.4	10342.1	0.4	122.6	34
R20A	200.0	200.0	3657.6	40.9	11031.6	0.4	251.0	48
R20B	200.0	200.0	3657.6	45.9	11721.1	0.39	251.0	64
R20C	200.0	200.0	3657.6	62.1	15168.5	0.46	125.5	61
R20D	200.0	200.0	3657.6	39.2	11031.6	0.43	125.5	42

Table A. 2: Column Test Data from Technical Report 10 Continued (AF&PA, 2003)

Designation	B	D	Length	$f_{c,avg}$	Modulus of Elasticity, E	Specific Gravity	Applied Load	Observed Failure Time
	mm	mm	mm	MPa	MPa		kN	min
H20A	200.0	200.0	3657.6	40.7	11721.1	0.38	251.0	43
H20B	200.0	200.0	3657.6	41.6	12410.6	0.39	251.0	60
H20C	200.0	200.0	3657.6	59.8	14479.0	0.45	125.5	52
H20D	200.0	200.0	3657.6	50.8	13789.5	0.45	125.5	65
H20/40A	200.0	400.1	3657.6	45.9	11031.6	0.44	502.1	74
H20/40B	200.0	400.1	3657.6	37.3	8963.2	0.45	502.1	60
H24A	241.3	241.3	3657.6	38.9	10342.1	0.4	400.1	56
H24B	241.3	241.3	3657.6	45.6	12410.6	0.38	400.1	62
H26A	260.4	260.4	3657.6	43.8	11721.1	0.42	492.3	62
H26B	260.4	260.4	3657.6	38.5	10342.1	0.42	492.3	57
R27A	269.9	269.9	3657.6	36.0	8963.2	0.38	538.4	54
R27B	269.9	269.9	3657.6	37.9	11031.6	0.4	538.4	76
R27C	269.9	269.9	3657.6	42.9	11031.6	0.41	538.4	59
H27A	269.9	269.9	3657.6	42.9	13100.0	0.42	538.4	56
H27B	269.9	269.9	3657.6	37.6	9652.7	0.4	538.4	71
H27C	269.9	269.9	3657.6	42.6	11031.6	0.41	538.4	59
H28A	279.4	279.4	3657.6	40.0	10342.1	0.4	591.3	67
H28B	279.4	279.4	3657.6	43.2	11031.6	0.42	591.3	114
H40	400.1	400.1	3657.6	39.0	9652.7	0.41	1372.9	55
FU1	228.6	228.6	2082.8	35.8	11721.1	0.59	320.2	74
FR3	142.2	381.0	2082.8	35.8	11721.1	0.59	160.1	45
FP4	228.6	228.6	2082.8	35.8	11721.1	0.59	640.4	73
HU5	228.6	228.6	2082.8	30.7	10342.1	0.54	138.0	49
HR7	175.3	304.8	2082.8	30.7	10342.1	0.54	276.1	69
HP8	228.6	228.6	2082.8	30.7	10342.1	0.54	276.1	47
RU9	142.2	381.0	2082.8	27.3	8273.7	0.54	245.7	45
RR11	228.6	228.6	2082.8	27.3	8273.7	0.54	491.3	76
RP12	175.3	304.8	2082.8	27.3	8273.7	0.54	122.8	35
CU13	175.3	304.8	2082.8	22.2	6894.8	0.38	398.2	43
CR15	228.6	228.6	2082.8	22.2	6894.8	0.38	199.1	39
CP16	142.2	381.0	2082.8	22.2	6894.8	0.38	199.1	48

Table A. 3: Beam Test Data from Technical Report 10 Continued (AF&PA, 2003)

Designation	B	D	Length	$f_{b,avg}$	Modulus of Elasticity, E	Specific Gravity	Applied Load	Observed Failure Time
	mm	mm	mm	MPa	MPa		kN m	min
TRADA	139.7	228.6	3650	51.9	13789.5	0.49	13.3	53
NFoPA	222.3	419.1	5172	47.2	11031.6	0.47	75.7	86
AF&PA-27	222.3	419.1	4572	47.2	11031.6	0.47	25.7	147
AF&PA-44	222.3	419.1	4572	47.2	11031.6	0.47	41.6	114
AF&PA-91	222.3	419.1	4572	47.2	11031.6	0.47	88.2	85
FCNSW-BB	149.9	419.1	4010	50.0	15168.5	0.82	101.4	59
FCNSW-RP	149.9	419.1	4010	35.9	12410.6	0.52	27.8	67

Table A. 4: Tension Member Test Data from Technical Report 10 Continued (AF&PA, 2003)

Designation	B	D	$f_{t,avg}$	Applied Load	Observed Failure Time
	mm	mm	MPa	kN	min
Test 1	85.7	135.0	14.7	14.2	42
Test 3	128.6	223.9	31.4	156.4	58
Test 4	222.3	217.5	31.4	87.1	124

Appendix B: Technical Report 10 Results and Data

Table B. 1: Technical Report 10 - Observed and Predicted Failure Times of Columns

Designation	Observed Failure Time	Failure Time Results from TR10	% Difference
	min	min	
CSTB44	48	45	6.3
R14A	29	25	13.8
R14B	21	24	-14.3
R14C	36	36	0.0
R14D	29	28	3.4
H14A	26	22	15.4
H14B	27	25	7.4
H14C	43	36	16.3
H14D	34	28	17.6
H14/24A	35	21	40.0
H14/24B	32	21	34.4
H14/30A	39	23	41.0
H14/30B	59	43	27.1
H14/30C	53	36	32.1
H14/40	43	22	48.8
R15A	26	22	15.4
R15B	27	22	18.5
H15A	31	23	25.8
H15B	30	22	26.7
R16	30	18	40.0
H16A	31	23	25.8
H16B	37	26	29.7
R16/30	58	41	29.3
H16/30A	40	26	35.0
H16/30B	52	28	46.2
H16/30C	45	27	40.0
H16/30D	57	40	29.8
R20A	34	35	-2.9
R20B	48	37	22.9
R20C	64	61	4.7
R20D	61	53	13.1

Table B. 2: Technical Report 10 - Observed and Predicted Failure Times of Columns
Continued

Designation	Observed Failure Time	Failure Time Results from TR10	% Difference
	min	min	
H20A	42	37	11.9
H20B	43	38	11.6
H20C	60	59	1.7
H20D	52	56	-7.7
H20/40A	65	41	36.9
H20/40B	74	35	52.7
H24A	60	50	16.7
H24B	56	55	1.8
H26A	62	62	0.0
H26B	62	57	8.1
R27A	57	56	1.8
R27B	54	64	-18.5
R27C	76	65	14.5
H27A	59	70	-18.6
H27B	56	60	-7.1
H27C	71	65	8.5
H28A	59	67	-13.6
H28B	67	70	-4.5
H40	114	123	-7.9
FU1	55	77	-40.0
FR3	74	49	33.8
FP4	45	51	-13.3
HU5	73	96	-31.5
HR7	49	54	-10.2
HP8	69	77	-11.6
RU9	47	35	25.5
RR11	45	50	-11.1
RP12	76	68	10.5
CU13	35	35	0.0
CR15	43	76	-76.7
CP16	39	36	7.7

Table B. 3: Technical Report 10 - Observed and Predicted Failure Times of Beams

Designation	Observed Failure Time	Failure Time Results from TR10	% Difference
	min	min	
TRADA	53	52	1.9
NFoPA	86	84	2.3
AF&PA-27	147	134	8.8
AF&PA-44	114	125	-9.6
AF&PA-91	85	92	-8.2
FCNSW-BB	59	41	30.5
FCNSW-RP	67	72	-7.5

Table B. 4: Technical Report 10 - Observed and Predicted Failure Times of Tension Members

Designation	Observed Failure Time	Failure Time Results from TR10	% Difference
	min	min	
Test 1	42	44	-4.8
Test 3	58	60	-3.4
Test 4	124	126	-1.6

Appendix C: Microsoft Visual Basic for Applications

Source Code

Columns

Implementation of Eurocode 5 Zero Strength Layer Method

```
Public Sub findPcanadaZero()
```

```
Dim zdepth As Double
Dim b As Double
Dim xc As Double
Dim d As Double
Dim E As Double
Dim I As Double 'unsupported length
Dim t As Double
Dim z As Double
Dim Aelevated As Double
Dim beta As Double
Dim Cc As Double
Dim counter As Integer
Dim deltat As Double
Dim Ef5 As Double
Dim Ef5fire As Double
Dim exposedsides As Integer
Dim fc As Double
Dim fcfire As Double
Dim lelevated As Double
Dim Kcelev As Double
Dim Ke As Double
Dim Kse As Double
Dim Kstar As Double
Dim Kcfire As Double
Dim Kmoe5fire As Double
Dim Kt As Double
Dim Kzcg As Double
Dim phi As Double
Dim Pcanada As Double
Dim Pappied As Double
Dim timecounter As Double
Dim tfailure As Double
```

```
zdepth = Worksheets("Factors").Range("D4").Value
beta = Worksheets("Factors").Range("D3").Value
deltat = Worksheets("Factors").Range("D6").Value
exposedsides = Worksheets("Factors").Range("D5").Value
Ke = Worksheets("Factors").Range("D7").Value
Kse = Worksheets("Factors").Range("D8").Value
Kstar = Worksheets("Factors").Range("D13").Value
'kstar=Kd*Kh*Ksc*Kt
Kt = Worksheets("Factors").Range("D9").Value
phi = Worksheets("Factors").Range("D16").Value
Kcfire = Worksheets("Factors").Range("D17").Value
Kmoe5fire = Worksheets("Factors").Range("D18").Value
```

```
counter = 0
timecounter = 0
```

```
Worksheets("Time").Range("T14:T1000").ClearContents
If exposedsides < 4 Then
    Dim Msg, Style, Title, Response
    Msg = "The Program may only be used for 4 Sides Exposed  
to Fire" ' Define message.
    Style = vbOKOnly ' Define buttons.
    Title = "Improper Use" ' Define title.
```

```
Response = MsgBox(Msg, Style, Title)
Exit Sub
End If
```

```
If exposedsides = 4 Then
Do
Do
```

```
b = Worksheets("Time").Cells(6 + counter, 10).Value
d = Worksheets("Time").Cells(6 + counter, 11).Value
I = Worksheets("Time").Cells(6 + counter, 12).Value
E = Worksheets("Time").Cells(6 + counter, 14).Value
fc = Worksheets("Time").Cells(6 + counter, 13).Value
Pappied = Worksheets("Time").Cells(6 + counter, 16).Value
```

```
t = 0 + deltat * (timecounter)
fcfire = Kcfire * fc
```

```
Ef5 = 0.87 * E
Ef5fire = Kmoe5fire * Ef5
```

```
If t <= 20 Then
    z = (zdepth / 20) * t
Else
    z = zdepth
End If
```

```
xc = beta * t + z
' if varying charring rate is used xc = beta * 60 * (t / 60) ^
0.813 + z
```

```
If b - 2 * xc <= 0 Then Exit Do
If d - xc <= 0 Then Exit Do
```

```
Aelevated = (b - 2 * xc) * (d - 2 * xc)
```

```
Kzcg = 0.68 * (((b - 2 * (xc - z)) * (d - 2 * (xc - z))) * I) / 1000 ^ 3)
^ -0.13
If Kzcg >= 1# Then Kzcg = 1#
```

```
If Ke * I / (b - 2 * (xc - z)) > Ke * I / (d - 2 * (xc - z)) Then
    Cc = Ke * I / (b - 2 * (xc - z))
Else
    Cc = Ke * I / (d - 2 * (xc - z))
End If
```

```
Kcelev = (1 + (fcfire * Kzcg * Cc ^ 3 / (35 * Ef5fire * Kse * Kt)))
^ -1
```

```
Pcanada = phi * (fcfire * Kstar * Aelevated * Kcelev) * Kzcg /
1000
```

```
If b <= 2 * xc Then
Exit Do
End If
```

```
If Pcanada < Pappied Then Exit Do
```

```
timecounter = timecounter + 1
Loop
tfailure = t - deltat
Worksheets("Time").Cells(6 + counter, 20).Value = tfailure
counter = counter + 1
timecounter = 0
If counter > 61 Then Exit Do
Loop
End If
```

```
End Sub
```

Implementation of Constant Material Property Reductions Method

```
Public Sub findPcanadaConstant()
```

```
Dim b As Double
```

```

Dim xc As Double
Dim d As Double
Dim E As Double
Dim l As Double 'unsupported length
Dim t As Double
Dim z As Double
Dim Aelevated As Double
Dim beta As Double
Dim Cc As Double
Dim counter As Integer
Dim deltat As Double
Dim Efive As Double
Dim Efivefire As Double
Dim exposedsides As Integer
Dim fc As Double
Dim fcfire As Double
Dim lelevated As Double
Dim Kcelev As Double
Dim Ke As Double
Dim Kse As Double
Dim Kstar As Double
Dim Kcfire As Double
Dim Kmoeffire As Double
Dim Kt As Double
Dim Kzcg As Double
Dim phi As Double
Dim Pcanada As Double
Dim Pappied As Double
Dim timecounter As Double
Dim tfailure As Double

```

```

beta = Worksheets("Factors").Range("D3").Value
deltat = Worksheets("Factors").Range("D6").Value
exposedsides = Worksheets("Factors").Range("D5").Value
Ke = Worksheets("Factors").Range("D7").Value
Kse = Worksheets("Factors").Range("D8").Value
Kstar = Worksheets("Factors").Range("D13").Value
'kstar=Kd*Kh*Ksc*KT
Kt = Worksheets("Factors").Range("D9").Value
phi = Worksheets("Factors").Range("D16").Value
Kcfire = Worksheets("Factors").Range("D17").Value
Kmoeffire = Worksheets("Factors").Range("D18").Value

```

```

counter = 0
timecounter = 0

```

```

Worksheets("Time").Range("T14:T1000").ClearContents
If exposedsides <= 4 Then
    Dim Msg, Style, Title, Response
    Msg = "The Program may only be used for 4 Sides Exposed to Fire" ' Define message.
    Style = vbOKOnly ' Define buttons.
    Title = "Improper Use" ' Define title.

```

```

    Response = MsgBox(Msg, Style, Title)
Exit Sub
End If

```

```

If exposedsides = 4 Then
Do
    Do

```

```

        b = Worksheets("Time").Cells(6 + counter, 10).Value
        d = Worksheets("Time").Cells(6 + counter, 11).Value
        l = Worksheets("Time").Cells(6 + counter, 12).Value
        E = Worksheets("Time").Cells(6 + counter, 14).Value
        fc = Worksheets("Time").Cells(6 + counter, 13).Value
        Pappied = Worksheets("Time").Cells(6 + counter, 16).Value

```

```

        t = 0 + deltat * (timecounter)
        fcfire = Kcfire * fc

```

```

        Efive = 0.87 * E
        Efivefire = Kmoeffire * Efive

```

```

        xc = beta * t

```

```

' if varying charring rate is used xc = beta * 60 * (t / 60) ^
0.813

```

```

If b - 2 * xc <= 0 Then Exit Do
If d - xc <= 0 Then Exit Do

```

```

Aelevated = (b - 2 * xc) * (d - 2 * xc)

```

```

Kzcg = 0.68 * (((b - 2 * xc) * (d - 2 * xc)) * l) / 1000 ^ 3) ^ -0.13
If Kzcg >= 1# Then Kzcg = 1#

```

```

If Ke * l / (b - 2 * xc) > Ke * l / (d - 2 * xc) Then
    Cc = Ke * l / (b - 2 * xc)
Else
    Cc = Ke * l / (d - 2 * xc)
End If

```

```

Kcelev = (1 + (fcfire * Kzcg * Cc ^ 3 / (35 * Efivefire * Kse * Kt)))
^ -1

```

```

Pcanada = phi * (fcfire * Kstar * Aelevated * Kcelev) * Kzcg /
1000

```

```

If b <= 2 * xc Then
    Exit Do
End If

```

```

If Pcanada < Pappied Then Exit Do

```

```

timecounter = timecounter + 1
Loop
tfailure = t - deltat
Worksheets("Time").Cells(6 + counter, 20).Value = tfailure
counter = counter + 1
timecounter = 0
If counter > 61 Then Exit Do
Loop
End If

```

```

End Sub

```

Implementation of Eurocode 5 Material Property Reductions Method

```

Public Sub findPcanadaEurocode()

```

```

Dim b As Double
Dim xc As Double
Dim d As Double
Dim E As Double
Dim l As Double 'unsupported length
Dim t As Double
Dim z As Double
Dim Aelevated As Double
Dim beta As Double
Dim Cc As Double
Dim counter As Integer
Dim deltat As Double
Dim Efive As Double
Dim Efivefire As Double
Dim exposedsides As Integer
Dim fc As Double
Dim fcfire As Double
Dim lelevated As Double
Dim Kcelev As Double
Dim Ke As Double
Dim Kse As Double
Dim Kstar As Double
Dim Kcfire As Double
Dim Kmoeffire As Double

```

```

Dim Kt As Double
Dim Kzcg As Double
Dim phi As Double
Dim Pcanada As Double
Dim Pappied As Double
Dim perimeter As Double
Dim timecounter As Double
Dim tfailure As Double

beta = Worksheets("Factors").Range("D3").Value
deltat = Worksheets("Factors").Range("D6").Value
exposedsides = Worksheets("Factors").Range("D5").Value
Ke = Worksheets("Factors").Range("D7").Value
Kse = Worksheets("Factors").Range("D8").Value
Kstar = Worksheets("Factors").Range("D13").Value
'kstar=Kd*Kh*Ksc*KT
Kt = Worksheets("Factors").Range("D9").Value
phi = Worksheets("Factors").Range("D16").Value

counter = 0
timecounter = 0

Worksheets("Time").Range("T14:T1000").ClearContents
If exposedsides <> 4 Then
    Dim Msg, Style, Title, Response
    Msg = "The Program may only be used for 4 Sides Exposed to Fire" ' Define message.
    Style = vbOKOnly ' Define buttons.
    Title = "Improper Use" ' Define title.

    Response = MsgBox(Msg, Style, Title)
Exit Sub
End If

If exposedsides = 4 Then
Do
    b = Worksheets("Time").Cells(6 + counter, 10).Value
    d = Worksheets("Time").Cells(6 + counter, 11).Value
    l = Worksheets("Time").Cells(6 + counter, 12).Value
    E = Worksheets("Time").Cells(6 + counter, 14).Value
    fc = Worksheets("Time").Cells(6 + counter, 13).Value
    Pappied = Worksheets("Time").Cells(6 + counter, 16).Value

    t = 0 + deltat * (timecounter)
    xc = beta * t
    ' if varying charring rate is used xc = beta * 60 * (t / 60) ^ 0.813
    perimeter = 2 * (b - 2 * xc) + 2 * (d - 2 * xc)
    Aelevated = (b - 2 * xc) * (d - 2 * xc)

    Kfcfire = 1 - 1 / (125 * ((Aelevated / 1000 ^ 2) / (perimeter / 1000)))
    Kmoefire = 1 - 1 / (330 * ((Aelevated / 1000 ^ 2) / (perimeter / 1000)))

    fcfire = Kfcfire * fc

    Efive = 0.87 * E
    Efivefire = Kmoefire * Efive

    If b - 2 * xc <= 0 Then Exit Do
    If d - xc <= 0 Then Exit Do

    Kzcg = 0.68 * (((b - 2 * xc) * (d - 2 * xc)) * l) / 1000 ^ 3) ^ -0.13
    If Kzcg >= 1# Then Kzcg = 1#

    If Ke * l / (b - 2 * xc) > Ke * l / (d - 2 * xc) Then
        Cc = Ke * l / (b - 2 * xc)
    Else
        Cc = Ke * l / (d - 2 * xc)
    End If

    Kcelev = (1 + (fcfire * Kzcg * Cc ^ 3 / (35 * Efivefire * Kse * Kt))) ^ -1

    Pcanada = phi * (fcfire * Kstar * Aelevated * Kcelev) * Kzcg / 1000

    If b <= 2 * xc Then
        Exit Do
    End If

    If Pcanada < Pappied Then Exit Do

    timecounter = timecounter + 1
Loop
tfailure = t - deltat
Worksheets("Time").Cells(6 + counter, 20).Value = tfailure
counter = counter + 1
timecounter = 0
If counter > 61 Then Exit Do
Loop
End If

End Sub

```

Beams

Implementation of Eurocode 5 Zero Strength Layer Method

Option Explicit

Public Sub findMcanadaZero()

```
Dim b As Double
Dim xc As Double
Dim d As Double
Dim E As Double
Dim f As Double
Dim beta As Double
Dim deltat As Double
Dim I As Double
Dim fb As Double
Dim fbfire As Double
Dim t As Double
Dim z As Double
Dim Aelevated As Double
Dim Cb As Double
Dim Ck As Double
Dim Efire As Double
Dim KL As Double
Dim kse As Double
Dim kstar1 As Double
Dim kT As Double
Dim kfbfire As Double
Dim kEfire As Double
Dim kx As Double
Dim kzb As Double
Dim counter As Integer
Dim le As Double
Dim Mcanada As Double
Dim Mcanada1 As Double
Dim Mcanada2 As Double
Dim Mapped As Double
Dim exposedsides As Integer
Dim phi As Double
Dim doverb As Double
Dim tfailure As Double
Dim zdepth As Double
```

```
zdepth = Worksheets("TimeConstant").Range("L5").Value
phi = Worksheets("TimeConstant").Range("Q3").Value
exposedsides =
Worksheets("TimeConstant").Range("L6").Value
kstar1 = Worksheets("TimeConstant").Range("W14").Value
kstar = Kd * Kh * Ksb * kT
kse = Worksheets("TimeConstant").Range("Q5").Value
kT = Worksheets("TimeConstant").Range("Q6").Value
kx = 1 ' All members assumed straight
```

```
beta = Worksheets("TimeConstant").Range("L4").Value
deltat = Worksheets("TimeConstant").Range("L7").Value
```

```
Worksheets("TimeConstant").Range("S17:T1000").ClearContents
Worksheets("TimeConstant").Range("W17:W1000").ClearContents
```

counter = 0

```
If exposedsides <= 3 Then
    Dim Msg, Style, Title, Response
    Msg = "The Program may only be used for 3 Sides Exposed to Fire" ' Define message.
    Style = vbOKOnly ' Define buttons.
    Title = "Improper Use" ' Define title.
```

```
Response = MsgBox(Msg, Style, Title)
Exit Sub
End If
```

Do 'step through beams

```
t = 0
fb = Worksheets("TimeConstant").Cells(17 + counter, 13).Value
b = Worksheets("TimeConstant").Cells(17 + counter, 10).Value
d = Worksheets("TimeConstant").Cells(17 + counter, 11).Value
I = Worksheets("TimeConstant").Cells(17 + counter, 21).Value
le = Worksheets("TimeConstant").Cells(17 + counter, 22).Value
E = Worksheets("TimeConstant").Cells(17 + counter, 14).Value
```

Do 'step through time steps

```
If t <= 20 Then
    z = (zdepth / 20) * t
Else
    z = zdepth
End If
xc = beta * t + z

'if varying charring rate is used xc = beta * 60 * (t / 60) ^
0.813 + z
Aelevated = (b - 2 * xc) * (d - xc)
kfbfire = 1
kEfire = 1
```

```
fbfire = kfbfire * fb
Efire = kEfire * E
```

```
Cb = (le * (d - (xc - z)) / (b - 2 * (xc - z))) ^ 2 ^ 0.5
Ck = (0.97 * Efire * kse * kT / fbfire) ^ 0.5
```

```
If Cb <= 10 Then
    KL = 1
End If
```

```
If Cb > 10 And Cb <= Ck Then
    KL = 1 - (1 / 3) * (Cb / Ck) ^ 4
End If
```

```
If Cb > Ck And Cb < 50 Then
    KL = 0.65 * Efire * kse * kT / ((Cb ^ 2) * fb * kx)
End If
```

```
If Cb > 50 Then
    Exit Do
End If
```

```
kzb = (1.03) * ((b / 1000) * (I / 1000)) ^ -0.18
If kzb > 1 Then
    kzb = 1
End If
```

```
Mapped = Worksheets("TimeConstant").Cells(17 + counter, 16).Value
```

```
Mcanada2 = (phi * kstar1 * fbfire * ((b - 2 * xc) * (d - xc) ^
2) / 6) * kx * KL / 1000000#
Mcanada1 = (phi * kstar1 * fbfire * ((b - 2 * xc) * (d - xc) ^
2) / 6) * kx * kzb / 1000000#
```

```
If Mcanada1 <= Mcanada2 Then
    Mcanada = Mcanada1
Else
    Mcanada = Mcanada2
End If
```

```
If Mcanada - Mapped < 0 Then
    Exit Do
End If
```

```
If b <= 2 * xc Then
    Exit Do
End If
```

```
doverb = (d - xc) / (b - 2 * xc)
```

```

Worksheets("TimeConstant").Cells(17 + counter, 28).Value = doverb

If doverb > 10 Then
    Exit Do
End If

t = t + deltat
Loop

tfailure = t - deltat
Worksheets("TimeConstant").Cells(17 + counter, 24).Value = tfailure
Worksheets("TimeConstant").Cells(17 + counter, 19).Value = Cb
counter = counter + 1

If counter >= 7 Then
    Exit Do
End If

Loop

End Sub

```

Implementation of Constant Material Property Reductions Method

```
Public Sub findMcanadaConstant()
```

```

Dim b As Double
Dim xc As Double
Dim d As Double
Dim E As Double
Dim f As Double
Dim beta As Double
Dim deltat As Double
Dim l As Double
Dim fb As Double
Dim fbfire As Double
Dim t As Double
Dim z As Double
Dim Aelevated As Double
Dim Cb As Double
Dim Ck As Double
Dim Efire As Double
Dim KL As Double
Dim kse As Double
Dim kstar1 As Double
Dim kT As Double
Dim kfbfire As Double
Dim kEfire As Double
Dim kx As Double
Dim kzbz As Double
Dim counter As Integer
Dim le As Double
Dim Mcanada As Double
Dim Mcanada1 As Double
Dim Mcanada2 As Double
Dim Mapplied As Double
Dim exposedsides As Integer
Dim phi As Double
Dim doverb As Double
Dim tfailure As Double

```

```

phi = Worksheets("TimeConstant").Range("Q3").Value
exposedsides = Worksheets("TimeConstant").Range("L6").Value
kstar1 = Worksheets("TimeConstant").Range("W14").Value
'kstar=Kd*Kh*Ksb*KT

```

```

kse = Worksheets("TimeConstant").Range("Q5").Value
kT = Worksheets("TimeConstant").Range("Q6").Value
kx = 1 'All members assumed straight

```

```

beta = Worksheets("TimeConstant").Range("L4").Value
deltat = Worksheets("TimeConstant").Range("L7").Value

```

```

Worksheets("TimeConstant").Range("S17:T1000").ClearContents
Worksheets("TimeConstant").Range("W17:W1000").ClearContents

```

```
counter = 0
```

```

If exposedsides <> 3 Then
    Dim Msg, Style, Title, Response
    Msg = "The Program may only be used for 3 Sides Exposed to Fire" ' Define message.
    Style = vbOKOnly ' Define buttons.
    Title = "Improper Use" ' Define title.

```

```

    Response = MsgBox(Msg, Style, Title)
    Exit Sub
End If

```

```
Do 'step through beams
```

```

t = 0
fb = Worksheets("TimeConstant").Cells(17 + counter, 13).Value
b = Worksheets("TimeConstant").Cells(17 + counter, 10).Value
d = Worksheets("TimeConstant").Cells(17 + counter, 11).Value
l = Worksheets("TimeConstant").Cells(17 + counter, 21).Value
le = Worksheets("TimeConstant").Cells(17 + counter, 22).Value
E = Worksheets("TimeConstant").Cells(17 + counter, 14).Value
kfbfire = Worksheets("TimeConstant").Range("Q7").Value
kEfire = Worksheets("TimeConstant").Range("Q8").Value

```

```
Do 'step through time steps
```

```

    xc = beta * t
    'If varying charring rate is used xc = beta * 60 * (t / 60) ^ 0.813
    Aelevated = (b - 2 * xc) * (d - xc)

    fbfire = kfbfire * fb
    Efire = kEfire * E

    Cb = (le * (d - (xc))) / (b - 2 * (xc)) ^ 2 ^ 0.5
    Ck = (0.97 * Efire * kse * kT / fbfire) ^ 0.5

    If Cb <= 10 Then
        KL = 1
    End If

    If Cb > 10 And Cb <= Ck Then
        KL = 1 - (1 / 3) * (Cb / Ck) ^ 4
    End If

    If Cb > Ck And Cb < 50 Then
        KL = 0.65 * Efire * kse * kT / ((Cb ^ 2) * fb * kx)
    End If

    If Cb > 50 Then
        Exit Do
    End If

    kzbz = (1.03) * ((b / 1000) * (l / 1000)) ^ -0.18
    If kzbz > 1 Then
        kzbz = 1
    End If

```

```
Mapplied = Worksheets("TimeConstant").Cells(17 + counter, 16).Value
```

```

Mcanada2 = (phi * kstar1 * fbfire * ((b - 2 * xc) * (d - xc) ^ 2 / 6) * kx * KL / 1000000#
Mcanada1 = (phi * kstar1 * fbfire * ((b - 2 * xc) * (d - xc) ^ 2 / 6) * kx * kzbz / 1000000#

```



```

If Mcanada1 <= Mcanada2 Then
    Mcanada = Mcanada1
Else
    Mcanada = Mcanada2
End If

If Mcanada - Mapplied < 0 Then
    Exit Do
End If

If b <= 2 * xc Then
    Exit Do
End If

doverb = (d - xc) / (b - 2 * xc)

Worksheets("TimeConstant").Cells(17 + counter, 28).Value = doverb

If doverb > 10 Then
    Exit Do
End If

t = t + deltat
Loop

tfailure = t - deltat
Worksheets("TimeConstant").Cells(17 + counter, 24).Value = tfailure
Worksheets("TimeConstant").Cells(17 + counter, 19).Value = Cb
counter = counter + 1

If counter >= 7 Then
    Exit Do
End If

Loop

End Sub

```

Implementation of Eurocode 5 Material Property Reductions Method

Public Sub findMcanadaEurocode()

```

Dim b As Double
Dim xc As Double
Dim d As Double
Dim E As Double
Dim f As Double
Dim beta As Double
Dim deltat As Double
Dim l As Double
Dim fb As Double
Dim fbfire As Double
Dim t As Double
Dim z As Double
Dim Aelevated As Double
Dim Cb As Double
Dim Ck As Double
Dim Efire As Double
Dim KL As Double
Dim kse As Double
Dim kstar1 As Double
Dim kT As Double
Dim kfbfire As Double
Dim kEfire As Double
Dim kx As Double
Dim kzb As Double

```

```

Dim counter As Integer
Dim le As Double
Dim Mcanada As Double
Dim Mcanada1 As Double
Dim Mcanada2 As Double
Dim Mapplied As Double
Dim exposedsides As Integer
Dim phi As Double
Dim doverb As Double
Dim tfailure As Double
Dim perimeter As Double

```

```

phi = Worksheets("TimeConstant").Range("Q3").Value
exposedsides =
Worksheets("TimeConstant").Range("L6").Value
kstar1 = Worksheets("TimeConstant").Range("W14").Value
kstar = Kd * Kh * Ksb * KT
kse = Worksheets("TimeConstant").Range("Q5").Value
kT = Worksheets("TimeConstant").Range("Q6").Value
kx = 1 ' All members assumed straight

```

```

beta = Worksheets("TimeConstant").Range("L4").Value
deltat = Worksheets("TimeConstant").Range("L7").Value

```

```

Worksheets("TimeConstant").Range("S17:T1000").ClearContents
Worksheets("TimeConstant").Range("W17:W1000").ClearContents

```

counter = 0

```

If exposedsides <> 3 Then
    Dim Msg, Style, Title, Response
    Msg = "The Program may only be used for 3 Sides Exposed to Fire" ' Define message.
    Style = vbOKOnly ' Define buttons.
    Title = "Improper Use" ' Define title.
    Response = MsgBox(Msg, Style, Title)
Exit Sub
End If

```

```

Response = MsgBox(Msg, Style, Title)
Exit Sub
End If

```

Do 'step through beams

```

t = 0
fb = Worksheets("TimeConstant").Cells(17 + counter, 13).Value
b = Worksheets("TimeConstant").Cells(17 + counter, 10).Value
d = Worksheets("TimeConstant").Cells(17 + counter, 11).Value
l = Worksheets("TimeConstant").Cells(17 + counter, 21).Value
le = Worksheets("TimeConstant").Cells(17 + counter, 22).Value
E = Worksheets("TimeConstant").Cells(17 + counter, 14).Value

```

```

Do 'step through time steps
    xc = beta * t
    ' if varying charring rate is used xc = beta * 60 * (t / 60) ^ 0.813
    Aelevated = (b - 2 * xc) * (d - xc)
    perimeter = 2 * (b - 2 * xc) + 2 * (d - xc)
    kfbfire = 1 - 1 / (200 * ((Aelevated / 1000 ^ 2) / (perimeter / 1000)))
    kEfire = 1 - 1 / (330 * ((Aelevated / 1000 ^ 2) / (perimeter / 1000)))

```

```

fbfire = kfbfire * fb
Efire = kEfire * E

```

```

Cb = (le * (d - (xc))) / (b - 2 * (xc)) ^ 2 ^ 0.5
Ck = (0.97 * Efire * kse * kT / fbfire) ^ 0.5

```

```

If Cb <= 10 Then
    KL = 1
End If

```

```

If Cb > 10 And Cb <= Ck Then
    KL = 1 - (1 / 3) * (Cb / Ck) ^ 4
End If

```

```

If Cb > Ck And Cb < 50 Then
    KL = 0.65 * Efire * kse * kT / ((Cb ^ 2) * fb * kx)
End If

If Cb > 50 Then
    Exit Do
End If

kzbg = (1.03) * ((b / 1000) * (l / 1000)) ^ -0.18
If kzbg > 1 Then
    kzbg = 1
End If

Mappld = Worksheets("TimeConstant").Cells(17 +
counter, 16).Value

Mcanada2 = (phi * kstar1 * fbfire * ((b - 2 * xc) * (d - xc) ^
2) / 6) * kx * KL / 1000000#
Mcanada1 = (phi * kstar1 * fbfire * ((b - 2 * xc) * (d - xc) ^
2) / 6) * kx * kzbg / 1000000#

If Mcanada1 <= Mcanada2 Then
    Mcanada = Mcanada1
Else
    Mcanada = Mcanada2
End If

If Mcanada - Mappld < 0 Then
    Exit Do
End If

If b <= 2 * xc Then
    Exit Do
End If

doverb = (d - xc) / (b - 2 * xc)

Worksheets("TimeConstant").Cells(17 + counter,
28).Value = doverb

If doverb > 10 Then
    Exit Do
End If

t = t + deltat
Loop

tfailure = t - deltat
Worksheets("TimeConstant").Cells(17 + counter, 24).Value =
tfailure
Worksheets("TimeConstant").Cells(17 + counter, 19).Value =
Cb
counter = counter + 1

If counter >= 7 Then
    Exit Do
End If

Loop

End Sub

```

Tension Members

Implementation of Eurocode 5 Zero Strength Layer Method

Option Explicit

Public Sub findTcanadaZero()

```
Dim b As Double
Dim xc As Double
Dim d As Double
Dim beta As Double
Dim deltat As Double
Dim ft As Double
Dim ftfire As Double
Dim t As Double
Dim z As Double
Dim Acold
Dim Aelevated As Double
Dim kd As Double
Dim kh As Double
Dim kst As Double
Dim kt As Double
Dim kftfire As Double
Dim counter As Integer
Dim Tcanada As Double
Dim Tcanadacold As Double
Dim Tappplied As Double
Dim exposedsides As Integer
Dim phi As Double
Dim kft As Double
Dim doverb As Double
Dim tfailure As Double
```

```
phi = Worksheets("TimeConstant").Range("O3").Value
exposedsides = Worksheets("TimeConstant").Range("J6").Value
kft = Worksheets("TimeConstant").Range("O8").Value
kd = Worksheets("TimeConstant").Range("O4").Value
kh = Worksheets("TimeConstant").Range("O5").Value
kst = Worksheets("TimeConstant").Range("O6").Value
kt = Worksheets("TimeConstant").Range("O7").Value
kftfire = Worksheets("TimeConstant").Range("O8").Value
beta = Worksheets("TimeConstant").Range("J4").Value
deltat = Worksheets("TimeConstant").Range("J7").Value
```

```
Worksheets("TimeConstant").Range("Q17:R20").ClearContents
Worksheets("TimeConstant").Range("O17:O20").ClearContents
```

counter = 0

```
If exposedsides <> 4 Then
    Dim Msg, Style, Title, Response
    Msg = "The Program may only be used for 4 Sides Exposed to Fire"
    Style = vbOKOnly ' Define buttons.
    Title = "Improper Use" ' Define title.

    Response = MsgBox(Msg, Style, Title)
Exit Sub
End If
```

Do 'step through tension members

```
t = 0
ft = Worksheets("TimeConstant").Cells(17 + counter, 10).Value
b = Worksheets("TimeConstant").Cells(17 + counter, 8).Value
d = Worksheets("TimeConstant").Cells(17 + counter, 9).Value
Tappplied = Worksheets("TimeConstant").Cells(17 + counter, 12).Value
```

Acold = b * d

```
Tcanadacold = phi * ft * (kd * kh * kst * kt) * (Acold) / 1000
Worksheets("TimeConstant").Cells(17 + counter, 17).Value = Tcanadacold
```

Do 'step through time steps

```
If t <= 20 Then
    z = (7 / 20) * t
Else
    z = 7
End If
xc = beta * t + z
' if varying charring rate is used xc = beta * 60 * (t / 60) ^ 0.813
```

Aelevated = (b - 2 * xc) * (d - 2 * xc)

Tcanada = phi * kftfire * ft * (kd * kh * kst * kt) * (Aelevated) / 1000

If Tcanada - Tappplied < 0 Then

```
Exit Do
End If
```

```
If b <= 2 * xc Then
Exit Do
End If
```

doverb = (d - 2 * xc) / (b - 2 * xc)

Worksheets("TimeConstant").Cells(17 + counter, 16).Value = doverb

```
If doverb > 10 Then
Exit Do
End If
```

```
t = t + deltat
Loop
```

```
tfailure = t - deltat
Worksheets("TimeConstant").Cells(17 + counter, 18).Value = tfailure
counter = counter + 1
```

```
If counter >= 3 Then
Exit Do
End If
```

Loop

End Sub

Implementation of Constant Material Property Reductions Method

Public Sub findTcanadaConstant()

```
Dim b As Double
Dim xc As Double
Dim d As Double
Dim beta As Double
Dim deltat As Double
Dim ft As Double
Dim ftfire As Double
Dim t As Double
```

```
Dim Acold
Dim Aelevated As Double
```

```

Dim kd As Double
Dim kh As Double
Dim kst As Double
Dim kt As Double
Dim ktfire As Double
Dim counter As Integer
Dim Tcanada As Double
Dim Tcanadacold As Double
Dim Tappplied As Double
Dim exposedsides As Integer
Dim phi As Double
Dim kft As Double
Dim doverb As Double
Dim tfailure As Double

```

```

phi = Worksheets("TimeConstant").Range("O3").Value
exposedsides =
Worksheets("TimeConstant").Range("J6").Value
kft = Worksheets("TimeConstant").Range("O8").Value
kd = Worksheets("TimeConstant").Range("O4").Value
kh = Worksheets("TimeConstant").Range("O5").Value
kst = Worksheets("TimeConstant").Range("O6").Value
kt = Worksheets("TimeConstant").Range("O7").Value
ktfire = Worksheets("TimeConstant").Range("O8").Value
beta = Worksheets("TimeConstant").Range("J4").Value
deltat = Worksheets("TimeConstant").Range("J7").Value

```

```

Worksheets("TimeConstant").Range("Q17:R20").ClearContents
Worksheets("TimeConstant").Range("O17:O20").ClearContents

```

```
counter = 0
```

```

If exposedsides <> 4 Then
    Dim Msg, Style, Title, Response
    Msg = "The Program may only be used for 4 Sides Exposed to Fire" ' Define message.
    Style = vbOKOnly ' Define buttons.
    Title = "Improper Use" ' Define title.

```

```

    Response = MsgBox(Msg, Style, Title)
    Exit Sub
End If

```

```
Do 'step through tension members
```

```

t = 0
ft = Worksheets("TimeConstant").Cells(17 + counter, 10).Value
b = Worksheets("TimeConstant").Cells(17 + counter, 8).Value
d = Worksheets("TimeConstant").Cells(17 + counter, 9).Value
Tappplied = Worksheets("TimeConstant").Cells(17 + counter, 12).Value

```

```

Acold = b * d
Tcanadacold = phi * ft * (kd * kh * kst * kt) * (Acold) / 1000
Worksheets("TimeConstant").Cells(17 + counter, 17).Value = Tcanadacold

```

```

Do 'step through time steps
    xc = beta * t
    'If varying charring rate is used xc = beta * 60 * (t / 60) ^
0.813

```

```
Aelevated = (b - 2 * xc) * (d - 2 * xc)
```

```

Tcanada = phi * kftfire * ft * (kd * kh * kst * kt) * (Aelevated) / 1000

```

```

If Tcanada - Tappplied < 0 Then
    Exit Do
End If

```

```

If b <= 2 * xc Then
    Exit Do
End If

```

```
doverb = (d - 2 * xc) / (b - 2 * xc)
```

```

Worksheets("TimeConstant").Cells(17 + counter, 16).Value = doverb

```

```

If doverb > 10 Then
    Exit Do
End If

```

```

t = t + deltat
Loop

```

```

tfailure = t - deltat
Worksheets("TimeConstant").Cells(17 + counter, 18).Value = tfailure
counter = counter + 1

```

```

If counter >= 3 Then
    Exit Do
End If

```

```
Loop
```

```
End Sub
```

Implementation of Eurocode 5 Material Property Reductions Method

Option Explicit

```
Public Sub findTcanadaEurocode()
```

```

Dim b As Double
Dim xc As Double
Dim d As Double
Dim beta As Double
Dim deltat As Double
Dim ft As Double
Dim kftfire As Double
Dim t As Double

```

```

Dim Acold
Dim Aelevated As Double
Dim perimetercold As Double
Dim perimeterelevated As Double
Dim kd As Double
Dim kh As Double
Dim kst As Double
Dim kt As Double
Dim kftfire As Double
Dim kftoverallcold As Double
Dim counter As Integer
Dim Tcanada As Double
Dim Tcanadacold As Double
Dim Tappplied As Double
Dim exposedsides As Integer
Dim phi As Double
Dim kft As Double
Dim doverb As Double
Dim tfailure As Double

```

```

phi = Worksheets("TimeConstant").Range("O3").Value
exposedsides =
Worksheets("TimeConstant").Range("J6").Value
kft = Worksheets("TimeConstant").Range("O8").Value
kd = Worksheets("TimeConstant").Range("O4").Value
kh = Worksheets("TimeConstant").Range("O5").Value

```

```

kst = Worksheets("TimeConstant").Range("O6").Value
kt = Worksheets("TimeConstant").Range("O7").Value
kftfire = Worksheets("TimeConstant").Range("O8").Value

beta = Worksheets("TimeConstant").Range("J4").Value
deltat = Worksheets("TimeConstant").Range("J7").Value

Worksheets("TimeConstant").Range("Q17:R20").ClearContents
Worksheets("TimeConstant").Range("O17:O20").ClearContents

counter = 0

If exposedsides <> 4 Then
    Dim Msg, Style, Title, Response
    Msg = "The Program may only be used for 4 Sides Exposed  
to Fire " ' Define message.
    Style = vbOKOnly ' Define buttons.
    Title = "Improper Use" ' Define title.

    Response = MsgBox(Msg, Style, Title)
Exit Sub
End If

Do 'step through tension members

t = 0
ft = Worksheets("TimeConstant").Cells(17 + counter, 10).Value
b = Worksheets("TimeConstant").Cells(17 + counter, 8).Value
d = Worksheets("TimeConstant").Cells(17 + counter, 9).Value
Tapped = Worksheets("TimeConstant").Cells(17 + counter, 12).Value

Acold = b * d
perimetercold = 2 * b + 2 * d

Tcanadacold = phi * ft * (kd * kh * kst * kt) * (Acold) / 1000
Worksheets("TimeConstant").Cells(17 + counter, 17).Value = Tcanadacold

Do 'step through time steps

xc = beta * t
'if varying charring rate is used xc = beta * 60 * (t / 60) ^
0.813

Aelevated = (b - 2 * xc) * (d - 2 * xc)
perimeterelevated = (2 * (b - 2 * xc) + 2 * (d - 2 * xc))
kftfire = 1 - 1 / (330 * ((Aelevated / 1000 ^ 2) / (perimeterelevated / 1000)))

Tcanada = phi * kftfire * ft * (kd * kh * kst * kt) * (Aelevated) / 1000

If Tcanada - Tapped < 0 Then
    Exit Do
End If

If b <= 2 * xc Then
    Exit Do
End If

doverb = (d - 2 * xc) / (b - 2 * xc)

Worksheets("TimeConstant").Cells(17 + counter, 16).Value = doverb

If doverb > 10 Then
    Exit Do
End If

t = t + deltat
Loop

tfailure = t - deltat
Worksheets("TimeConstant").Cells(17 + counter, 18).Value = tfailure
counter = counter + 1

```

```

If counter >= 3 Then
    Exit Do
End If

Loop

End Sub

```

Appendix D: Detailed Prediction Method Results

Table D. 1: Detailed Method Failure Time Results for Columns

Designation	Observed Failure Time	Failure Time Using Lie Assumptions	Failure Time Using TR10 Assumptions	Failure Time Using Eurocode 5 Zero-Strength Layer Method	Failure Time Using Eurocode 5 Material Property Reduction Method
	min	min	min	min	min
CSTB	48	48.1	41.1	45.3	44.3
R14A	29	29.6	22.1	26.9	28.2
R14B	21	28.6	21.3	25.9	27.4
R14C	36	41.6	31.4	37.6	39.0
R14D	29	33.1	24.7	30.0	31.4
H14A	26	26.3	19.6	23.9	25.4
H14B	27	29.1	21.7	26.4	27.8
H14C	43	41.6	31.4	37.6	39.0
H14D	34	33.1	24.7	30.0	31.4
H14/24A	35	24.8	18.9	23.8	25.1
H14/24B	32	23.6	18.0	22.7	24.0
H14/30A	39	25.5	19.5	24.8	26.0
H14/30B	59	48.0	37.2	45.0	45.9
H14/30C	53	41.2	31.6	38.9	39.9
H14/40	43	24.8	19.1	24.5	25.7
R15A	26	26.2	20.0	24.2	25.5
R15B	27	24.8	18.8	22.8	24.2
H15A	31	27.6	21.0	25.4	26.8
H15B	30	25.1	19.1	23.2	24.5
R16	30	12.7	10.7	13.9	13.5
H16A	31	28.0	21.7	26.1	27.3
H16B	37	30.9	23.9	28.7	30.0
R16/30	58	45.7	36.1	43.6	44.4
H16/30A	40	30.1	23.8	29.6	30.6
H16/30B	52	31.8	25.1	31.1	32.1
H16/30C	45	30.3	24.0	29.8	30.8
H16/30D	57	45.6	36.0	43.4	44.3
R20A	34	42.8	35.5	41.2	41.8
R20B	48	45.4	37.5	43.5	44.1
R20C	64	70.4	59.0	65.9	66.4
R20D	61	62.3	51.8	58.5	59.1

Table D. 2: Detailed Method Failure Time Results for Columns Continued

Designation	Observed Failure Time	Failure Time Using Lie Assumptions	Failure Time Using TR10 Assumptions	Failure Time Using Eurocode 5 Zero- Strength Layer Method	Failure Time Using Eurocode 5 Material Property Reduction Method
	min	min	min	min	min
H20A	42	44.0	36.5	42.2	42.8
H20B	43	45.4	37.7	43.5	44.1
H20C	60	69.5	58.1	65.0	65.6
H20D	52	67.8	56.7	63.5	64.1
H20/40A	65	48.7	41.2	48.4	48.9
H20/40B	74	41.1	35.1	41.7	42.2
H24A	60	57.9	50.9	56.7	56.7
H24B	56	64.8	56.8	62.7	62.7
H26A	62	70.1	63.0	68.5	68.1
H26B	62	64.4	58.1	63.5	63.1
R27A	57	63.0	57.6	62.8	62.4
R27B	54	69.0	63.2	68.2	67.6
R27C	76	72.3	65.7	70.9	70.5
H27A	59	75.9	69.3	74.2	73.5
H27B	56	65.8	60.1	65.3	64.9
H27C	71	72.1	65.5	70.8	70.3
H28A	59	72.4	66.7	71.6	71.0
H28B	67	75.9	69.7	74.7	74.0
H40	114	113.3	117.7	115.9	113.4
FU1	55	84.6	75.9	79.6	77.8
FR3	74	61.2	49.1	57.0	57.2
FP4	45	53.2	49.4	52.6	50.6
HU5	73	105.7	95.4	98.3	96.7
HR7	49	65.0	54.9	61.5	61.0
HP8	69	84.8	76.0	79.7	77.9
RU9	47	46.1	36.8	43.7	43.9
RR11	45	52.0	48.4	51.5	49.7
RP12	76	79.8	67.6	74.7	74.4
CU13	35	38.6	34.2	38.6	38.0
CR15	43	83.9	75.2	79.0	77.3
CP16	39	46.6	37.2	44.0	44.2

Table D. 3: Detailed Method Failure Time Results for Beams

Designation	Observed Failure Time	Failure Time Using Lie Assumptions	Failure Time Using TR10 Assumptions	Failure Time Using Eurocode 5 Zero-Strength Layer Method	Failure Time Using Eurocode 5 Material Property Reduction Method
	min	min	min	min	min
TRADA	53	54.9	43.9	50.8	52.4
NFoPA	86	78.0	69.1	76.0	75.4
AF&PA-27	147	133.6	126.3	127.4	125.8
AF&PA-44	114	126.4	117.5	118.5	118.6
AF&PA-91	85	95.7	90.0	93.0	93.9
FCNSW-BB	59	42.9	38.7	42.3	43.2
FCNSW-RP	67	79.2	66.7	72.9	74.0

Table D. 4: Detailed Method Failure Time Results for Tension Members

Designation	Observed Failure Time	Failure Time Using Lie Assumptions	Failure Time Using TR10 Assumptions	Failure Time Using Eurocode 5 Zero-Strength Layer Method	Failure Time Using Eurocode 5 Material Property Reduction Method
	min	min	min	min	min
Test 1	42	56.4	43.7	44.6	49.4
Test 3	58	70.0	59.7	60.7	65.3
Test 4	124	134.1	126.0	120.6	123.8

Appendix E: Simplified Design Method Results

Table E. 1: Simplified Method Failure Time Results for Columns

Designation	Fifth Percentile Strength Value f_c	Observed Failure Time	Simplified Method Failure Time
	MPa	min	min
CSTB	13.9	48	6.6
R14A	40.0	29	15.1
R14B	43.1	21	16.3
R14C	44.1	36	25.8
R14D	40.4	29	19.6
H14A	43.7	26	16.5
H14B	41.5	27	15.7
H14C	44.1	43	25.8
H14D	40.4	34	19.6
H14/24A	33.9	35	26.7
H14/24B	33.5	32	26.5
H14/30A	37.5	39	30.8
H14/30B	47.2	59	40.5
H14/30C	38.9	53	39.1
H14/40	36.2	43	32.7
R15A	32.6	26	14.7
R15B	32.4	27	13.7
H15A	35.4	31	16.3
H15B	31.9	30	14.2
R16	23.4	30	2.2
H16A	31.1	31	16.9
H16B	35.8	37	20.1
R16/30	32.3	58	47.9
H16/30A	33.8	40	36.5
H16/30B	36.2	52	38.0
H16/30C	35.1	45	37.4
H16/30D	31.0	57	47.3
R20A	32.2	34	33.3
R20B	36.1	48	36.8
R20C	48.9	64	60.0
R20D	30.9	61	50.7

Table E. 2: Simplified Method Failure Time Results for Columns Continued

Designation	Fifth Percentile Strength Value f_c	Observed Failure Time	Simplified Method Failure Time
	MPa	min	min
H20A	32.1	42	33.2
H20B	32.7	43	33.8
H20C	47.1	60	59.4
H20D	40.0	52	56.2
H20/40A	36.1	65	60.2
H20/40B	29.4	74	53.5
H24A	30.6	60	47.9
H24B	35.9	56	54.1
H26A	34.5	62	59.4
H26B	30.3	62	53.7
R27A	28.3	57	54.0
R27B	29.9	54	56.6
R27C	33.8	76	62.3
H27A	33.8	59	62.2
H27B	29.6	56	56.1
H27C	33.6	71	62.0
H28A	31.5	59	62.3
H28B	34.0	67	65.8
H40	30.7	114	105.9
FU1	28.2	55	43.2
FR3	28.2	74	35.8
FP4	28.2	45	11.9
HU5	24.2	73	65.2
HR7	24.2	49	36.1
HP8	24.2	69	43.0
RU9	21.5	47	23.3
RR11	21.5	45	11.5
RP12	21.5	76	53.4
CU13	17.5	35	9.0
CR15	17.5	43	43.1
CP16	17.5	39	23.4

Table E. 3: Simplified Method Failure Time Results for Beams

Designation	Fifth Percentile Strength Value f_b	Observed Failure Time	Simplified Method Failure Time
	MPa	min	min
TRADA	40.9	53	49.3
NFoPA	37.1	86	87.6
AF&PA-27	37.1	147	125.7
AF&PA-44	37.1	114	112.5
AF&PA-91	37.1	85	79.4
FCNSW-BB	39.4	59	29.2
FCNSW-RP	28.2	67	65.9

Table E. 4: Simplified Method Failure Time Results for Tension Members

Designation	Fifth Percentile Strength Value f_t	Observed Failure Time	Simplified Method Failure Time
	MPa	min	min
Test 1	11.6	42	41.5
Test 3	24.8	58	57.9
Test 4	24.8	124	118.7