

Fire resistance of timber connections

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Abstract

This research investigate the possibility of predicting the fire resistance of bolted timber connections using Johansen's equations. It gives a model of the variation of the timber embedment strength with temperature. From this informations, the load capacity of the connections can be calculated during a fire knowing the variations of temperatures in the timber and thus a theoretical time of failure can be deduced. The temperatures in the timber are obtained from tests on one hand, and from a numerical model on an another hand. The numerical model also allows to understand better the influence of bolts in the conduction of heat in the connections.

1 Introduction

Timber is widely used in New-Zealand notably thanks to the fast growing radiata pine. This tree is used to produce laminated veneer timber (LVL), similar to glue laminated timber, which offers very good mechanical properties compared to sawn timber, comparable to reinforced concrete. Thus LVL timber may be used in the future for large-scale building. In that objective, the resistance of connections to fire is one of the aspects that need to be better understood. Indeed very little research has been made on the subject and there is no analytical method proposed to design timber connection under fire exposure. The only information provided is some tabular values in the Eurocode 5-12 for the minimum fire resistance of some connection systems. Such tables are, however, very general and can be used only for a preliminary design. At ambient temperature, Johansen's equations can be used to predict the strength of a connection knowing the timber embedment strength. These equations give a good analytical method to design timber connections. The first idea of this research was to adapt these equations to fire conditions to predict the load capacity during a fire. Thus, the timber embedment strength needed to be investigated at different temperatures as well as the repartition of temperatures in the connections. It appeared that the effects of bolts on the temperature in the wood and on the connections strength needed to be investigated.

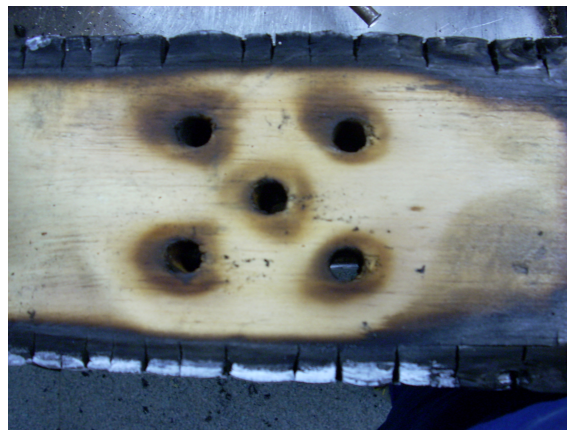


Figure 1: Bolts'effect: after a fire test the timber around the bolts has been heated at least to $250^{\circ}C$ (that is when it starts turning brown)

In other words, the objectives of this research were:

- To determine the variation of the embedment strength of LVL timber with temperature
- To compare the fire performance of different connections
- To find an analytical method to predict the fire resistance of a bolted connection.

Thus, some tests at different temperature were carried out to deduce the embedment strength of LVL as well as some fire tests to determine the fire performance. From the results, an attempt to predict the fire resistance of the connections using the yield theory (Johansen's formulas) was made. In parallel, thermal numerical models of the connections were implemented in the software "safir". The aim was to determine the temperature in the bolt and in the timber during a fire. From curves giving these temperatures as a function of the time, to exposure to a standard fire, for different connection systems and different sizes, it might be possible to predict fire resistances of connections.

2 Literature review

2.1 LVL timber

2.1.1 Thermal properties

To determine the distribution of temperatures using the software safir, values of different parameters between 20°C and 800°C are needed such as conductivity (λ), specific heat (c) and density (ρ). Figure 2 shows the variations with temperature for a normal wood of the ratio $\lambda/(\rho c)$ that affects the laws of thermal conduction. The huge differences from an author to another show that these parameters are not well defined yet and there is no agreement among researchers on the values to assume for them. [5] [3] Different values were tried in the numerical model on the base of a trial error procedure. In other words, using the numerical model on heating tests and making comparisons with experimental results, the values that suit the best the experiments were identified.

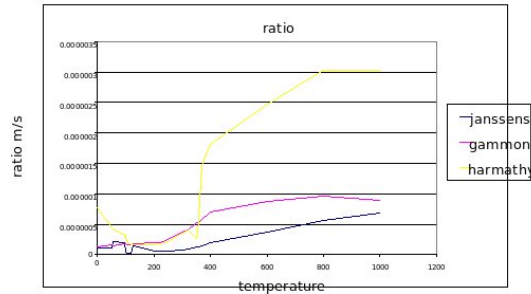


Figure 2: Variation of the ratio $\lambda/(\rho c)$ with temperature

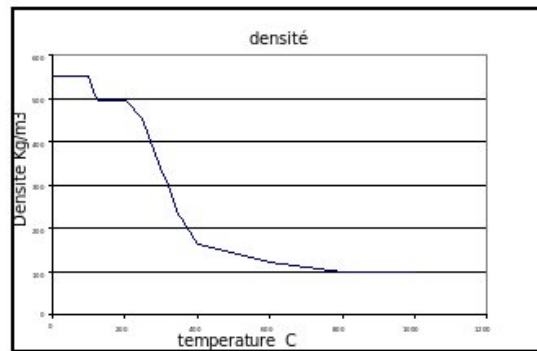


Figure 3: Variation of the density with temperature

2.1.2 Mechanical properties

LVL timber is made from 3mm layers of timber veneers glued together in order to distribute the defaults (knots) randomly in the member. Thus LVL timber is much stronger than sawn timber.

		LVL	Sawn timber
Elastic moduli (GPa)	E	13200	6000
Rigidity moduli	G	660	400
Characteristic strength			
Bending	f_b	42	10
Tension parallel to grain	f_t	27	4
Compression parallel to grain	f_c	34	15
Shear in beams	f_s	4.50	3.80
compression perpendicular to grain	f_p	12	8.90

Table 1: Comparison LVL/Sawn timber

Table 1 shows comparison in terms of strength between sawn radiata pine, and LVL timber made from the same wood.

2.2 Bolts

In all the tests carried out, 12 mm bolts were used. They have a yield moment of 165 kNmm at ambient temperature which drops to 36 kNmm at $750^{\circ}C$.

The graph depicting the bolt yield moment as a function of temperature according to NZS 3404 is reported in figure 4. These values will be needed to predict the time to failure, the failure mode, and to deduce embedment strength of timber from the experimental outcomes of the tests.

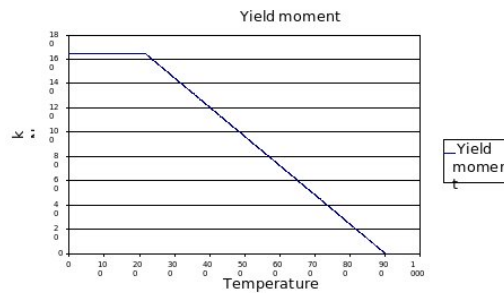


Figure 4: Variation of the bolt yield moment with temperature

Type of connection	k	load applied (kN)	Load capacity (kN)	predicted fire resistance (mins)	experimental fire resistance (mins)
SWS	0,085	7.3	31.5	17.20	11.4
WSW	0.085	6.8	29.5	17.3	17.2
WWW	0.065	4.9	21	22.4	17.2

Table 2: Fire resistance predicted with the reduced load method

2.3 Timber connections design in fire conditions

2.3.1 The reduce load method

According to the Eurocode 5-12, the time to failure for a timber connection under fire exposure can be calculated according to the following equation:

$$t = -\frac{1}{K} \ln\left(\frac{F_{fire}}{F_{max}}\right)$$

Where

- F_{fire} is the load applied under fire conditions
- F_{max} is the load carrying capacity of the connection at ambient temperature
- K is a coefficient that depends on the type of connection (0,065 for wood-wood-wood connections and 0.085 for steel-wood-steel and wood-steel-wood connections)

The results obtained using that equation for the types of connection investigated in this research are reported in table 2. It can be noted that this method over predicts the fire resistance.

2.3.2 The reduced cross section method

A structure is designed for fire conditions such that it can resist a certain amount of time under the standard fire. This method assumes that the cross-sectional reduction of the beam due to charring during such a fire is uniform, and the timber strength is not affected by temperature. By calculating the residual cross-section after some time of exposure to the fire, the strength capacity can then be evaluated and compared with the strength demand under the load combination for ultimate limit state under fire.

If D is the average charring rate (in mm/min), the residual section thickness after θ minutes of fire is

$$t_{residual} = t - nD\theta$$

Where

- t is the original timber thickness (mm)
- n is the number of charring surfaces

This formula does not take into account the rounding effect at the edges of the bolts observed on the specimens. As a consequence the next formula will be used

$$t_{residual} = t - 2nD\theta$$



Figure 5: Rounding effect

where the factor 2 takes into account the char rounding effect.

Picture 5 shows the side member of a connection after a fire where the rounding effect can be observed.

For the experiments reported in this report, a furnace that does not reproduce exactly a standard fire was used. Therefore the fire resistance found (the time until failure) is different from what it would be in real condition. To convert the failure time in the furnace to failure time in a standard fire the formula below was used:

$$t_{standard} = \frac{C_{standard}}{C_{furnace}} t_{furnace}$$

Where

- $t_{standard}$ is the fire resistance time in a standard fire
- $t_{furnace}$ is the fire resistance in the furnace
- $C_{standard}$ is the charring rate in standard fire
- $C_{furnace}$ is the charring rate in the furnace

For the tests carried out, the charring rate was measured and the expected times to failure was calculated using the reduced cross section method and ignoring the presence of the fasteners. There are significant differences between the experimental results and the predictions made by this method. Therefore it is necessary to take into account the effects of temperature through the variation of the yield moment of the bolt and of the timber embedment strength. Table 3 shows the comparison of the times of failure.

2.4 Embedment strength

The embedment strength is the average compressive stress at maximum load at the interface between a timber specimen and a stiff linear fastener, with the fastener's axis perpendicular to the surface of the specimen.

It is not a wood property but a system property as it depends on the diameter of the bolt and the friction between the timber and the fastener. It is one of the most important factors that influences the load carrying capacity of the connections.

According to the Eurocode 5, the embedment strength for timber loaded parallel to the grain, using bolts and dowels of less than 30mm is given by (in MPa) [2]:

	Experimental time of failure (mins)	Predicted time of failure (charring rate method) (mins)
One bolt connections		
SWS	11.4	29.3
WSW	17.2	22.6
WWW	17.2	23.9
Multi-bolted connections		
SWS	10.4	32
WSW	15.0	23.3
WWW	20.4	23.3

Table 3: Fire resistance predicted with the charring rate method

$$f = 0.082(1 - 0.01d)\rho$$

where

- ρ is the wood density (kg/m³)
- d is the diameter of bolts (mm)

Knowing how the timber's density changes with temperature, the variation of the embedment strength of LVL timber with temperature can be calculated according to the Eurocode. Assuming the density vs temperature relationship is the one given in 2.1.2 (thermal properties), the trend of embedment strength vs the temperature reported in the graph below can be obtained.

This property was also experimentally investigated for LVL timber and very different results were obtained.

To determine the embedment strength of timber, steel-wood-steel (SWS) specimens with one bolt were tested. The maximum load was determined for different temperatures, and the embedment strength f was calculated using the relation below:

$$f = \frac{F_{max}}{dt}$$

where

- F_{max} is the maximum load applied during the test
- d is the diameter of the bolt
- t is the thickness of the timber specimen

This law can be applied as long as the bolt is still straight after the test. If this is not the case, the Johansen's Yield theory summarised in the next section can be used.

2.5 Johansen's yield theory

Johansen's yield theory is used to calculate the maximum load of timber-to-timber and timber-to-steel connections and, also, to predict failure mode. The equations involve the timber member thickness, the yield moment and diameter of the bolt, the timber embedment strength. This theory is based on the assumption of rigid plastic materials (no movement detected in the joint until the load reaches the ultimate load). [4] The equations are given in the appendix. They give the maximum load a connection can withstand per shear plane (to obtain the maximum load for the all connection tested, such value must be multiplied by 2).

3 Description of the tests

3.1 Types of tests

Three types of experiments were performed:

- Ambient test: it was conducted on all the types of connections to know the maximum load they can carry. The results from steel-wood-steel connections were used to determine the embedment strength of timber at ambient temperature. For each of these tests and for heating tests too, 40% of the expected load capacity was applied, then the specimen was unloaded down to 10% and finally loaded to failure.
- Heating test: the aim was to determine the embedding strength of timber at different temperature, from $20^{\circ}C$ to 300° when the wood starts charring and loose its strength. A SWS connection specimen was placed in the furnace for some hours, the time needed to have a uniform temperature in the specimen, then it was quickly loaded to failure like for ambient test.
- Fire test: the aim was to see how long a connection resists under fire exposure. The specimens were loaded with their designed fire load and then the fire was started.

3.2 Description of testing equipment

To set fire and heat the specimen a furnace that can provide temperatures up to $800^{\circ}C$ was used (see the picture).

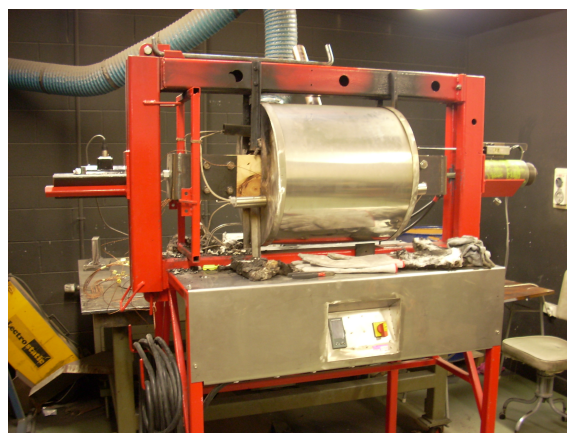


Figure 6: The furnace

During each test were measured the load, the displacement and the temperature in different places, using an Universal Data Logger (UDL) to record the data.

To measure the temperature K-type thermocouples were used. They are made of two wires of different metals (chromium and aluminium) welded at the end. The temperature is given by the difference of potentials created in the welding. With this type of thermocouple, temperature between -270°C and 1320°C can be measured. However, during the fire test the wires burn and the thermocouples sometimes start giving unreasonable results. Furthermore, the same thermocouples were used for several tests despite their bad condition. Consequently some of the data from thermocouples had to be ignored for some tests. Moreover these thermocouples are not very accurate since the result they give can have ten degree of difference with the actual temperature.

3.3 Design of the connections

All the specimens are made from LVL timber, of 65mm or 45mm thickness as they are used in New Zealand, with 12mm diameter bolts made of grade 4.6 steel.

3.3.1 Types of connections

Steel-wood-steel connection (SWS) This connection is made of two timber members sandwiched in between steel plates on the side to join the members. For the fire tests, 65 mm thick timber and 6mm thick steel plates on the sides were used. The 45mm timber samples were also used for heating and ambient tests using two plates on each side to avoid bending the bolts. Fourteen thermocouples the locations of which are indicated by black spots were used: between the side members and the bolt head, along the bolt at mid-depth, between side members and the main member, in the air, at mid-depth of the timber members.

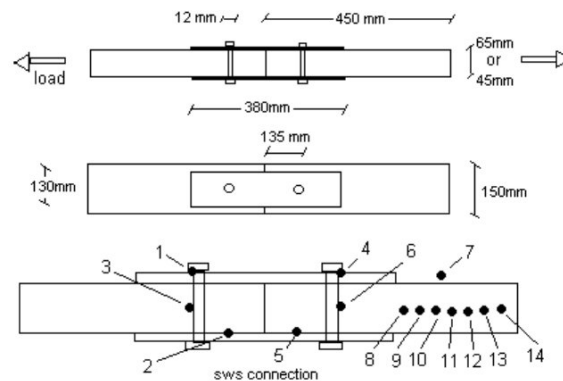


Figure 7: SWS connection

Wood-steel-wood connections (WSW) This connection is made of four pieces of timber, two on each side of a steel plate that connects the two members. A 6mm steel plate is sandwiched between the timber members. Washers were added to avoid crushing the timber when the bolts are tightened.

Wood-wood-wood connections (WWW) This connection is similar to SWS connection except for the side steel plates which are replaced by timber members of 45 mm thickness.

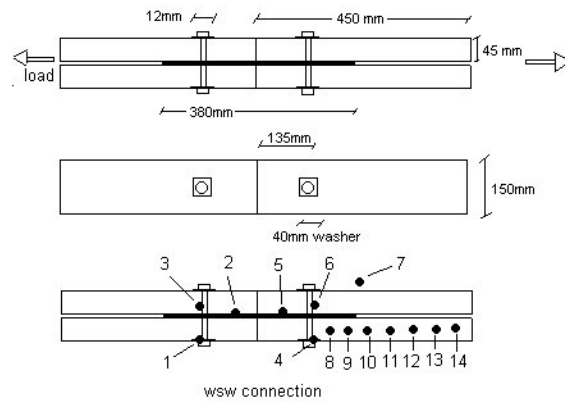


Figure 8: WSW connection

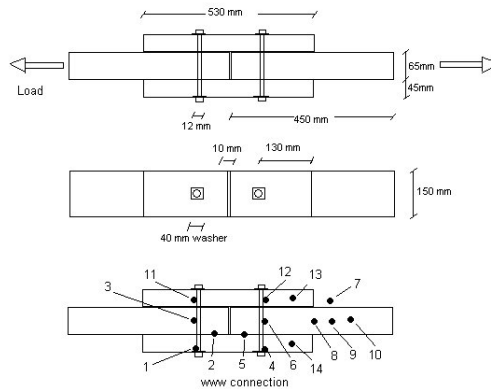


Figure 9: WSW connection

3.3.2 Load applied to the connections

The design of these connections was made before by other students [Lau], [Chuo], so this paragraph will only summarise their design and make some comparisons between the Eurocode and the New Zealand code.

Load combinations In the New Zealand code (NZS 4203 clause 2.4.3.4) there are three load combinations that have to be considered for the ultimate limit design and two for fire design. These combinations take into account the gravity load, the live load and the snow load.

From table 4, can be calculated the load factor defined in the following:

$$\text{Loadfactor} = \frac{\text{max fireload}}{\text{maxultimelimitload}}$$

With this factor the load to apply to a specimen to test its fire resistance can be calculated. If F is the design load of a connection at ambient temperature, the load given by $F * \text{Load} - \text{factor}$ will need to be applied to test its fire resistance.

Design load of the connections Table 5 gives the load capacities of the different connections according to the New Zealand code and the Eurocode.

	Roof (KPa)	Floor (KPa)
Gravity	0.2	0.5
Live load	0	2.5
Snow load	0.5	0
Ultimate limit combinaisons		
1.4G	0.28	0.7
$1.2G + 1.6Q$	0.24	4.6
$1.2G + 1.2S$	0.84	0.6
Fire combinaisons		
G	0.2	0.5
$G + 0.4Q$	0.2	1.5
Load factor	$0.2/0.84 = 0.24$	$1.5/4.6 = 0.33$

Table 4: Design load combinations - Load factors

Using the Eurocode The design with the Eurocode is based on the use of the Johansen's equations. The load capacity corresponding to different modes of failure is calculated, taking into account some safety coefficients that depend among other things on the number of bolts. The load capacity of the connection is the lowest of these values. The design load is obtained by multiplying the load capacity by the safety coefficient 0.7 [2].

Using the New-Zealand code The load capacities are given by tables [1].

4 Experimental results

4.1 Ambient tests

These tests had two purposes: to determine the maximum load of different types of connections and to determine the embedment strength of timber at ambient temperature. The second point was trickier because it was hard to recognize what the failure mode was in order to deduce the embedment strength using Johansen's equations. The first test conducted was on a SWS connection made with timber of 63 mm and it seemed that the bolts were bent in mode m or k, more likely k. Then some tests with timber of 45 mm and double thickness of the steel plates on the sides were performed with the hope the bolts would remain straight. It appeared that in some cases they were still straight and in some other they were not. It seems that they were still straight when the test was stopped at a 10 mm displacement and that they started bending at 30 mm displacement. Moreover the holes were straight suggesting that the mode of failure was mode j. That is why we assumed that the mode of failure was j (straight bolt).

	Load capacity (Eurocode) (kN)	Capacity (New Zealand code) (kN)
One bolt connections		
SWS	20.9	31.5
WSW	29.9	29.5
WWW	20.9	21
Multi-bolted connections		
SWS (4 bolts)	70.8	126
WSW (4 bolts)	101	118
WWW (5 bolts)	88	105

Table 5: Expected load capacity of the connections

Table 6 gives the experimental load capacity of the different connections based also on the results of other students [6] [7].

4.2 Heating tests

Like for the ambient tests, for low temperatures, it was hard to recognize the failure mode. For the same considerations reported above, it seemed to be mode j. The graph of the embedment strength of LVL timber deduced from the heating and ambient tests is reported in the figure below:

It is hard to say what the embedment strength would be below 20°C and above 270°C because it is impossible to obtain this temperature into the wood without charring. Two hypotheses were made: one assumes that before 20°C the strength does not change with temperature and that after 270°C it remains constant at 10 MPa. The other one assumes a linear variation below 20°C and above 270°C . In the next paragraph the two approximations will be compared using the results from the fire tests. The first approximation seems to correspond better to the test outcomes.

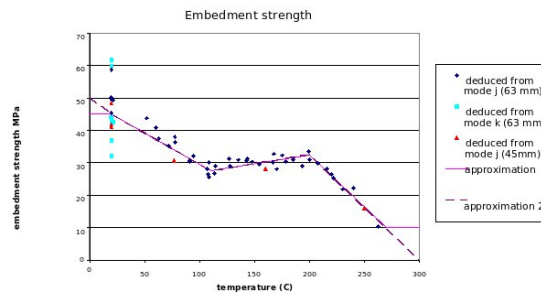


Figure 10: Approximations of the timber embedment strength

	Experimental maximum load (kN)	Expected capacity (New Zealand code) (kN)
One bolt connections		
SWS	34	31.5
WSW	30	29.5
WWW	22	21
Multi-bolted connections		
SWS (4 bolts)	161	126
WSW (4 bolts)	216	118
WWW (5 bolts)	200	105

Table 6: Experimental capacities of the connections

4.3 Fire tests

4.3.1 Definition

The fire resistance of a connection is defined as the time the connection can resist to a standard fire with a certain load. Different definitions of failure were considered:

- When the displacement is greater than 10 mm
- When the displacement is greater than 15 mm or the rate of displacement is greater than 10 mm/min
- When the displacement is greater than 15 mm

Even the notion of displacement is ambiguous: it may be measured from the moment when the connection starts being loaded or from the moment the fire was started. The initial displacement however can vary a lot from a test to another, and depends on other parameters. For example, the brackets that hold the specimen in the furnace can cause a large displacement because the holes are 1 or 2 mm larger than the bolts. Therefore, up to 4 mm of the initial displacement should not be taken into account. As a proof of this displacement not being reliable, for a same type of connection in a test the initial displacement was 8mm while in another it was 4 mm. As a consequence, a decision was taken to measure the displacement from the moment the fire was started.

4.3.2 Average times of failure

Table 7 gives the average times of failure for the different connections, according to different definitions of failure.

Definition considered for the time of failure	10mm displacement (min)	15mm displacement (min)	15mm or 10mm/min (min)
One bolt connections			
SWS	11.4	11.7	11.4
WSW	17.2	18.5	18.5
WWW	17.2	17.9	17.9
Multi-bolted connections			
SWS (4 bolts)	10.4	10.9	10.7
WSW (4 bolts)	15.0	15.6	15.4
WWW (5 bolts)	20.4	19.7	19.7

Table 7: Experimental fire resistances

5 Prediction of failure load using Johansen's theory

During the fire tests, the temperature along the bolt was recorded. Due to the high conductivity of steel, this temperature was assumed to be uniform all along the bolt. The yield moment of the bolt can then be calculated using the approximations suggested by the AS NZ standard. The embedment strength of timber around the bolt can be calculated using the approximation reported in 4.2. Moreover, the charring rate of the experiments can be measured and the residual section of timber during the tests can be calculated. By using these data, the maximum load given by Johansen's equation at any time during the test can be calculated and compared to the actual load applied.

5.1 Validity of the embedment strength approximation

For the embedment strength, the two different approximations were used. Their accuracy was tested by comparing the analytical results at the time of failure with the experimental load applied.

The results using the two approximations of the embedment strength of timber, for a WWW connection and a SWS connection, are reported in figures 11 to 14.

With the first approximation For the WWW connection, it appears that the predicted failure load at the time of the actual failure was 4.39 kN. This value is quite close to the applied load which was at that moment 4.88 which represents a 10% difference.

For the SWS test the predicted failure load at the time of experimental failure was 5.77 kN and the applied load was 5.87 kN, which represents only a 2% difference.

With the second approximation In that case, there are significant differences between the predicted failure load and the load applied at the time of failure, 59% for the WWW connection and 52% for the SWS connection.

It can be conclude that the first approximation predicts the failure load better than the other

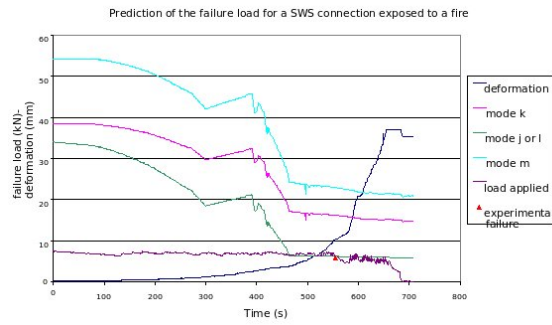


Figure 11: Prediction of the failure of sws using the first approximation

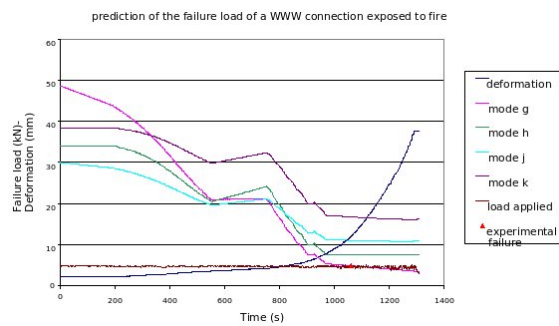


Figure 12: Prediction of the failure of wwv using the first approximation

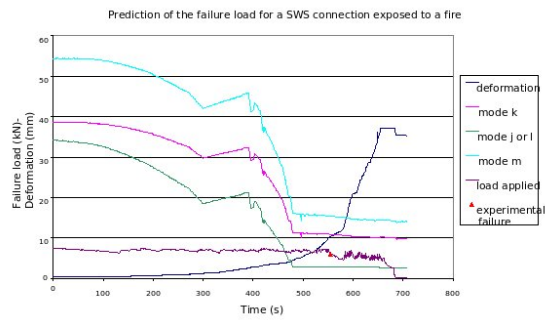


Figure 13: Prediction of the failure of sws using the second approximation

with acceptable accuracy. Thus, the first approximation of the timber embedment strength will be used to predict the failure.

5.2 Comparisons between the experimental results and the predictions given by Johansen's equations

Table 8 reports the comparisons between the experimental time to failure and the predicted time (when Johansen's curve meets the curve of the experimental load), and between the experimental

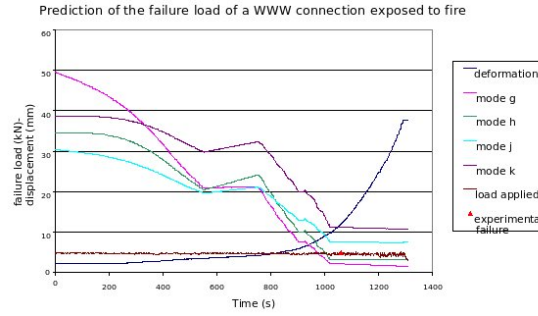


Figure 14: Prediction of the failure of wwww using the second approximation

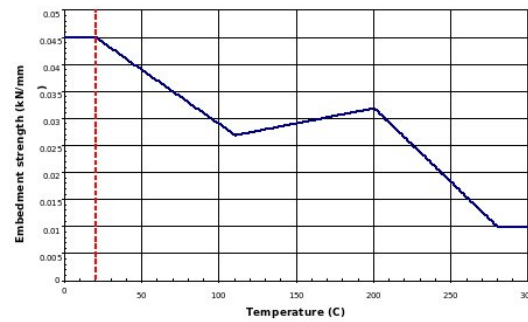


Figure 15: Approximation chosen for the embedment strength

failure load and the predicted failure load (the load capacity at the time of the experimental failure).

As can be seen in table 8, the predicted time of failure can be very different from the experimental time for SWS connections. Indeed, as around the time of failure the variation of the predicted failure load is only due to charring, the curve is very flat, the charring rate for SWS connections being much lower than for WSW and WWW connections because the steel plates protect the timber members. As a consequence of that, the uncertainty is considerable: on the one hand, in 2 minutes (20% of the fire resistance) the predicted failure load would just vary of 0.3 kN and on an other hand we could not apply a constant load with much precision so it could vary of more than 0.3 kN in a few seconds. Therefore it is hard to predict the time to failure using Johansen's equations. Perhaps Johansen's equations could be used to predict a minimum time the connection could resist. For SWS connections, the predictions of the failure load are affected by an error up to 17.6 %. For the other connections, except for the one bolt WSW test (s-WSW) where thermocouples gave unreasonable results, similar results were found for the time to failure and for the failure load, the differences were less than 10% . Therefore Johansen's equations seem to provide a good prediction of the time to failure and of the failure load for WWW connections and WSW connections.

However, Johansen's equations give the maximum load of a connection, so when the predicted maximum load is equal to the applied load, it may not necessarily be the time of failure but it should fail after that time. Thus, what is called predicted time to failure should just be a minimum time of fire resistance.

	Time to 10mm displacement (min)	predicted time to failure (min)	difference %	failure load (applied) kN	predicted failure load kN	difference %
s-SWS	9.3	7.8	16.3	6.1	6.2	-1.6
s-SWS2	14.1	4.6	67.7	6.8	5.6	17.6
s-SWS3	9.8	4.9	49.6	6.6	6.2	6.1
m-SWS1	10.2	no		21.4	24.4	-14.0
m-SWS2	10.4	no		22.1	24.2	-9.5
m-SWS3	10.6	no		22.1	24.1	-9.0
s-WSW	17.2	11.5	-32.6	7.2	5.5	-31
m-WSW	15.3	15	1.6	20.6	22.7	-10.2
m-WSW2	14.7	15.0	-2.6	22.8	23.5	-3.1
s-WWW	18.0	16.6	7.8	4.7	4.4	6.4
s-WWW2	16.4	16.7	-1.8	4.7	5.1	-8.5
m-WWW	19.3	18.1	5.9	22.3	21.6	3.1

Table 8: Prediction of the time of failure with Johansen's equations

5.3 Reliability of the thermocouples

Figure 16 shows how different the temperatures are in the bolt from a test to another and even from a bolt to another in the same test. Therefore, the thermocouples give doubtful results, and the predictions above are questionable.

Figure 16 is an illustration of the problems encountered with the thermocouples: these seven curves represent the temperature in the wood during a fire test on SWS. Theoretically they should be identical; however this is not the case, one temperature is four times another for example.

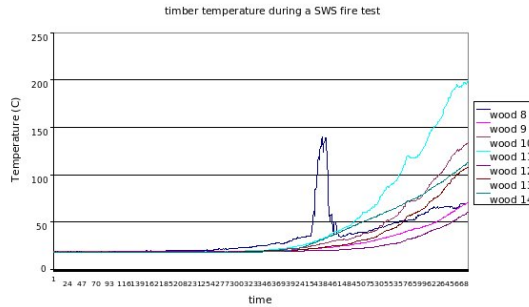


Figure 16: Exemple of doubtful results from the thermocouples

What can be expected from the use of the numerical model is to determine with more accuracy the bolt temperature and the timber temperature in the section knowing the type of connection, the thickness and the time of exposure to fire. This information would then be used to predict the time to failure in conjunction with Johansen’s formulas.

6 Numerical model

6.1 Determination of the thermal parameters of LVL timber

As it was said in the literature review, there is no agreement among researchers on the parameters to be used in thermal analysis. The different models gave unrealistic results when they were used in the numerical model. That is why these parameters were determine using the software through a trial error process.

A model of a SWS connection was made and the numerical results were compared to the experimental results of heating tests. The timber parameters were modified in order to make the numerical model suits as well as possible the experimental results. Contrary to fire tests, the temperatures given by the thermocouples were quite regular during heating tests and it was possible to select the data that seemed right (if three thermocouples on seven gave the same results, it was assumed as real temperature). The input data for the air temperature used for the numerical model was the one recorded in the furnace.

The timber parameters can only be defined for six different temperatures which limits notably the accuracy of the model; between these values safir makes linear interpolations. Since only the ratio is important, the density and specific heat were fixed and only the conductivity was modified. The method consisted in finding the conductivity step by step. To start, a comparison at 100°C was made to determine the parameters at 20°C and 90°C. Then with a 150°C test the parameters could be determined at 100°C and 110°C, with a 200°C test at 210°C and with a 280°C test at 300°C.

These values did not always provide great accuracy. The ones that work very well at 100°C and 150°C seemed too low for 200°C and 280°C tests. That way, safir gives very close values at the

end of the heating tests but not always at the beginning. As far as the temperature in bolts is concerned, the only parameters that can be changed are the convection coefficient on cold and hot surfaces and the emissivity. However they have very little influence on the temperature so it was no use trying to modify them.

Figures 17 to 20 show the experimental and numerical temperatures in the middle of the timber section for different heating tests.

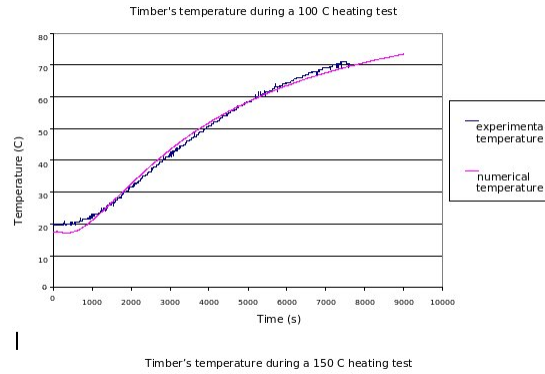


Figure 17: Experimental and numerical timber temperature during a 100°C heating test

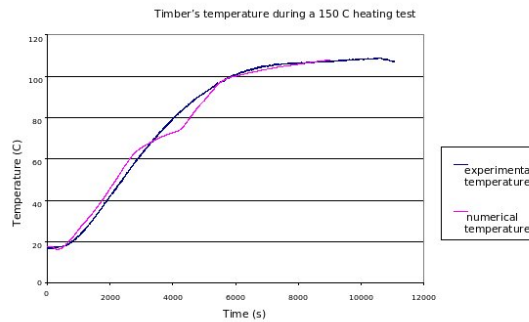


Figure 18: Experimental and numerical timber temperature during a 150°C heating test

6.2 Verification of these parameters

In order to make sure that the choice of the parameters was adequate, a heating test on a simple piece of wood and two bolts with no load applied was carried out. It was heated to 100°C for two hours, then to 150°C for one hour, and finally to 200°C for another hour. Eight thermocouples were placed in the timber to see if a gradient exists in the section. The aims of this test were:

- (i) to see if the thermal behaviour of LVL timber is isotropic or not, as the model on safir assumes it to be
- (ii) to see if a gradient exists in the section of timber
- (iii) to compare the experimental results to the numerical results once more.

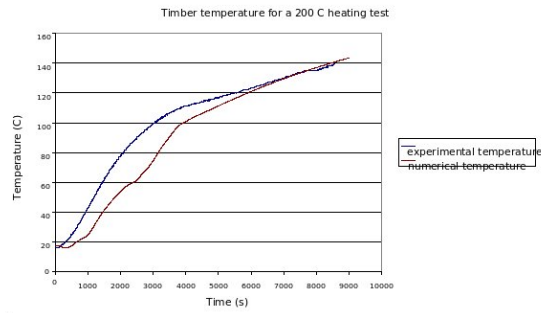


Figure 19: Experimental and numerical timber temperature during a 200°C heating test

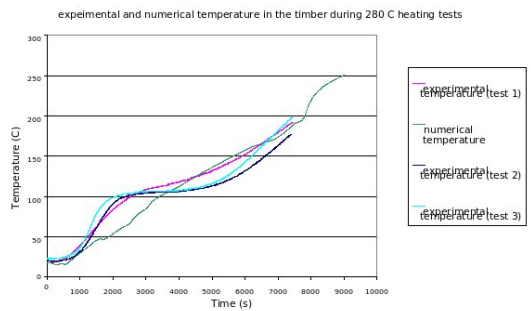


Figure 20: Experimental and numerical timber temperature during a 280°C heating test

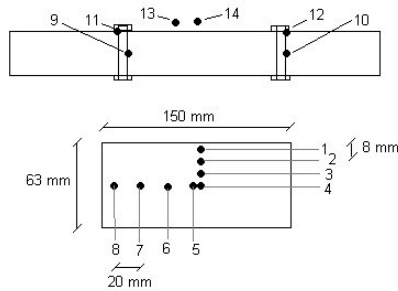


Figure 21: Place of the thermocouples for the test of verification of the timber parameters

The thermocouples were placed as shown on picture 21.

Figure 22 shows the experimental temperatures in the section of timber and the numerical temperature in the middle of the section. The temperature recorded in the thermocouples 4 and 5 should be the same but they were not. The temperature in 1, 2 and 4 were found to be quite the same with no noticeable gradient. A slightly larger variation can be noticed along the thermocouples 5,6 and 8 with therefore some gradient in that direction. The thermocouple 3 and 6 gave unrealistic results and should be ignored. A numerical simulation of this test was ran and surprisingly it gave results quite close to the temperatures in the thermocouples 5, 7 and 8. Nevertheless, the experimental data are not fully reliable so this comparison cannot be considered as a proof of the validity of the parameters.

Temperature (C)	conductivity	specific heat	density	ratio
20	0.3	1500	550	$3.6 \cdot 10^{-7}$
90	0.05	1500	550	$6.06 \cdot 10^{-8}$
100	0.2	1600	550	$2.27 \cdot 10^{-7}$
110	0.14	2000	550	$1.27 \cdot 10^{-7}$
210	0.02	2000	495	$2.02 \cdot 10^{-8}$
800	6	2000	100	$9 \cdot 10^{-5}$

Table 9: Thermal parameters

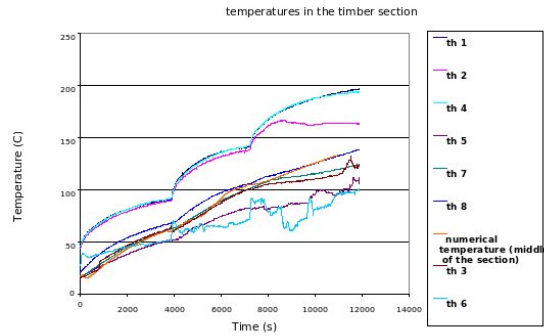


Figure 22: Temperature in the section during the test of verification

6.3 Results of safir on the fire tests and comparisons with the experimental results

6.3.1 SWS connections

Picture 23 and 24 show the mesh used on the SWS connection and the repartition of temperatures. It represents just one eighth of the connection, the rest can be deduced by symmetry. The effects of bolts on the connection can be seen: around the bolt, the temperature appears to be much higher than elsewhere in the wood.

Pictures 25 and 27 show the temperatures for different depth in the wood and in the bolt shown on pictures 26 and 28. According to the numerical model, the temperature in the timber remains constant for some time, depending on the depth, and then increases very quickly. The temperature recorded during the fire tests on SWS connections does not look like the numerical results, except that the temperature remains constant for some minutes and then increases, but much slower. As far as the temperature along the bolt is concerned, the difference between experimental results does not allow any final conclusion. Even if the numerical temperature of the bolt is too low, the results show that the temperature in the wood is quite as high as in the bolt and there is not a great gradient between the wood and the bolt after 10 minutes. Thus it may be concluded that it is right to use the bolt temperature to deduce the timber embedment strength in Johansen's equations.

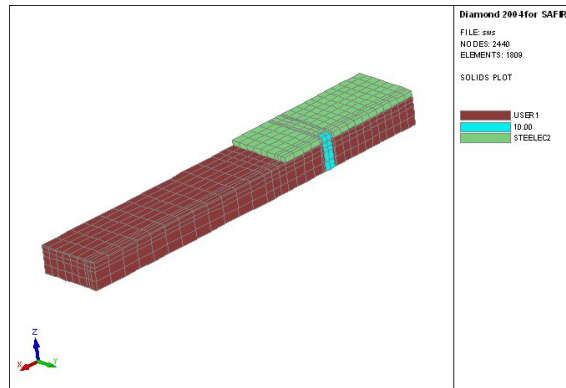


Figure 23: Mesh used for sws connections

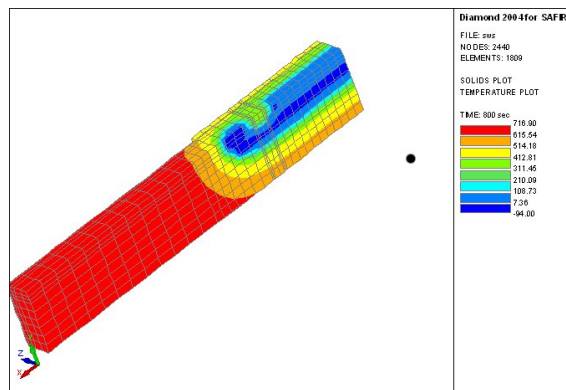


Figure 24: Temperature in a sws connection during a fire test

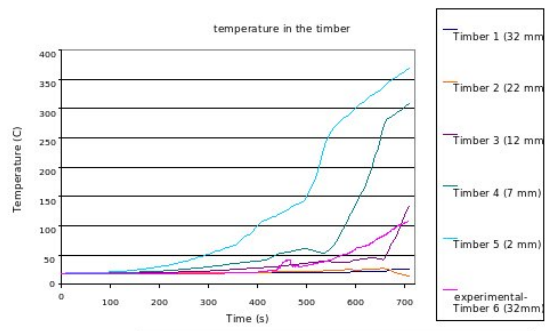


Figure 25: Numerical temperature in the wood in a sws connection during a fire test

Figure 29 shows the prediction of the fire resistance of a SWS connection with one bolt using the temperatures given by safir in Johansen's equations. It predicts the failure after 640 seconds, when the applied load become greater than the maximum load the connection can withstand. To predict the time to failure for the multi-bolted connections, it was assumed that the temperature in the bolt would be the same as for the same type of connection with one bolt. Numerical models were only made for connections with one bolt.

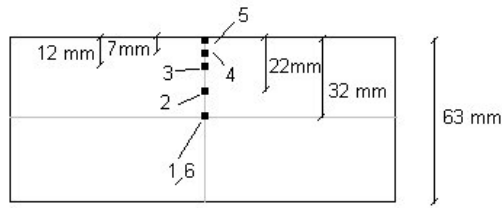


Figure 26: Places where temperatures were picked out for figure 25

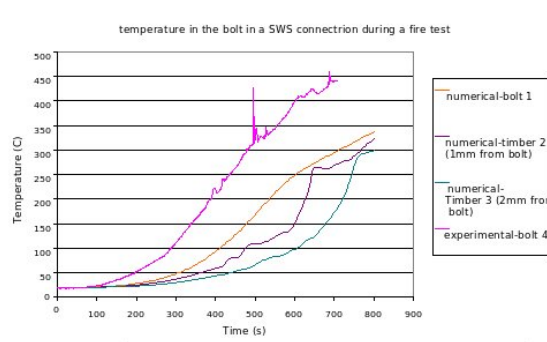


Figure 27: Numerical temperatures along the bolt in a sws connection during a fire test

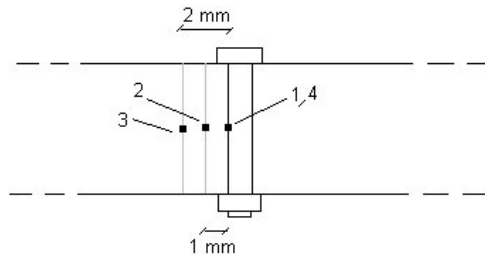


Figure 28: Places where temperatures were picked out for figure 27

Table 10 gives the average experimental times of failure and the times obtained from the numerical temperatures for SWS connections. The differences between the experimental time to failure and the time predicted with safir are less than 13.5%.

6.3.2 WSW connections

Pictures 30 and 31 show the mesh used on the WSW connection and the repartition of temperature at a moment of a fire test. It represents just one eighth of the connection, the rest can be deduced by symmetry.

The graphs of the temperature in the wood section and in the bolt are reported in figures 32 and 34.

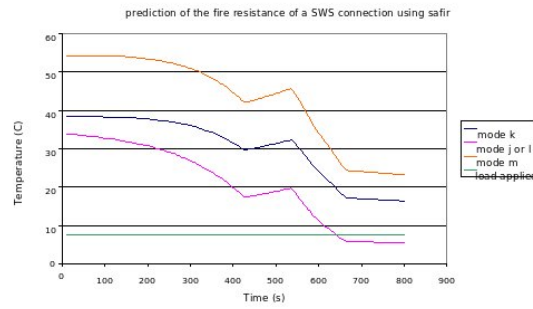


Figure 29: Prediction of the failure of one-bolt sws connection from safir results

	Experimental time of failure (at 10mm) (min)	Predicted time using numerical temperatures (min)	Difference % experimental-numerical
s-SWS	11.1	10.7	-3.6%
m-SWS	10.4	11.8	13.5%

Table 10: Prediction of the time of failure of SWS connection from numerical temperature

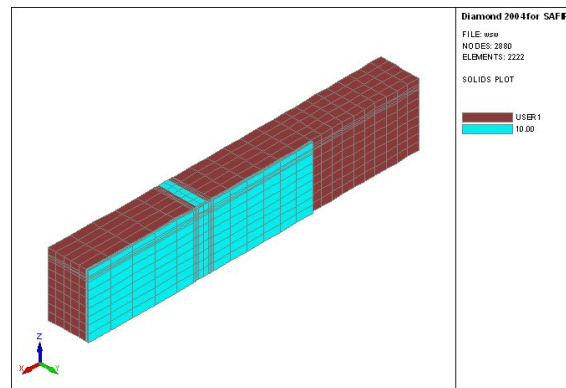


Figure 30: Mesh used for WSW connections

There are some difference of temperature between the bolt and the timber around but after some minutes the temperature becomes uniform. At the time of failure (after 870 seconds) the temperature in the timber at 4mm from the fastener is the same as in the bolt. Therefore, the bolt temperature can be used to deduce the timber embedment strength.

Again, the experimental results are not accurate enough to make any final conclusion as the numerical results are lower than some experimental results or higher than some others.

Table 11 summarizes the experimental times to failure and the predicted times for WSW connections.

The time to failure and the failure load predicted with the numerical model for WSW connections with four bolts are quite close to the average experimental result (a 5.3 % difference).

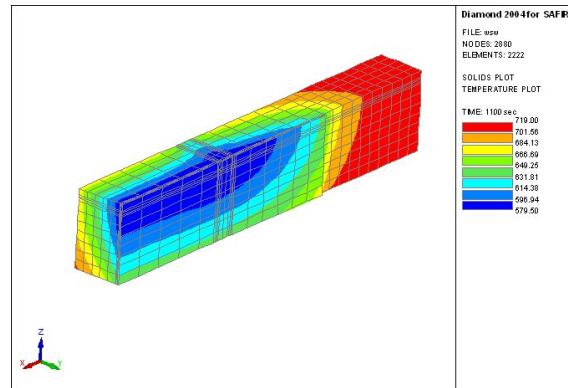


Figure 31: Temperature in a WSW connection during a fire test

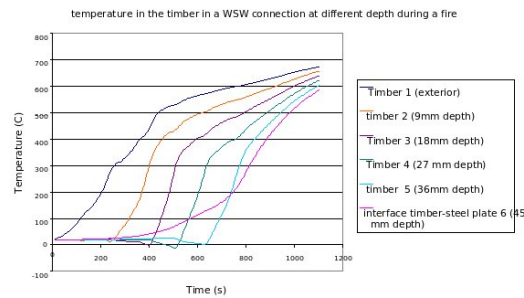


Figure 32: Numerical temperature in the wood in a WSW connection during a fire test

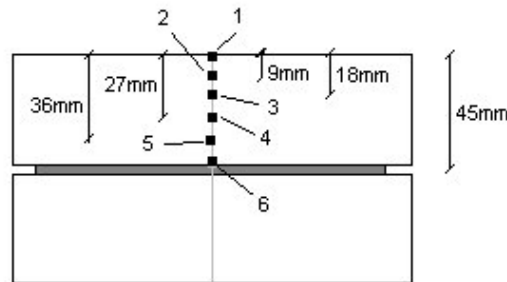


Figure 33: Places where temperatures were picked out for figure 32

However, for single-bolted wsw connections there are 28.2 % differences between the numerical and the experimental results.

6.3.3 WWW connections

Pictures 36 and 37 show the mesh used on the WWW connection and the repartition of temperatures. It represents just one eighth of the connection, the rest can be deduced by symmetry. It

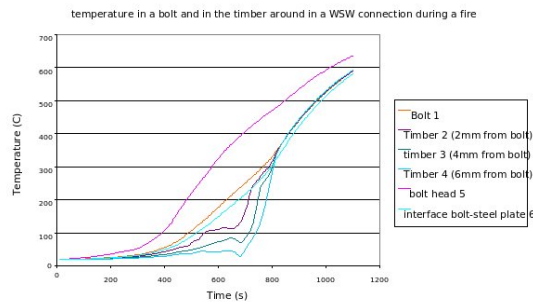


Figure 34: Numerical temperatures along the bolt in a WSW connection during a fire test

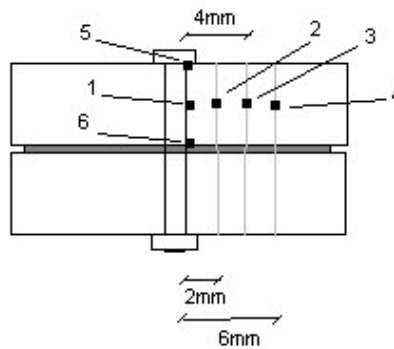


Figure 35: Places where temperatures were picked out for figure 34

can be seen on picture 37 that the timber around the bolt is heated on some millimetres.

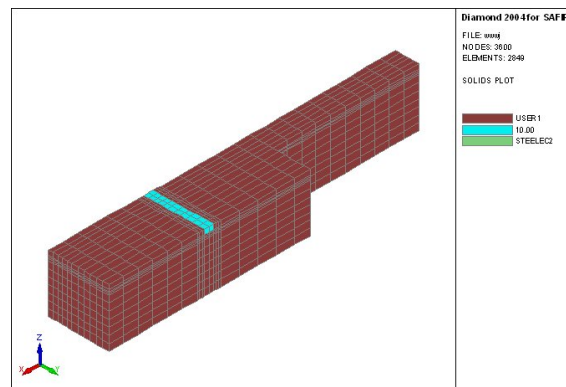


Figure 36: Mesh used for WSW connections

The appearances of the numerical curves are very different from the experimental results as it can be seen on pictures 38 and 39. It appears that the timber conductivity must have been underestimated for low temperatures and over estimated for high temperatures.

The numerical temperature of the bolt is close from one of the experimental results, but no conclusion can be made as there are a lot of differences from a test to another. A gradient of temperature exist between the bolt and the timber around at the beginning of the test but after

	Experimental time of failure (at 10mm) (min)	Predicted time using numerical temperatures (min)	Difference % experimental-numerical
s-WSW	17.2	12.3	-28.2%
m-WSW	15.0	15.8	-5.3%

Table 11: Prediction of the time of failure of WSW connection from numerical temperature

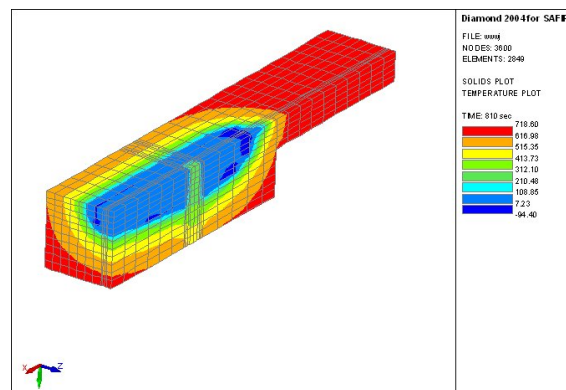


Figure 37: Temperature in a WSW connection during a fire test

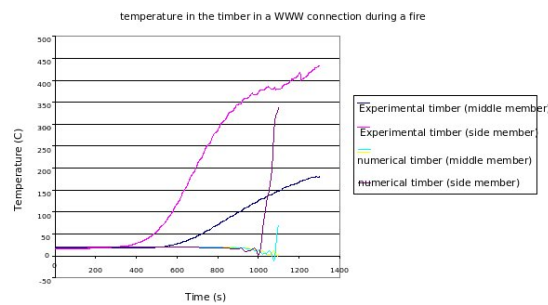


Figure 38: Numerical temperature in the wood in a WSW connection during a fire test

900 seconds, the bolt and the 3mm of timber around are quite at the same temperature (less than 10% of difference). Again, the numerical results justify the use of the bolt temperature to deduce the timber embedment strength.

The graph below shows the prediction of the time of failure using the numerical results in Johansen's equations.

Table 12 gives the experimental and numerical times to failure for WSW connections

For WSW connections, the numerical times are close to the average experimental times (less than 3.5% of difference). The use of the numerical model in Johansen's equations seems to give a good method to predict the time to failure of a WSW connection.

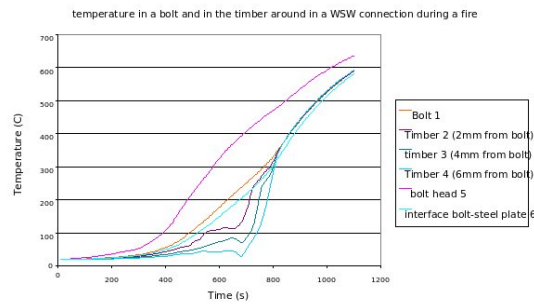


Figure 39: Numerical temperatures along the bolt in a WSW connection during a fire test

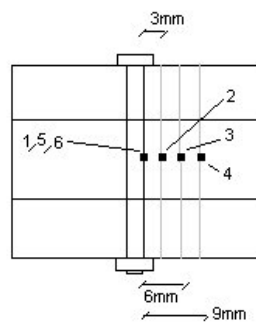


Figure 40: Places where temperatures were picked out for figure 39

6.4 Conclusion on the numerical model

The numerical model gives an acceptable prediction of the fire resistance of timber connections. In the worst case, the model over estimate the resistance of 13.6%. For WSW connection with one bolt, the difference numerical-experimental reaches 28.8%. But the model only under estimate the fire resistance so that by using an error coefficient of 13.6% the numerical model would be able to predict an average minimum time of fire resistance. Even if the temperature obtained with safir are very different of the expermental temperature, the thermal parameters determined with a trial error method give acceptable predictions of fire resistance, so that it is difficult to make any final conclusion about their valadity. The aim of the numerical study was to determine in the future the fire resistance of all types and sizes of connections during a standard fire from numerical temperatures because it can't be done with tests as too many would be needed. But the differences between the numerical and experimental results are too variable to be trusted and not to do anymore tests.

	Experimental time of failure (at 10mm) (min)	Predicted time using numerical temperatures (min)	Difference % experimental-numerical
s-WWW	17.2	17.8	3.5%
m-WWW	18.6	18.3	-1.6%

Table 12: Prediction of the time of failure of WWW connection from numerical temperature

7 Conclusion

The aim of this research was to investigate the possibility of developing an analytical method using Johansen's theory to predict the fire resistance of timber connections. From temperatures obtained during tests, it has been possible to see if Johansen's equations provide a good estimation of the fire resistance when the parameters are adapted to fire conditions. These results were not all satisfying but the uncertainty on experimental results does not allow to reject this method. A numerical method was made in order to provide the temperatures needed for Johansen's equation and also to have more informations on the repartition of temperatures in the connections, mainly around the bolts. From these temperatures, the fire resistances of the different connections were calculated using Johansen's equation and the differences from the experimental results were acceptable. However, the results were not accurate enough to envisage calculating the fire resistance of some connection from numerical results without testing them. It seems that such a method would demand more accuracy in testing to get more reliable temperature. It would allow to define the thermal parameters used in the numerical model better and trust the numerical results. Because even if the fire resistances predicted from numerical temperatures are acceptable, the temperature given by this model are very far from the experimental results which discredit the results.

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