FIRE DESIGN FOR MASS TIMBER CONNECTIONS

MyTiCon Timber Connectors
www.myticon.com | 1.866.899.4090 | info@myticon.com

ABSTRACT

This newsletter reviews guidelines and concepts applicable to the fire design of structural members and connection systems for mass timber construction. These concepts are compared against the results of the first full-scale fire test on pre-engineered mass timber connection systems in North America.

FIRE DESIGN AND PERFORMANCE OF MASS TIMBER POST AND BEAM CONNECTIONS

Concealed connection systems are often selected for mass timber structural systems where the wood is left exposed for architectural purposes. Since the structural members are not encased in additional fireproofing material such as drywall, the fire protection for the connection systems must come from the members themselves.

Mass timber and heavy timber elements have long been recognized as having superior fire performance over dimensional lumber due to the beneficial effects of charring. Charring reduces the rate of combustion and insulates the unburned wood within. Since charring rates are predictable functions of time, beams and columns can be designed such that reduced cross-sectional dimensions of the unburned wood will be sufficient to carry required fire design loads. Charred wood is assumed to possess zero mechanical strength. Ahead of the charring front, wood in the pyrolysis zone experiences thermal decomposition, resulting in discoloration of the wood fibre and a slight reduction in mechanical strength. Approximately 35mm beyond the charring front, wood maintains it original structural strength and temperature.

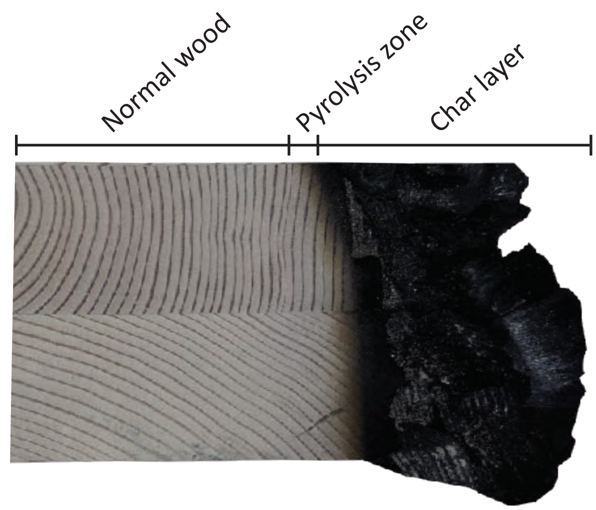


Figure 1. Anatomy of burned wood

Various models are available to designers in North America to estimate the fire-resistance rating of large structural wood elements based on the depth of the char layer that develops from exposure to fire. These analytical methods model char rate as a function of time, thus allowing designers to calculate the depth of the sacrificial char layer required for fire safety design regarding structural integrity.

This newsletter will focus on the fire design of connections developed for use with mass timber. Exposed steel or aluminum connections can be problematic, as these materials not only loose strength at elevated temperatures, but they can also conduct heat rapidly into the core of the wood members they connect. Concealed pre-engineered connections, however, have been recognized by designers and building authorities alike as a suitable solution to fire safety design requirements.

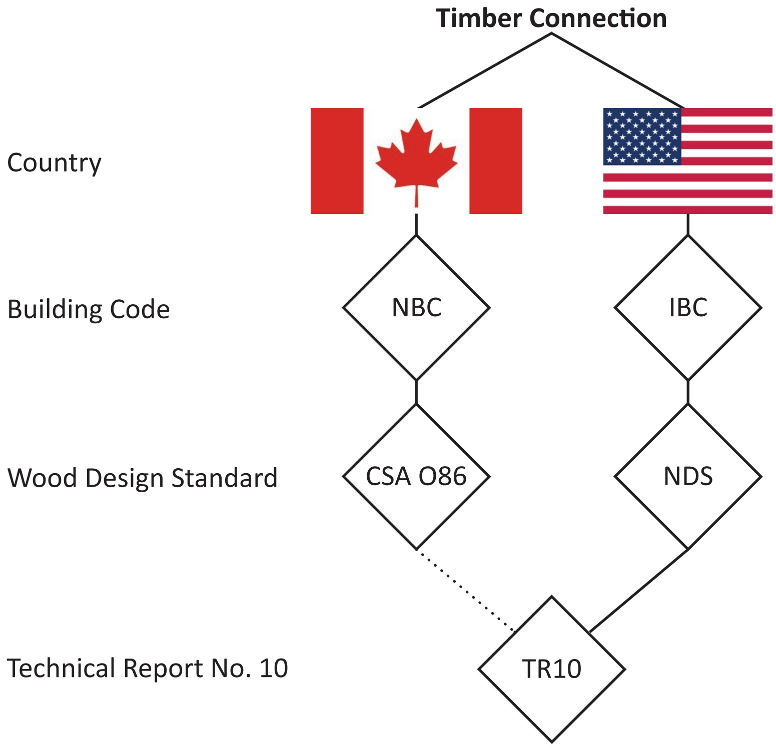
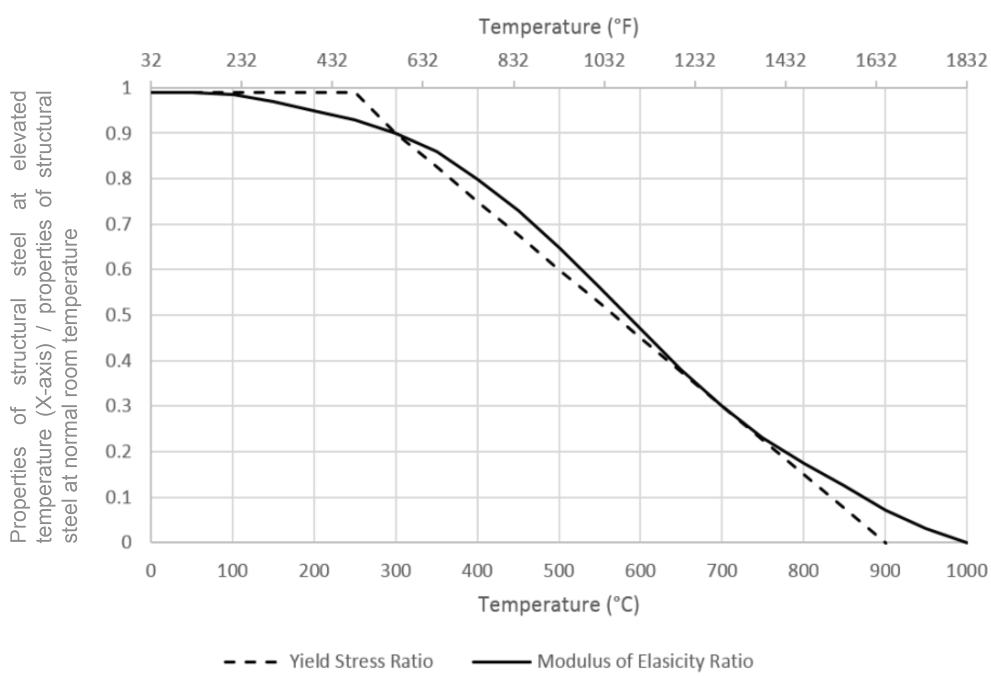


Figure 2. Building authorities and design standards of North America

Both NDS and CSA O86 require that all connections that are critical to the support of all intended loads must be designed with at least the same fire resistance as the element they support. For the purpose of testing, ASTM E119 & CAN / ULC S101 specifies a temperature curve that reaches 1700° (over 900°C). Graph 1 shows that under these conditions steel connections can be especially vulnerable to elevated temperatures, which is why protective covering is so important.



Graph 1. Mechanical properties of structural steel at elevated temperatures [1]

[1] Adapted from Fire Engineering Design Guide (1994), University of Canterbury, New Zealand

TR 10

Technical Report No. 10 (TR 10), published by the American Wood Council, is a widely recognized document pertaining to fire safety design of timber structures in North America. Both the NDS and CSA O86 reference this report. According to TR 10, the nominal char layer depth after one hour exposure to fire is 1.5” (38 mm). TR 10 further explains that based on multiple fire test results charring rates are non-linear, and that linear models tend to underestimate the depth of the char layer at times less than one hour, and overestimate the depth of the char layer at times greater than one hour. The non-linear behaviour is a result of the insulating properties of the char layer.

In addition, a unidirectional model used to estimate the char thickness would exclude the effect of multiple side fire exposure on a wood member. Columns and beams, for example, may be exposed to fire on more than one side, which results in the corners charring faster. To account for this effect, corner rounding needs to be considered in the structural fire design, where the radius of the corner (r) is equal to the estimated char layer thickness as shown in Figure 3.

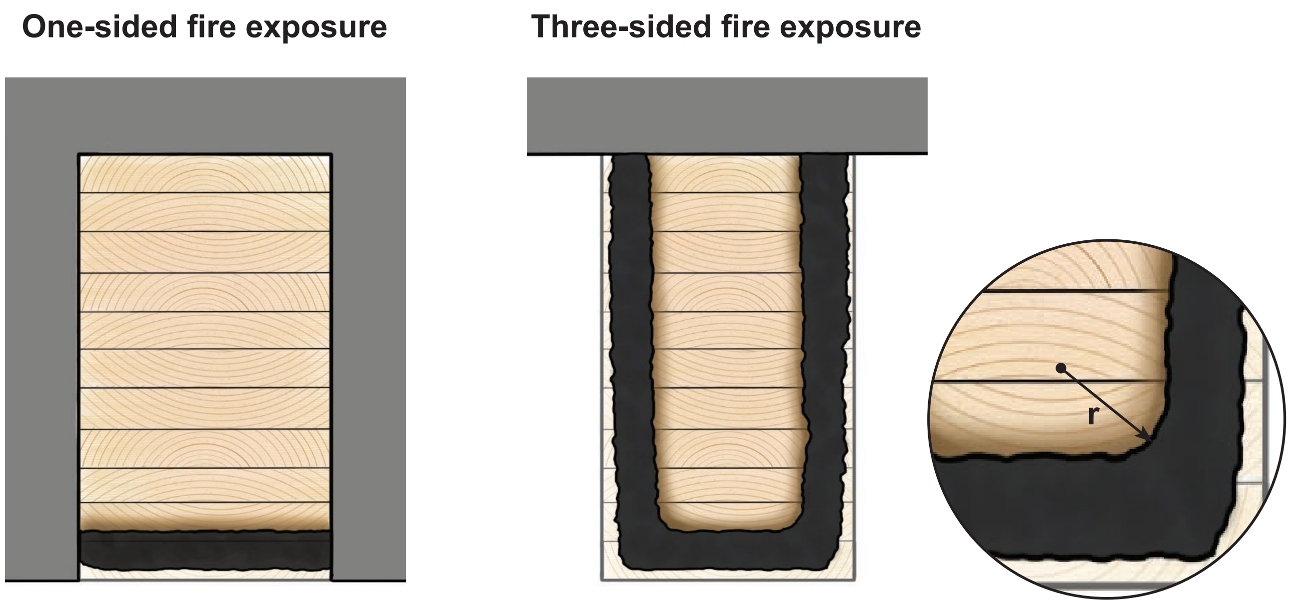


Figure 3. Charring behavior of glulam members with corner rounding effect illustrated

According to TR 10, the nominal char depth is adjusted to account for the effects of the pyrolysis zone, the effects of corner rounding, fire exposure time, and to adjust for actual non-linear charring rates by using the following equation:

Effective char depth (a_{char}):

$$a_{char} = t \cdot \frac{1.2 \cdot 1.5''}{t^{0.187}} \quad \text{Equation 1.}$$

where t = exposure time (hrs.)

United States

In the United States the International Building Code (IBC) is the preferred code standard for most US states. It includes a large portion dedicated to fire related issues in structural design approaches. The IBC mentions that a design containing fire-suppression systems for structural elements capable of conserving their structural integrity can achieve economical fire protection. The NDS (section C16.1) commentary states that “heavy timber construction has traditionally been recognized to provide a fire-resistant building.”

The NDS allows the designer to use either an experimentally rated assembly or an analytically rated assembly. In the case where experimentally derived test data is not available, the building code accepts analytical approaches on the determination of the expected fire resistance. As of now a maximum fire-resistance rating of 2 hours is possible when using an analytical approach in the US, limiting the use of mass timber to only certain building types.

The non-linear calculation approach presented in the NDS is based on research conducted and described in TR 10 and the wood cover on top of a concealed connection element may be calculated according to the effective char depth (a_{char}) as described in Equation 1.

Canada

The National Building Code (NBC) provides very few guidelines on the fire design of wood structures, whereas most of the design approaches are based on research conducted by T.T. Lie in 1977. Therefore most designers use the Annex B of the CSA O86 which provides a more detailed guideline. Annex B is described as “an alternative approach for determining fire-resistance ratings for establishing compliance to the NBC.”

According to Annex B of the CSA O86, fire ratings for structural wood members are calculated using actual gravity loads (i.e., D + L), while strength properties are multiplied by a short term load duration factor (K_D) and other modification factors for fire design. The directive given for connections is: “Connections in which the steel is located within the reduced cross-section of the wood element shall be considered to be properly protected.”

For post and beam members the reduced cross section is either calculated using the one-dimensional char depth (which implies a manual calculation of the corner rounding effect) or the simplified notional char depth to account for this effect. In both cases, an additional zero strength layer shall further reduce the cross-section. The CSA calculation approach uses a linear charring model and is therefore likely to overestimate the wood cover for concealed connection systems with a required FRR over one hour.

Wood cover design for concealed connections

As described earlier the North American building codes give relatively similar approaches, while yielding slightly different results. In general, mass timber connections can be divided into two different categories: exposed and concealed connections.

Exposed connections can be a simple fully or partially exposed steel plate, but concealed steel plates with exposed bolts also fall in that category. With the inherent thermal conductivity of the steel or aluminium, the sudden temperature raise can affect the structural integrity of the connection and quickly weaken the entire system. Therefore special calculation approaches need to be considered. In addition, research has shown that the use of intumescent paint on exposed steel connector plates may not be effective.

Concealed connections on the other hand, have the advantage of being more predictable, as heat transfer to the connection elements is limited through a sacrificial char layer or the use of an approved fire retardant material. Concealed connections thus offer an easier and safer approach with regards to the determination of the fire resistance of the connection. According to the guidelines, connection in which the steel is located within the reduced cross-section of the wood element shall be considered to be properly protected. However, the actual design of the wood cover may be perceived as challenging.

For example, in most cases connector plates are not placed on the very bottom of the connecting element section, where the effects of corner rounding could be considered negligible in the design. In order to obtain an effective char depth NDS suggests to increase the nominal char depth by 20%, accounting for the corner rounding effect and pyrolysis layer.

As explained earlier, the NDS and CSA O86 follow a similar approach with regards to the provision of a sacrificial char layer. However, due to the linear model of CSA O86, the results are more conservative, as shown in Table 1.

Table 1. Char depth estimates according to TR 10, CSA O86 and NDS

Time	TR 10	CSA O86			NDS
	Nominal char depth	Notional char depth	Zero strength layer	total	Effective char depth
hour	**inch** [mm]	inch [mm]	inch [mm]	**inch** [mm]	**inch** [mm]
1	**1.5”** [38]	1.65” [42]	0.28” [7]	**1.93”** [49]	**1.8”** [46]
1.5	N/A	2.48” [63]	0.28” [7]	**2.76”** [70]	**2.5”** [64]
2	N/A	3.31” [84]	0.28” [7]	**3.58”** [91]	**3.2”** [81]
3	N/A	4.96” [126]	0.28” [7]	**5.24”** [133]	N/A

A simple design approach could be to follow the recommendation of TR 10 section 3.4, where wood cover equivalent to a depth of $a_{char}/1.2$ is sufficient for a concealed beam to column connection. TR 10 also makes note of the fact that the charring front is approximately 550°F (288°C), a temperature at which steel is generally accepted as maintaining over 90% of its yield strength.

FULL-SCALE TESTING

In order to provide a FRR rated "off the shelf" solution for post and beam connection systems for mass timber buildings, a collaboration between the Softwood Lumber Board and industry partners has conducted the first full-scale fire test for loaded post to beam connectors in North America. The research project was conducted in an approved testing facility in San Antonio, Texas.

The IBC typically requires member sizes that meet the minimal dimensions to provide a certain fire-resistance rating (FRR) when utilizing mass timber materials such as glulam or CLT. As the code gives only limited guidelines on how to achieve a satisfying fire-resistance rating for used connections, a full-scale fire test was the best option to provide ratings for pre-engineered connection systems. In most cases a fire-resistance rating of one hour is required for the design of IBC construction types IIIA and IV (heavy timber). Therefore the test was designed to achieve at least 1 hour FRR through full-scale testing.

Methodology

Fire tests were conducted in a furnace controlled to deliver a standard temperature curve, fulfilling the requirements of ASTM E119. The loading frame was placed within the furnace to maintain a constant load during the test. A five-ply CLT floor panel was attached to the top of a glulam beam, acting as the furnace lid. All glulam members were selected from typical commodity glulam stock to achieve an economical design. The connection systems were housed in routed sections in the columns and attached to the end grain face of the glulam beam. A 1/2" (13 mm) bead of fire stop sealant was applied around the connector.

The load applied on the connection system was based on the assumption of typical office building grid. The assumed glulam beam length was 30 ft. (9 m) supporting a 5-ply CLT floor tributary to the beam of 15 ft. (4.6 m). The load combinations were calculated according to LRFD, applying a dead load of 30 psf. and a live load of 50 psf. The applied load was unfactored as per ASTM E119 and used a reduced live load as per IBC section 1607.10.

The pre-engineered connection systems tested in this scenario are:

- Ricon S VS 290x80 with minimum required fasteners.
- Double Ricon S VS 200x80 with maximum required fasteners.
- Megant 430x150 with reduced number of fasteners.

A summary of the tests and applied loads can be found in Table 2 below:

Table 2. Applied load and connection capacity

Test	Applied load at the connection		Connector design resistance with reduced amount of screws		Connector design resistance with full amount of screws		Fire test duration
	lbs	[kN]	lbs	[kN]	lbs	[kN]	min
Single Ricon S VS 290x80	3,905[1]	[17.4][1]	9,127	[40.6]	16,905	[75.2]	60
Double Ricon S VS 200x80	16,620	[73.9]	27,426	[122.0]	27,426	[122.0]	90
Megant 430x150	16,620	[73.9]	31,898	[141.9]	38,277	[170.5]	90

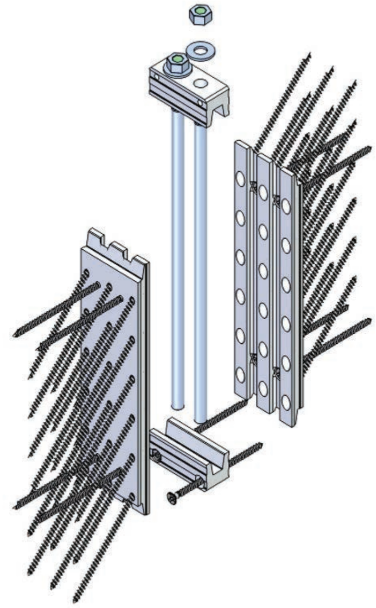
Note: Connection design resistances are applicable to LRFD in the United States and LSD in Canada. All loads are given for glulam members made of Douglas Fir (D.Fir).

[1] Applied load was reduced to match the capacity reduction of the connector with the minimum amount of screws.

Connector types used in the fire test used fully threaded ASSY VG CSK screws (ICC ESR 3178 and CCMC 13677-R) to connect with the glulam members.

Ricon S VS system

A pre-engineered connection system manufactured from mild steel with a welded collar bolt. A simple installation procedure is possible with only perpendicular to plate screws. The Ricon S VS can be installed fully concealed or visible with only 1-1/2" (35mm) of travel required to engage the connector.

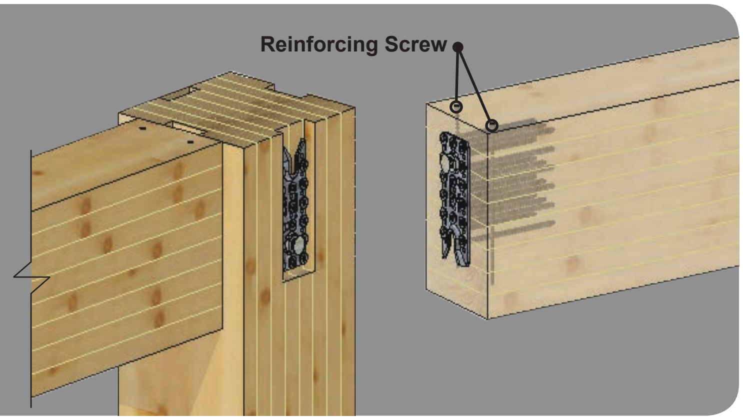


Megant system

A pre-engineered connection system manufactured from machined aluminum. A simple installation procedure is possible with perpendicular to plate setting screws, followed by 45° fully threaded structural screws. The Megant system can be installed fully concealed or visible, with installation possible from all four sides.

Did you know ?

Fully threaded screws can be used to reinforce pre-engineered connection applications against perpendicular to grain splitting and are often required to avoid brittle failure modes.



The following figures show the selected connector plates and position in the glulam section. To monitor the heat propagation during the test, four heat sensors were placed on the connector plates, two sensors were placed 1" (25 mm) from the edge of the beam and two additional sensors were placed 2" (51 mm) from the beam edge.

Test #1
Single Ricon S VS 290x80

Test #2
Double Ricon S VS 200x80

Test #3
Megant 430x150

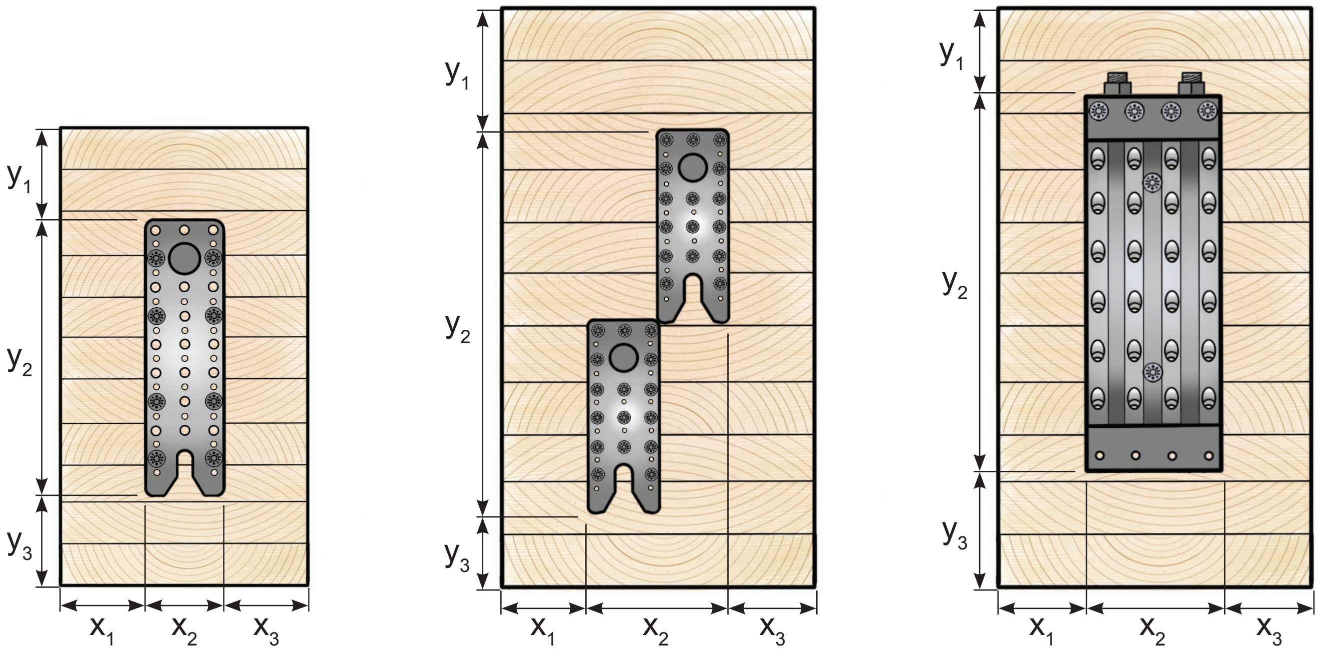


Table 3. Beam section and connector location

Test	Beam size width in	Beam size width [mm]	Beam size height in	Beam size height [mm]	x_1 in	x_1 [mm]	x_2 in	x_2 [mm]	x_3 in	x_3 [mm]	y_1 in	y_1 [mm]	y_2 in	y_2 [mm]	y_3 in	y_3 [mm]
Single Ricon S VS 290x80	8-3/4”	[222]	18”	[457]	2.80”	[71]	3.15”	[80]	2.80”	[71]	2.56”	[65]	11.42”	[290]	4.00”	[102]
Double Ricon S VS 200x80	10-3/4”	[273]	24”	[610]	2.25”	[57]	6.30”	[160]	2.25”	[57]	4.25”	[108]	15.75”	[400]	4.00”	[102]
Megant 430x150	10-3/4”	[273]	24”	[610]	2.42”	[62]	5.91”	[150]	2.42”	[62]	2.72”	[69]	16.93”	[430]	4.37”	[111]

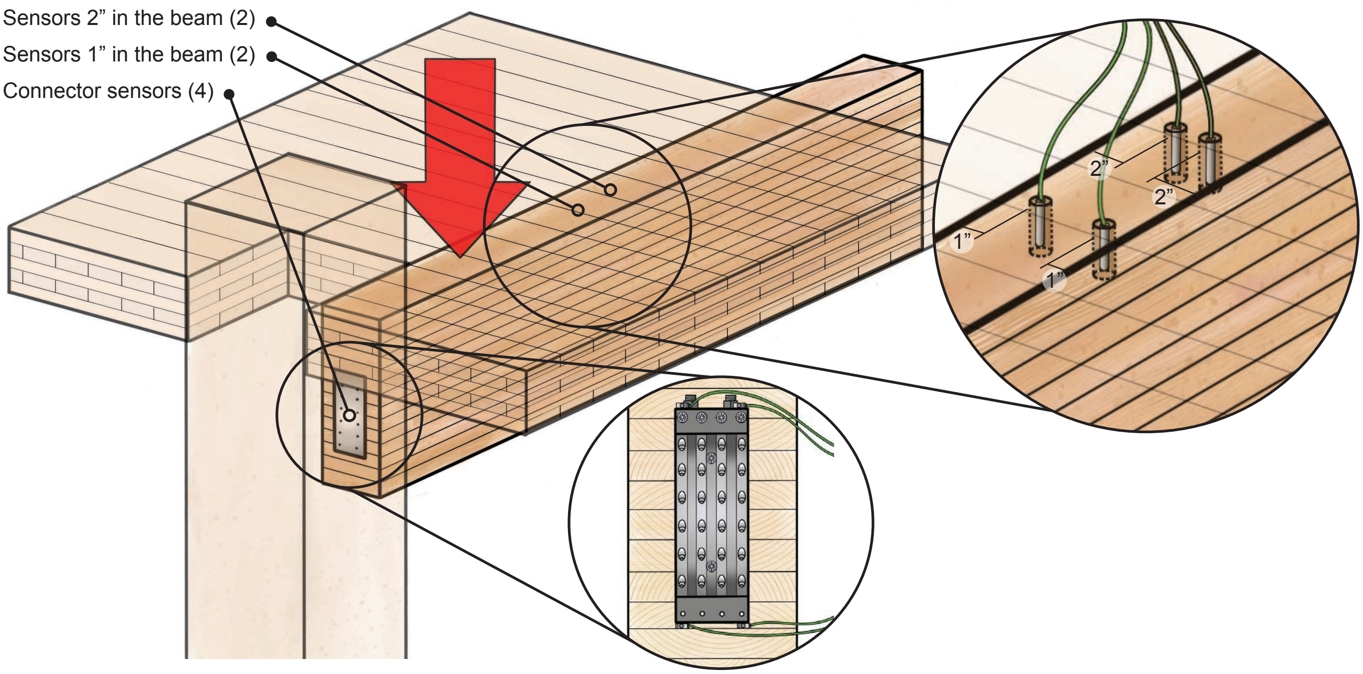
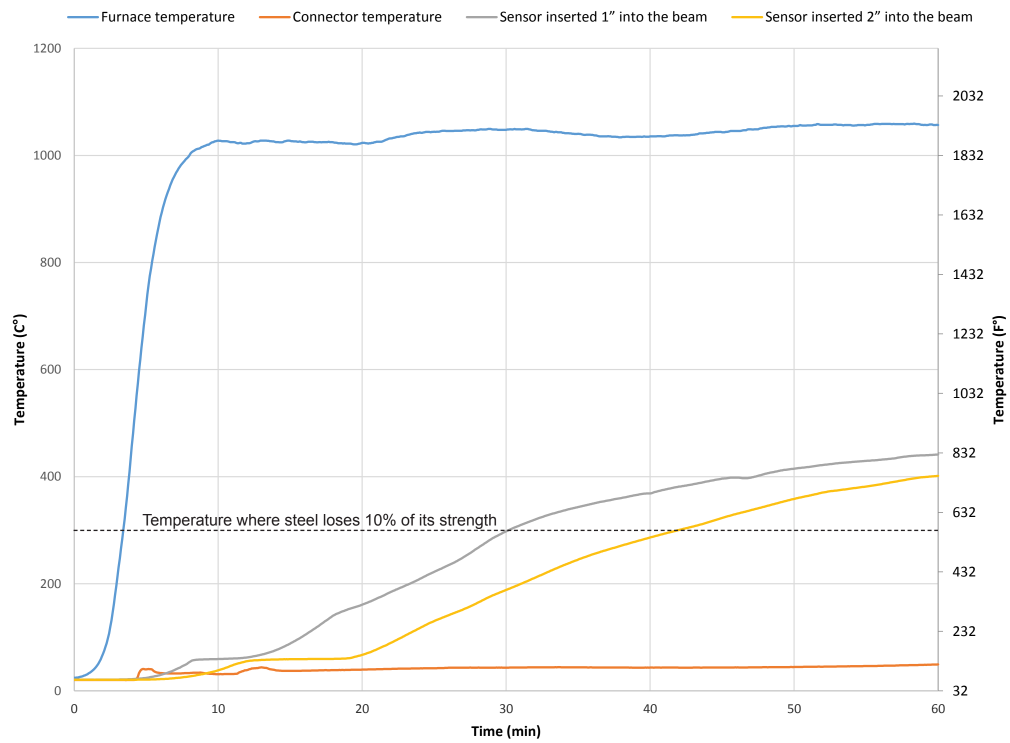
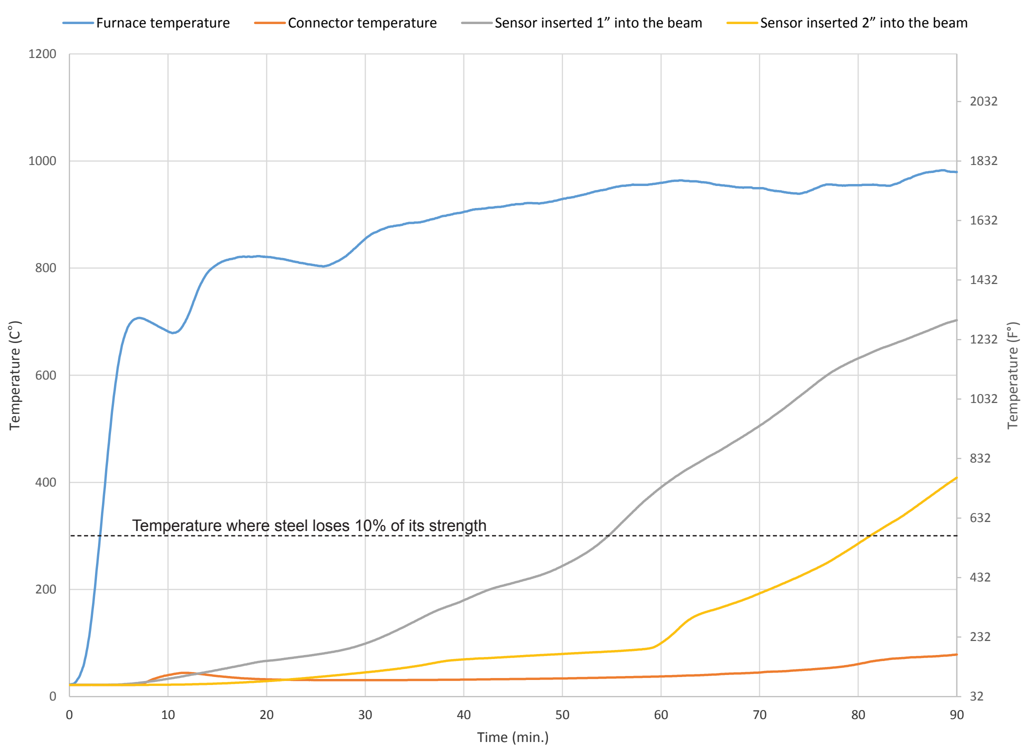


Figure 4. Thermo sensor locations in the specimen.

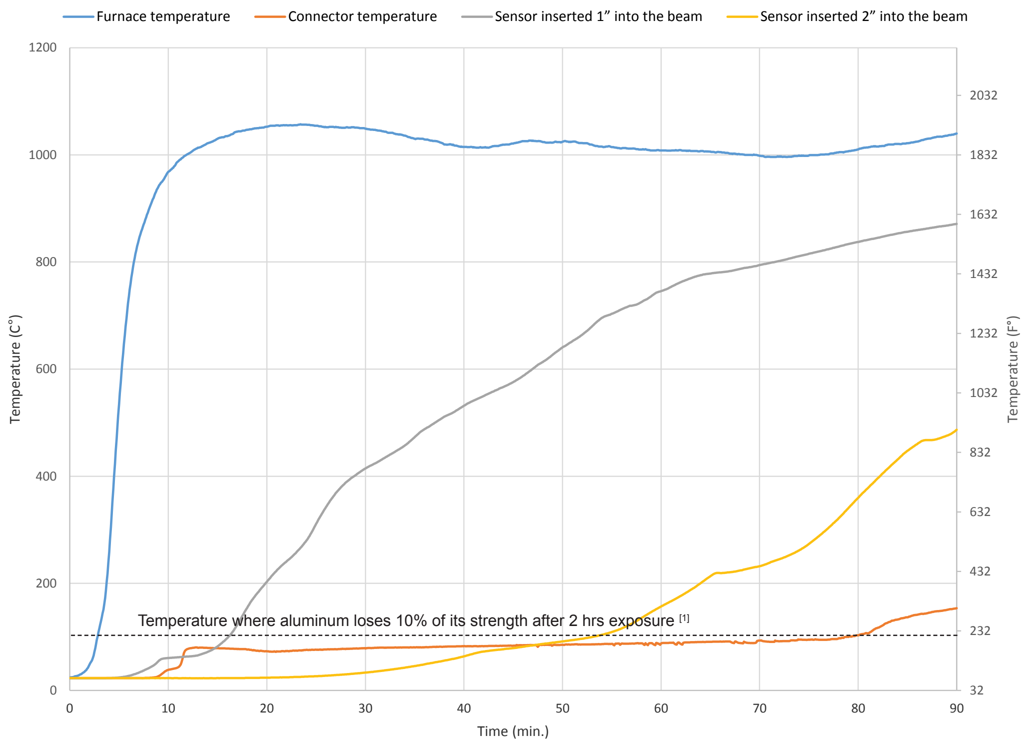
Results



Graph 2. Test #1 Single Ricon S VS 290x80 test, temperature over time.



Graph 3. Test #2 Double Ricon S VS 200x80 test, temperature over time.



Graph 4. **Test #3 Single Megant 430x150 test, temperature over time.**

Analysis

All three full-scale fire tests passed the requirements for fire-resistance ratings between 1h (Test #1) or 1.5h (Test #2 & #3). The low temperature increases measured by the heat sensors placed at various locations inside of the specimen clearly highlight the favorable insulation properties of mass timber. In all cases, the sensors located 1" (25mm) underneath the surface of the member picked up heat faster than the ones located 2" (51mm) underneath the surface. This shows that when appropriate wood cover is provided, steel and aluminum connectors ought to stay protected from reaching critical temperatures.

For tests #2 & #3 the designated wood cover was slightly under the required thickness determined in accordance with NDS and significantly lower than required by CSA O86. Since tests #2 & #3 passed a 1.5h FRR it can be mentioned that both linear and non-linear approaches result in conservative fire design and are likely providing a safe approach for the determination of the fire resistance of concealed connections.

Figure 5 shows the removal of the tested specimen from the test frame. After the test was stopped at 60 or 90 minutes, the assembly remained in the furnace for an additional 15-20 minutes before it was removed and extinguished completely, hence Table 4 shows the measured char layer thickness.

[1] Source: EN1999-1-2

Figure 5. Opening of furnace (left); removal of specimen (middle); extinguishing of specimen (right).

Table 4. Estimated char layer thickness and charring rate results

Fire exposure time	Estimated average char thickness (a_{char}) measured		Estimated average Charring rate (β_{eff}) measured		Ajusted estimated char thickness	
hours	inch	[mm]	in/hr	[mm/min]	inch	[mm]
1	1.75″	[44]	1.75	[0.74]	1.40	[33]
1.5	2.41″	[61]	1.61	[0.68]	2.07	[51]

Note: The adjusted estimated char thickness was calculated with a linear interpolation considering the actual fire exposure being extended for 15 minutes.

The average charring rate was approximated through basic measurement of the char layer thickness, with the results contained in Table 4. Since the assemblies were not fully extinguished until at least 15 minutes after the test was stopped, an adjusted char layer depth, which estimates the char layer depth at the time of the end of each test is included.

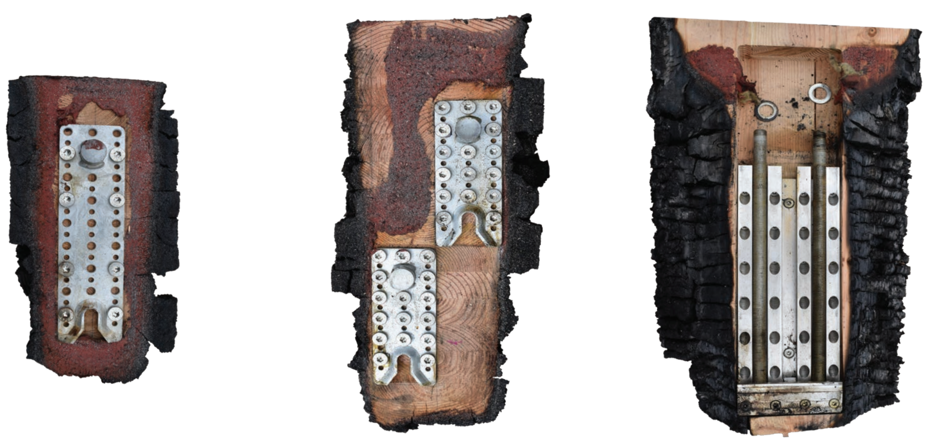


Figure 6. Picture of the single Ricon S VS, double Ricon S VS beam side and Megant column side of the connections after the tests.

CONCLUSION

Despite the fact that wood is a combustible material, unlike structural metals, wood is generally a poor conductor of heat. Furthermore, the insulation provided through charring makes wood suitable as a protective fire covering for non-combustible steel and aluminum connections. Protective wood covering for connections is recognized in the NDS (cl. 16.3) and CSA O86 Annex B, both of which refer to TR 10.

The full-scale fire testing of glulam and CLT assemblies demonstrates that analytical methods available to North American designers are suitable for design of modern concealed connection systems. Furthermore, the concealed mass timber connection systems achieved fire-resistance ratings sufficient to meet the typical requirements for type IV construction building permits.

We strive to provide sustainable, high-quality mass-timber and heavy-timber connection solutions to a rapidly evolving and thriving industry. We drive innovation through certified research and development and contribute our part to the education of young talent and experienced professionals.

Please contact our team to arrange a free Lunch & Learn Seminar on Modern Timber Connection Systems at:

education@myticon.com

For all our technical resources, visit:

www.myticon.com/resources

Contact Us

info@myticon.com
1.866.899.4090

Technical Support

support@myticon.com
1.866.899.4090

WOOD you like to CONNECT?

MyTiCon Timber Connectors

3-8287, 124th Street, Surrey, BC, Canada, V3W 9G2
www.myticon.com