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VALIDATION OF OUTER PLATE BOLTED GLULAM TIMBER CONNECTION IN FIRE

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ABSTRACT
A few hundred years ago, people began employing wood to construct buildings with ten stories or more. Today, wood is used extensively in architectural construction around the globe. With a contemporary design, the cost of full-scale testing for bolted glued laminated (glulam) connection experiments is very high and time-consuming. Therefore, using computer software to simulate the behaviour of the glulam connection will save time and money for the research. The results obtained from the computer software shall be within the acceptable margin of error. Finite element modelling (FEM) through Abaqus 6.14 software was used to simulate the behaviour of glulam connections under different conditions by modifying the test methodology and input parameters. Experimental results are used to validate the results from FEM so that the differences are compared. This research uses FEM to validate the results from the work of previous researchers on the tensile test without fire and heat test with constant load. The parameters are used to predict the behaviour of the model subjected to tensile load and heat.

Keywords:
Abaqus, FEM, glulam, tensile, heat

INTRODUCTION

Timber is a fibrous, rigid material of a plant origin. It is a valuable natural resource that can be used as a building material for construction and to make specialised wood goods like more astatic in the building. In modern construction language, the word "timber" is occasionally used to refer to wood that has been processed for use in building construction. Broadly speaking, it is divided into hardwood and softwood. Timber is natural and renewable. Even in situations when only basic techniques and procedures are available, it is extremely helpful because of its high strength-to-weight ratio and ease of usage (Apu, 2003). Timber remained the most common building material up to the second part of the 19th century, according to Douglas (1995).

However, accidents such as short circuits could happen anytime without warning so it is crucial for buildings to retain their structural integrity in order to prevent them from collapsing. Fire plays an important role in our life but a small careless mistake is all it takes to turn its surroundings into an inferno, making it a double-edged sword. When fire is in contact with timber or fibrous materials, they tend to spread very quickly, making it hard to control the situation. Structures constructed with timber should be kept away from inflammable sources as a prevention method of fire.

Due to the tendency of fire to spread quickly, the damage caused can be massive as well. A layer of carbon will form when timber is burnt. The member of the structure will lose its load capacity as the timber has turned into charcoal, which is weak and brittle. While the carbon layer is forming on the timber, it acts as a barrier that protects the remaining timber from fire. The formation of this carbon layer allows us to predict the rate of charring below the surface. Predicting the rate of charring is important in determining the strength of the remaining timber; therefore, the endurance of the structure can be determined.

LITERATURE REVIEW

The use of creativity in the domains of design, engineering, architecture, and construction management has grown significantly and, the Model of Architectural Information is another development in a normal environment (Lu et al., 2017a). In order to predict the tensile capacity of bolted timber connections in fire, the timber connections will be modelled with Abaqus 6.14 with the verification of FEM. The tensile behaviors of the outer plate bolted timber connection in fire is predicted after the FEM results are verified with experimental results.

RESEARCH METHODOLOGY

Finite Element Modelling

The FEM results are verified with the experimental results of bolted glulam connection shown in Figure 1. The material properties of the glulam beam are shown in Tables 1, 2, 3, 4 and 5 whereas the material properties of the steel sections are shown in Tables 6, 7 and 8.

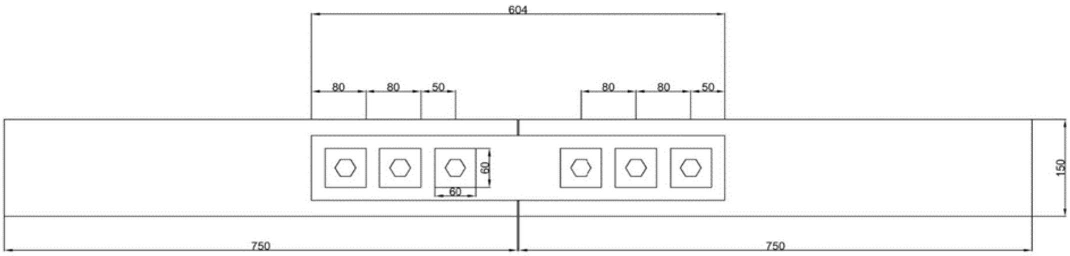

Figure 1: Details of the experimental test setup.

Table 1: Specification of glulam timber used in the research. (ISO Standard No. 834)

Species of Timber	*Heritiera* spp.
Density of Timber, ρ	650 kg/m^3
Modulus of Elasticity, E_1	14,300 N/mm^2
Modulus of Elasticity, E_2	1,144 N/mm^2
Modulus of Elasticity, E_3	715 N/mm^2
Shear Modulus, G_{12}	1,020 N/mm^2
Shear Modulus, G_{13}	960 N/mm^2
Shear Modulus, G_{23}	102 N/mm^2
Poisson's Ratio, ν_{12}	0.3
Poisson's Ratio, ν_{13}	0.2
Poisson's Ratio, ν_{23}	0.2

Table 2: Thermal properties of glulam beam. (ISO Standard No. 834)

Thermal	
Conductivity	Temp
0.12	20
0.12	50
0.12	100
0.12	150
0.12	200
0.15	250
0.15	300
0.15	400
0.07	500
0.07	600
0.09	700
0.09	800
0.35	900
1.5	1,200
Specific Heat	Temp
1.53	20
1.77	50
13.6	100
13.5	150
2.12	200
2	250
1.62	300
0.71	400
0.85	500
1	600
1	700
1.4	800
1.65	900
1.65	1,200

Table 3: Density of glulam beam with regard to temperature. (ISO Standard No. 834)

General, Density	
Density	Temp
650	20
585	50
585	100
585	200
544	250
446	300
307	400
224	500
166	600
154	700
60	800
43	900
34.4	1,200

Table 4: Elastic properties of glulam beam. (ISO Standard No. 834)

Mechanical, Elasticity, Elastic	
E1	14,300,000,000
E2	1,144,000,000
E3	715,000,000
Nu12	0.3
Nu13	0.2
Nu23	0.2
G12	1,020,000,000
G13	960,000,000
G23	102,000,000

Table 5: Plastic properties of glulam beam with regard to temperature. (ISO Standard No. 834)

Mechanical, Plasticity, Plastic		
Yield Stress	Plastic Strain	Temp
1,000	0	20
2,750,000	0.005	20
5,500,000	0.01	20
16,000,000	0.03	20
15,500,000	0.035	20
1,000	0	100
2,750,000	0.005	100
5,500,000	0.01	100
16,000,000	0.03	100
15,500,000	0.035	100
1,000	0	400
2,000,000	0.005	400
2,500,000	0.01	400
3,000,000	0.03	400
2,750,000	0.035	400
1,000	0	600
1,500,000	0.005	600
1,750,000	0.01	600
2,000,000	0.03	600
1,800,000	0.035	600
1,000	0	800
1,200,000	0.005	800
1,300,000	0.01	800
1,400,000	0.03	800
1,300,000	0.035	800
1,000	0	900
1,050,000	0.005	900
1,050,000	0.01	900
1,050,000	0.03	900
1,050,000	0.035	900
1,000	0	1,000
1,050,000	0.005	1,000
1,050,000	0.01	1,000
1,050,000	0.03	1,000
1,050,000	0.035	1,000

Table 6: Specification of S275 steel used in the research. (Andreolli – 2011)

Bolt Grade	Grade 4.6
Bolt Size	M20
S275 Steel Density	7850 kg/m^3
S275 Steel Modulus of Elasticity, E	210,000 N/mm^2
S275 Steel Poisson's Ratio, ν	0.30

Table 7: Thermal properties of S275 steel.

Thermal	
Conductivity	Temp
53.3	20
50.7	100
47.3	200
47.3	250
44	300
44	350
37.4	400
34	500
30.7	600
27.4	700
27.4	800
Specific Heat	Temp
439.8	20
487.6	100
529.8	200
547.3	250
564.7	300
583.7	350
605.9	400
666.5	500
760.2	600
1,008.2	700
803.3	800
650	900

Table 8: Plastic properties of S275 steel. (Andreolli – 2011)

Mechanical, Plasticity, Plastic	
Yield Stress	Plastic Strain
290,000,000	0
290,000,000	0.02
400,000,000	0.05
450,000,000	0.1
470,000,000	0.15
470,000,000	0.2
460,000,000	0.25
450,000,000	0.3

Tie constraint is used as the interaction between the cylindrical face of the bolt and timber hole as well as the steel plate. Incremental displacement load is used to simulate the tensile test. In the analyses with heat, the fire temperature curve is in accordance with ISO 834 as shown in Table 9 and Figure 2. The assembly of the model is shown in Figure 3.

Table 9: Fire temperature curve in accordance with ISO 834.

Time (min)	Temperature (ºC)	Time (min)	Temperature (ºC)	Time (min)	Temperature (ºC)
0	20	21	788.62	41	888.43
1	349.21	22	795.55	42	892.03
2	444.50	23	802.17	43	895.55
3	502.29	24	808.52	44	898.98
4	543.89	25	814.60	45	902.34
5	576.41	26	820.45	46	905.62
6	603.12	27	826.08	47	908.84
7	625.78	28	831.50	48	911.98
8	645.46	29	836.74	49	915.07
9	662.85	30	841.80	50	918.08
10	678.43	31	846.69	51	921.04
11	692.54	32	851.43	52	923.95
12	705.44	33	856.02	53	926.79
13	717.31	34	860.48	54	929.59
14	728.31	35	864.80	55	932.33
15	738.56	36	869.01	56	935.02
16	748.15	37	873.10	57	937.67
17	757.17	38	877.08	58	940.27
18	765.67	39	880.96	59	942.83
19	773.72	40	884.74	60	945.34
20	781.35				

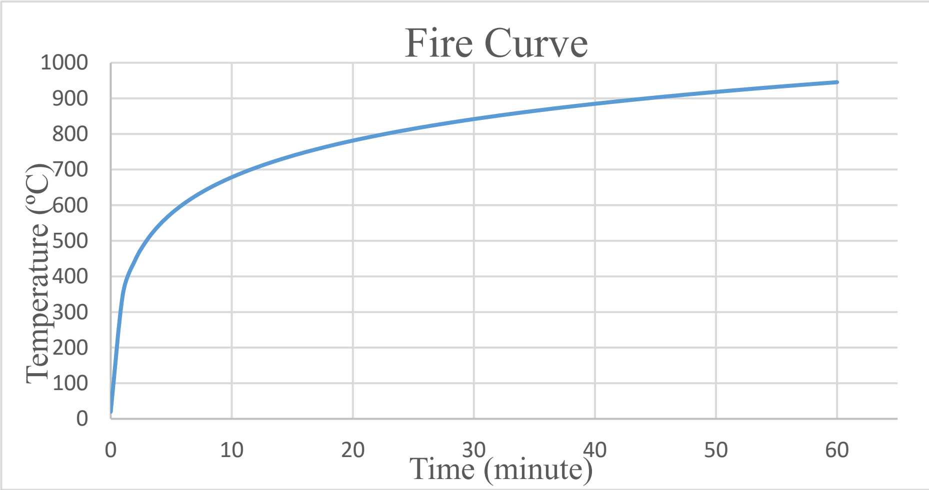

Figure 2 Fire temperature curve in accordance with ISO 834.

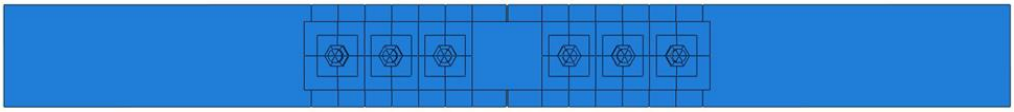

Figure 3 The FEM assembly of the glulam timber beam connection (Gečys- 2013)

DISCUSSION AND RESULTS

Incremental Load Without Heat

Figure 4 shows the comparison of the load-displacement curve of the timber beam connection between the experiment and FEM results. Figure 5 shows the point of failure of both experiment and FEM results. The results from finite element analysis are close to the experiment results. Both finite element analysis and experiment data show that the timber beam connection will fail at around 284 kN with a displacement of about 18.7 mm. The error percentage is less than 10%.

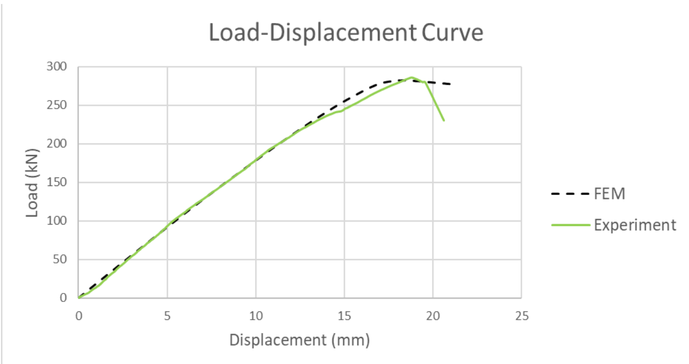

Figure 4 Load-displacement curve of timber beam connection subjected to tensile load.

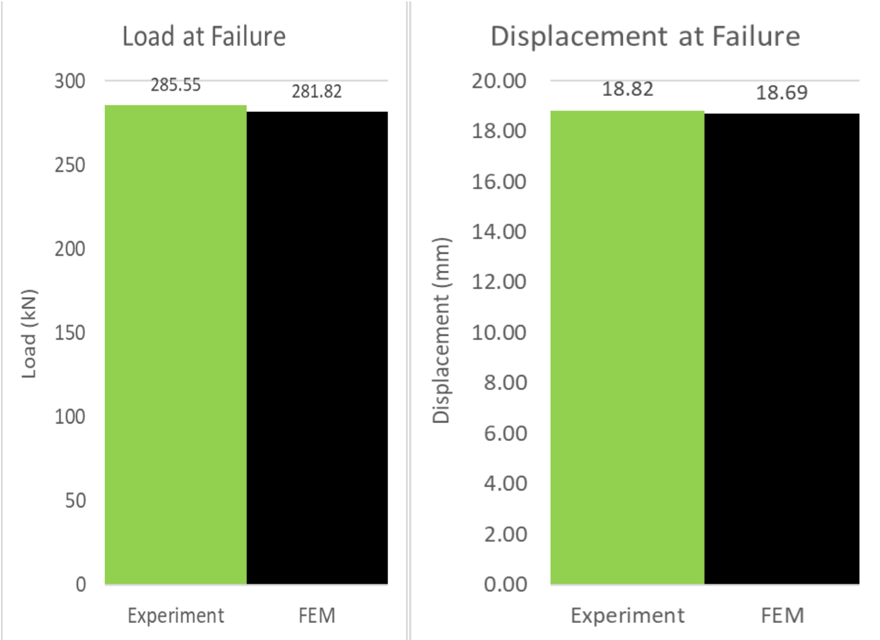

Figure 5: Comparison of load (left) and displacement (right) at failure between FEM and experiment results.

Constant Load With Fire

Table 10 shows the point of failure and differences between the experiment and FEM results. Figure 6 shows the displacement of the glulam beam subjected to 1.9 tons of constant load in fire. Figure 7 shows the FEM load-displacement curve. The difference of temperature at failure between finite element analysis and experimental results is small, indicating the model subjected to 1.9 tons of constant load will fail at around 903ºC. The difference of time to failure between finite element analysis and experimental results is bigger than the temperature difference, within the range of 10%. The difference could be caused by the inconsistent increment of temperature in the experiment.

Table 10: Comparison of temperature, time, and displacement at failure between FEM and experiment results.

	The temperature at Failure (ºC)	Time to Failure (min)	Displacement at Failure (mm)
Experiment	903.0	43.0	-
FEM	907.3	46.5	2.67
Difference (%)	0.5	8.1	-

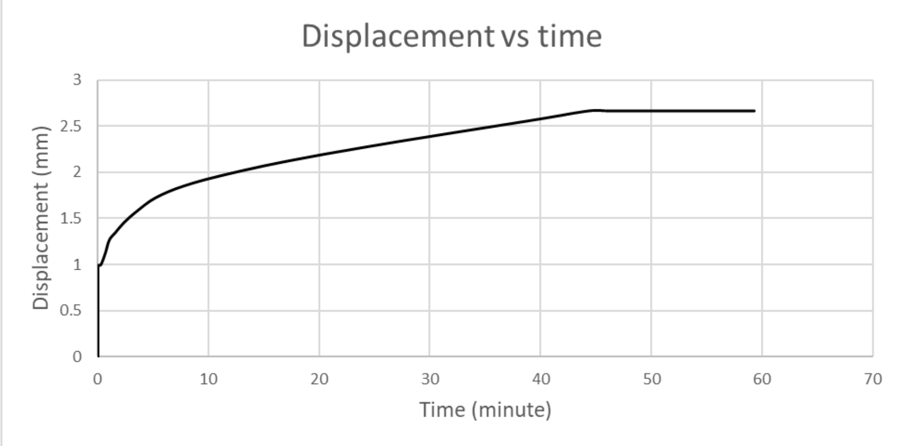

Figure 6: Displacement of glulam beam subjected to 1.9 tons of constant load until failure in the fire.

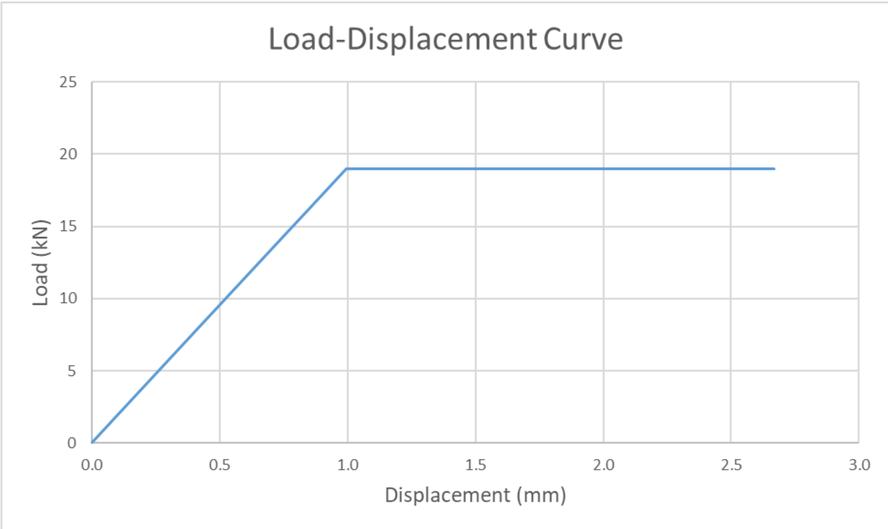

Figure 7: Load-displacement curve of timber beam connection subjected to 1.9 tons constant load and heat

Incremental Load With Heat

Figure 8 shows the load-displacement curve of the timber beam connection subjected to both tensile load and heat. Figure 9 shows the comparison of load-displacement curve between the experiment and FEM results. Table 11 shows the prediction for the point of failure of the model. The results show that the glulam beam connection is expected to fail much earlier when fire is involved. It is predicted to fail at 872℃, with a load of 21.7 kN and 8.2 mm displacement at 36.7 minutes.

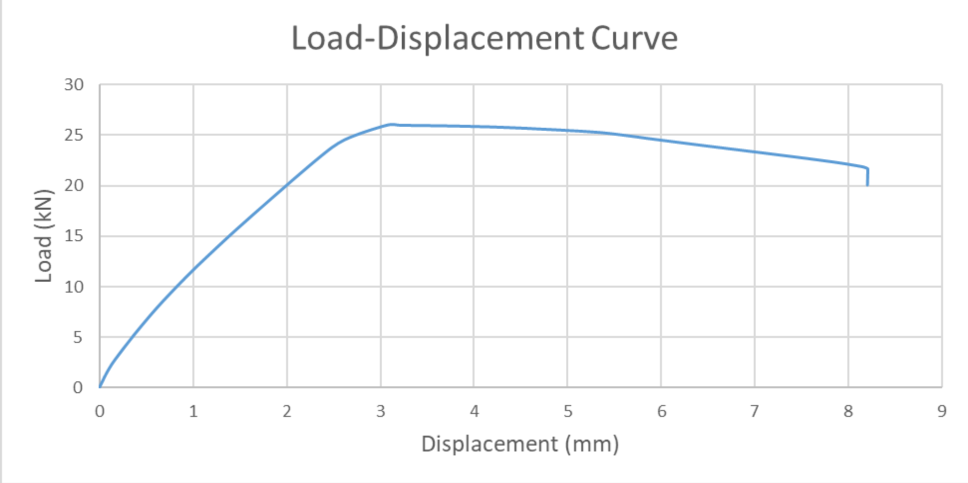

Figure 8: Load-displacement curve of timber beam connection subjected to tensile load and heat.

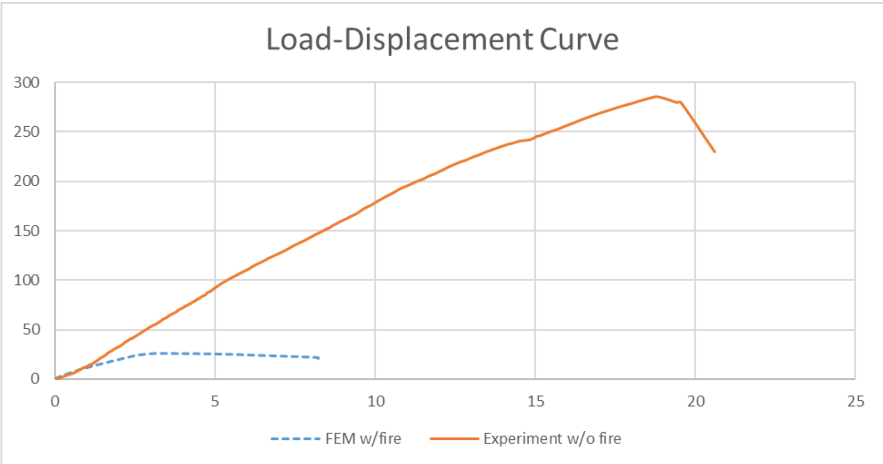

Figure 9: Comparison of load-displacement curve between FEM with fire and experiment without fire.

Table 11: Temperature, load, displacement, and time at failure.

Temperature at Failure (°C)	Load at Failure (kN)	Displacement at Failure (mm)	Time to Failure (minute)
872	21.7	8.2	36.7

CONCLUSION

The finite element analysis of outer plate bolted timber connection is comparable to the experimental works with a small variance of less than 2%. The tensile capacity of Mengkulang glulam timber from this research can be taken at 281 kN. Timber is an anisotropic material, that is, it has different properties in different directions, so the tensile capacity can only be applied if the orientation of the material is the same as in the model. The fibre direction of the glulam timber is along the beam axis. Timber is an anisotropic material, that is, it has different properties in different directions. The tensile capacity of timber is higher along its grain than across it.

From the finite element analysis for the model subjected to constant load and fire, the temperature at failure has a very small difference of 0.5%. However, the time taken for it to fail has a difference of 8.1%. This may be caused by the inconsistent firing of the chamber from the experiment. The data for the actual displacement from the experiment is not available since there is a limitation to the test equipment, making it impossible to install LVDT sensor.

The prediction for heat and tensile load shows that it is significantly weaker when compared to the model without heat. Fire will weaken the cellulose fibre structure found in timber; therefore, it will not be able to withstand the same level of stress and strain as the model without heat. The results obtained from the model with fire can be used to predict the behaviour of bolted timber connections when exposed to heat or fire. In case of fire, the steel plate and bolts are more likely able to withstand the heat as the temperature will be lower than the melting point of steel.

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