STSM Report – Uncertainty Quantification arising from Timber Fire Tests

STSM Performed by Alastair Bartlett at SP, Borås

Summary

- The purpose of this STSM is to explore sources of uncertainty arising from timber fire tests. As a natural material, timber is subject to significant uncertainty, due to natural variations in material properties such as density, strength, and grain direction within the material.

- The STSM and its goals were discussed with Simon Wynistorf at ETH Zurich, whose PhD topic is on reliability based design of timber in fire.

- During the STSM, key parameters which could be causes of uncertainty were identified and explored. A detailed literature study was performed to determine typical statistical values for the key variables, namely coefficient of variation. Discussion of each parameter and its likely effects on modelling and/or testing is provided, showing the interdependence of many of the parameters explored.

- Additionally, test data from experiments at both the University of Edinburgh and SP were used to calculate coefficients of variation of additional parameters.

- The data collected will be used to produce a simple model of timber using SP's Uncertainty Quantification methodology, to determine the effects of uncertainty of input parameters on the uncertainty on the model results. An abstract is being prepared for submission to the 14th International Probabilistic Workshop, with the aim of producing a collaborative paper on the topic.

- Future work to expand the database of uncertainty values is suggested within the report.

- The confirmation from the host is attached in Appendix 1, and the STSM report in Appendix 2.

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Appendix 1: Confirmation from host

Alastair Bartlett short term scientific mission COST FP 1404 – confirmation letter

In the name of the host institution, SP Technical Research Institute of Sweden department of fire research, I the undersigned Dr David Lange confirm the successful completion of the STSM by Mr Alastair Bartlett within the scope of COST action FP1404.

The STSM took place between the 22nd and the 25th of February 2016.

The purpose of the STSM was to begin to evaluate the uncertainties arising in fire testing of timber structures. The outcome of the STSM is currently being compiled in a report to be submitted to the COST action.

Yours sincerely,

SP Technical Research Institute of Sweden
Fire Research - Fire Resistance

David Lange

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Appendix 2: STSM Report

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1. Introduction

Without considering the effects of uncertainties in material and system properties, deterministic models can produce seemingly random behaviour, with small variations in input potentially having significant effects on the output(s). As many numerical and analytical models are often performed with minimal consideration of these uncertainties, designs risk being based on potentially inaccurate information. When modelling is performed in multiple stages using different tools, there is the further risk of uncontrolled propagation of these uncertainties.

Uncertainty Quantification (UQ) is the science of quantitatively characterising and reducing uncertainties in models and experiments. It aims to predict the relative probability of certain outcomes if some input parameters are unknown. Deterministic Sampling (DS) [1] is a relatively new method used for Uncertainty Quantification (UQ), as a more efficient alternative to brute-force Monte Carlo analysis. DS replaces a continuous probability density function with a set of discrete deterministic samples with the same statistical moments. Numerical and analytical models can thus be performed with uncertainties associated with a number of input parameters regarding thermal and mechanical exposure.

Numerous parameters which can affect the thermal and mechanical exposure were discussed, and are listed in Tables 1 and 2 for standard furnace tests as well as radiant panel tests and similar. Different numbers of parameters will require consideration depending on the analysis method used, or in modelling, depending on how detailed the model is. For each of these parameters, data from literature, as well as testing at both SP and the University of Edinburgh was used to calculated variability values, expressed dimensionlessly as a coefficient of variation (CoV). These values can then be used with DS to place bounds on the uncertainty of model outputs or test results. Due to SP's interests in UQ and large experience with furnace testing, a collaboration with SP was an ideal vehicle to pursue this area of research with a focus on timber elements and issues specific to this material.

2. Thermal Exposure

Table 1: Parameters Affecting Thermal Exposure

#	Furnace	Radiant Panel/FPA	Units		Coefficient of Variation Values	
1	Furnace temperature	Incident heat flux	K	kW/m^2	See Figure 1	0.0008-0.0223[1] (H-TRIS) 0.0863[1] (radiant panel) 0.0072-0.0192[1] (FPA)
2	Airflow velocity		m/s			
3	Convective heat transfer coefficient		W/m^{2}K			
4	Furnace geometry		-			
5	Emissivity of test sample*		-			
6	Heat losses*		kW/m^2			
7	Thermal conductivity of furnace walls		W/mK			
8	Specific heat capacity of furnace walls		J/kgK			
9	Density of furnace walls		kg/m^3			
10	Char crack width*		mm			
11	Char crack spacing*		mm			
12	Char oxidation rate*		mm/min			
13	Char density				0.0600[2] (redwood) 0.1143[2] (southern pine) 0.0894[2] (red oak) 0.0704[2] (basswood)	
14	Corner rounding		mm			
15	Thermal conductivity of test sample*		W/mK			
16	Specific heat capacity of test sample*		J/kgK			
17	Local density variations in test sample*		kg/m^3		See Table 2	
18	Heat of combustion		MJ/kg		0.1170[2] (redwood) 0.1530[2] (southern pine) 0.0970[2] (red oak) 0.0664[2] (basswood)	
19	Oxygen concentration		%			

*temperature-dependent
[1]Testing at University of Edinburgh
[2]Reference [2]

1a. Furnace Temperature

BS EN 1363-1:2012 [3] states that “there are many factors which can affect the result of a fire resistance test. Those concerned with the variability of the specimen including its materials, manufacture and installation are not related to the uncertainty of measurement. Of the remainder, some, such as the different thermal dose provided by different furnaces, are much more significant than others such as the accuracy of calibration of the data logging system. Because of the very labour intensive nature of the test, many of the factors that have a bearing on the result are operator-dependent. The training, experience and attitude of the operator is thus crucial to eliminate such variables which can significantly affect the degree of uncertainty of measurement. Unfortunately, it is not possible to numerically quantify these factors and therefore any attempt to determine uncertainty of measurement that does not take into account operator-dependent variables is of limited value.” Therefore in the following analysis, operator-dependent variables will be taken into account as much as possible.

A key variable which depends on operator experience is the measured temperature inside the furnace, which is defined as the average temperature of a number of plate thermometers. The temperature is varied by controlling the rate of gas flow from the burners, and it is up to the operator to adjust this as necessary to follow standard heating curves. Figure 1 shows temperature-time data for two furnace tests carried out under the ISO-834 temperature-time curve. The start of test furnace is subject to large uncertainties in temperature, as the operator has to make adjustments to follow the rapid heating of the curve. Due to the slow response time of plate thermometers, it is very difficult to follow exactly the heating curve in this phase. The portion of a test prior to formation of a char layer has previously been found to be the part in which the heating regime plays the most significant role [4], and so uncertainties in the thermal exposure prior to the formation of a char layer can significantly affect the final char depth. It can be seen from Figure 1 that the uncertainties for plate thermometers and thermocouples are quite similar, with the uncertainty for a thermocouple perhaps being slightly higher. It should be considered however, that since thermocouples have lower thermal mass and thus a faster thermal response, they will capture variations in temperature better than a plate thermometer, as it will capture convective effects and due its small size be less affected by radiation, whereas a plate thermometer will give a more stable temperature.

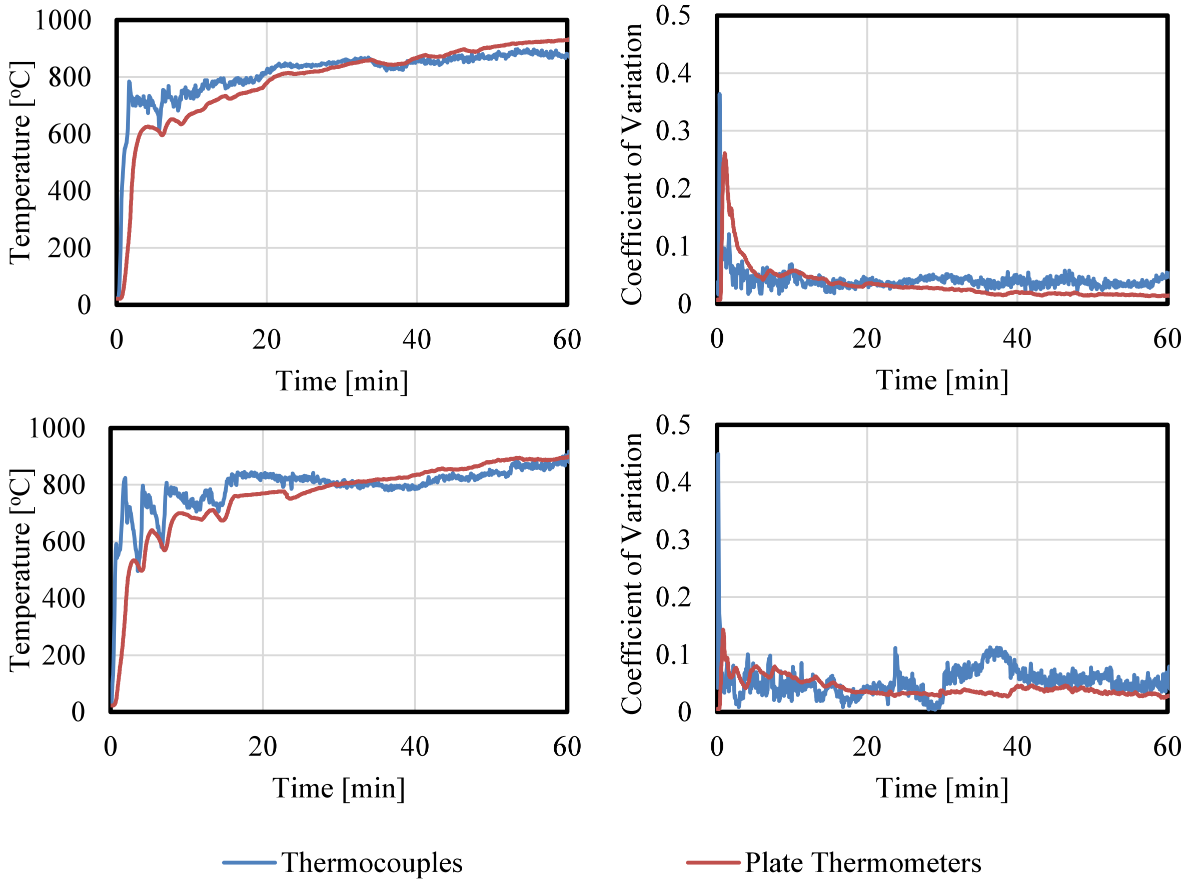

Figure 1: Temperature data for two furnace tests as measured by thermocouples and plate thermometers, showing coefficients of variation for each

1b. Incident Heat Flux

Incident heat flux for testing methods using radiant panels such as H-TRIS [5], or standard testing equipment such as the cone calorimeter or the Fire Propagation Apparatus (FPA) is typically measured using a water-cooled Schmidt Boelter heat flux gauge. From tests and calibration performed at the University of Edinburgh, uncertainty can easily be quantified on these measurements. The coefficient of variation was found to be between 0.0008 and 0.0223 for H-TRIS, around 0.0863 for a horizontally orientated radiant panel (in which convection will play a greater role due to the hot gases from the panel rising, thus increasing uncertainty as discussed above), and for the infrared lamps of the FPA, varying linearly with heat flux from around 0.0072 at $35kW/m^2$ to around 0.0192 at $14kW/m^2$. Part of this variability will come from the heat flux gauges themselves, and some from the apparatus. The uncertainty arising from the heat flux gauge can be easily quantified with data from heat flux gauge calibrations.

2. Airflow Velocity & 3. Convective Heat Transfer Coefficient

Airflow velocity is a vital parameter for calculation of the convective heat transfer, which in turn is key to understanding heat transfer to a test sample. In a furnace, airflow is very turbulent, and thus it is very difficult to obtain estimates of airflow velocity, which will vary significantly through the space of the furnace. Consequently, the convective heat transfer coefficient will also vary spatially within the furnace, resulting in temporal and spatial distribution in convective heating and/or cooling, both to the plate thermometers, and to the test sample. Häggkvist et al. [6] present a method for calculating incident heat radiation to the sample based on plate thermometer measurements, and acknowledge the uncertainties caused by the airflow conditions. Whilst they were able to create a model calculating the incident *radiative* heat flux to a good degree of accuracy, the *convective* heat exchange may dominate in some furnace tests, remains a significant source of uncertainty. This is also a very difficult parameter to quantify; to do so would require numerous measurements of airflow velocity inside a furnace during a test, and assessing the variation between these values. The effect of convective vs. radiative heat transfer has been identified in discussions as a major source of uncertainty in furnace testing. As mentioned above, for the same plate thermometer readings, differences in convective heating may result in significantly different heat exposure to the test specimen. Significant further work is needed to measure airflow conditions inside a furnace and to place bounds on their variability.

In radiant panel tests, such as H-TRIS, the dominant mode of heat transfer is radiation, with very low coefficients of variation as shown in Table 1. As such, the airflow velocity only effects the convective heat losses from the sample, and much of this uncertainty is mitigated. However, the convective heat transfer from the sample still requires consideration to accurately estimate the net heat exposure to the sample. Empirical expressions for convective heat transfer from a flat surface are available in [7], however these are still subject to uncertainties such as uniformity of the gas flow which are difficult to quantify, and further work is needed in this area.

4-9. Heat Losses and Furnace Properties

One factor affecting this initial heating phase is the furnace geometry and thermal inertia. This will govern the rate of heat transfer into the furnace walls, and affect how much of the heat put into the furnace from the burners acts to increase the furnace temperatures. Whilst these properties are implicitly included in the furnace temperature measurements, and for the majority of applications furnace properties may not be needed, they may require consideration in more detailed models, and should also be considered as a potential method to reduce variability between furnaces, as currently the only requirement for furnace walls is a density less than 1000kg/m^3 [3]. These properties are thus crucial to consider when modelling heat transfer to the sample.

10-14. Char Characteristics

Several factors relating to the char properties are included in Table 1. Again, for many analyses explicit consideration may not be necessary, but will be necessary for thermal modelling. Whilst data for char density variability are available for several species [2], data for other properties such as char crack depth, width and spacing are not widely available. These can be easily obtained after large-scale testing either by direct measurement or image analysis, and it is recommended that values be obtained from future testing to quantify both typical values and expected variation.

15-18. Thermal Properties of Test Sample

Thermal properties of the test sample are vital for any thermal modelling. These properties are well known to vary as a function of temperature [8, 9], and a wide range are available in the literature. Similarly to mechanical properties, discussed later in this report, understanding which thermal properties to use in which scenarios is vital to reducing the uncertainty in thermal modelling.

19. Oxygen Concentration in Furnace

Oxygen concentration has been shown to have a significant effect on charring behaviour and thus thermal response [10-14]. Quantification of the variability is thus important to understand its influence on thermal response of the timber specimen. Babrauskas [13] found that in furnace tests, typical oxygen concentration varies from 4% to 10%, and that charring rate at 4% O_2 is around 33% lower than at 10% O_2. Variability during a test and also between different furnaces should be explored to place bounds on this parameter.

3. Mechanical Exposure

Table 2: Parameters Affecting Mechanical Exposure

#	Parameter	Units	Coefficient of Variation Values
1	Applied load	kN	
2	Support conditions		
3	Loading positions	m	
4	Loading angle	°	
5	Imperfections	%, mm	
6	Strength*	MPa	0.171[1] (Class 302-24, 4-ply) 0.254[1] (Class L1, 4-ply) 0.190[1] (Class 302-24, 8-ply) 0.143[1] (Class L1, 8-ply) 0.185[1] (Class 302-24, 10-ply) 0.168[1] (Class L1, 10-ply) 0.1232[2] (CLT, 5-ply) 0.220[3] (Glu-lam, 5-ply, 130x420mm) 0.279[3] (Glu-lam, 5-ply, 92x400mm) 0.139[3] (Glu-lam, 5-ply, 54x380mm)
7	Elastic Modulus*	GPa	0.5580[1] (Class 301A, random) 0.3778[1] (Class L1, random) 0.3845[1] (Class L2, random) 0.8877[1] (Class 301A, weak) 0.4559[1] (Class L1, weak) 0.5040[1] (Class L2, weak) 0.0576[3] (CLT, 3- and 5-ply) 0.0293[4] 0.0082-0.0114[5] (CLT, within 1 sample) 0.0527[2] (CLT, 5-ply) 0.0829[6] (Glu-lam)
8	Shear Modulus*	GPa	0.1165[6] (Glu-lam)
9	Finger joint strength*	MPa	
10	Finger joint positions	m	
11	Grain direction	°	SD: 0.366°-1.54°
12	Bulk Density*	kg/m^3	0.0247[4] (5400mm x 265mm x 150mm) 0.0169[5] (2000mm x 300mm x 100mm beams) 0.0337-0.384[5] (300mm x 150mm x120mm) 0.05[7] (unspecified dimensions)
13	Local density variations in test sample*	kg/m^3	0.0466[4] (50mm x 265mm x 250mm) 0.0434[5] (85mm x 85mm x 100mm) 0.0806[5] (40mm x 40mm x 30mm)
14	Moisture Content*	%	0.0398[4] 0.0345[5] 0.12[7]
15	Adhesive strength*	MPa	

*Temperature-dependent

[1]Reference [15]: “Random” samples taken from any location in a beam, “weak” samples representing minimum quality timber. Strength values modulus of rupture from ambient temperature flexural tests.

[2]Reference [16]: Strength and MoE values from ambient temperature flexural tests.

[3]Reference [17]

[4]Testing at SP

[5]Testing at University of Edinburgh

[6]Reference [18]

[7]Reference [19]

1-4. Loading Conditions

BS EN 1363-1:2012 specifies that the load must be maintained to ±5% of its specified value.

Errors in the loading positions will affect the applied bending moment. Whilst such errors are likely to be small, actual loading positions should be measured to place bounds on the uncertainty for this parameter.

Errors in the loading angle can produce unwanted torsion or axial loading effects, which will affect the failure criteria of the member, and in the case of torsion in a furnace, may transfer loads into additional members being tested in the same furnace.

5. Imperfections

Imperfections present in a specimen can affect the local density, as well as the local thermal and mechanical properties, which have each been discussed elsewhere within this report. The effects of imperfections are captured globally with structural testing, but quantifying the amount of imperfections (such as knots or voids) in a sample may help in understanding the variations in density and mechanical properties within a sample. This is achieved to some extent through grading, but as this is a visual process is somewhat subjective.

6-8. Strength, Elastic Modulus, and Shear Modulus

The uncertainties in the ambient temperature strength of a test specimen are important to consider for mechanical analyses, and for understanding the expected range of mechanical properties for a given element. Bender et al. provide statistical analysis on a selection of glu-lam beams, with elastic moduli measured by flatwise vibration, providing separate analyses for three different timber strength classes: 302-24, L1, and L2, and for “random” and “weak” samples, representing near-minimum quality specimens. Bender et al. fit Weibull distributions to each of these six data sets, from which the coefficients of variation can be calculated. From bending tests, coefficients of variation for modulus of rupture were provided. These data are available in Table 2.

These data gave very high CoV values when compared to the other data in the table. Typical CoV values are around 0.1 to 0.3 for bending strength, and 0.03 to 0.06 for modulus of elasticity, discounting the values of Bender et al. It is noteworthy that the uncertainty is around an order of magnitude higher for bending strength than it is for elastic modulus.

Only one source was found for shear modulus, Hansen and Oleson [18]. Their data gives a value of 0.1165, compared to 0.0829 for elastic modulus.

The strength reductions at elevated temperature are also subject to much uncertainty, as illustrated in the wide range of temperature-dependent elastic moduli shown in Figure 2 [20-31]. This was identified as a key area of uncertainty for model inputs in the workshop on numerical simulation of timber in fire in Ljubljana in January. From the values in Figure 2, the coefficient of variation in relative elastic modulus at 100°C is 0.2826, which is very high. Understanding which mechanical reductions to use in which scenarios is a vital first step to reducing this uncertainty.

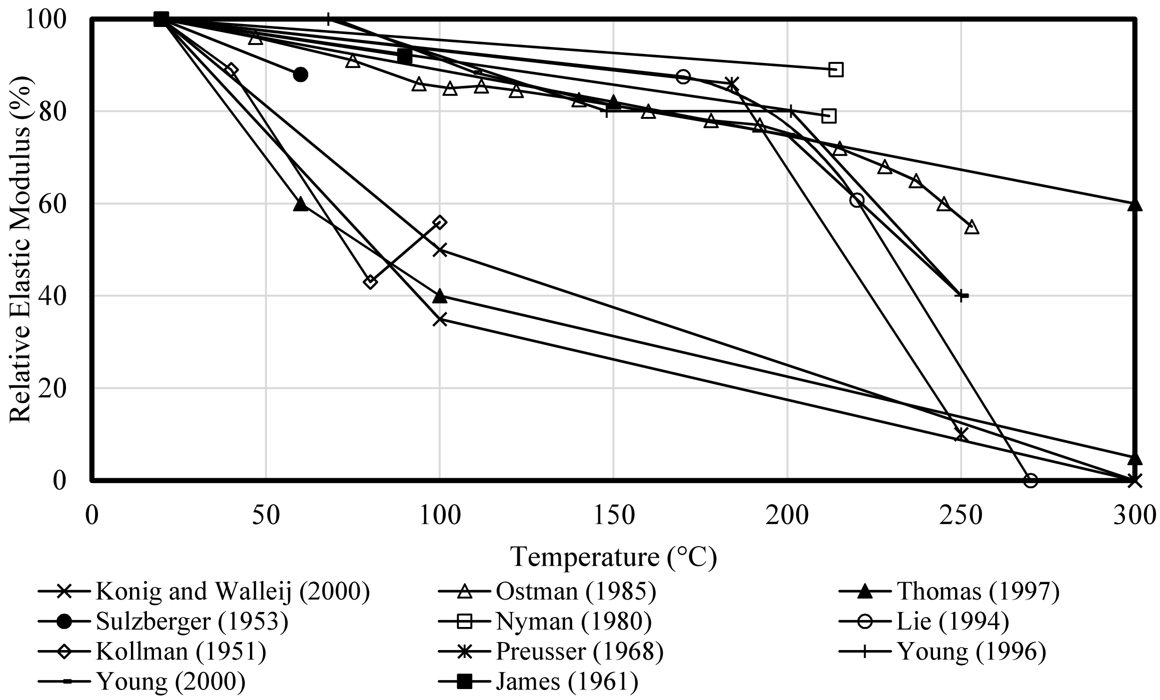

Figure 2: Temperature-dependent elastic moduli from different researchers

9-10. Finger Joints

As well as the strength of the timber itself, the strength, location and number of finger joints is important to consider, as these will have different properties to the timber itself. Numerous tests on finger joints should be undertaken to obtain values for the uncertainty in their strength and failure modes.

11. Grain Direction

Grain direction has a significant effect on structural properties; with elastic modulus parallel to the grain approximately thirty times that perpendicular [32], thus the grain angle will influence the material properties. In a timber sample, there will be slight variations in the grain angle such that not all grains will run exactly parallel, either to each other or to the tensile or compressive stresses. This is illustrated in Figure 3. Whilst from visual observations alone this variation appears small, it will account for some of the variability in mechanical properties, and variation should be quantified. Performing some basic angle measurements gives a standard deviation of 0.366° and 1.54° for the samples shown in Figure 3. (Calculating CoV for this parameter is meaningless, as it is entirely dependent on where the angle is measured from; with an average angle of 0°, this would give a CoV of ∞.)

Figure 3: Grain direction variation in CLT samples with low (left) and high (right) variability

12-13: Density

Due to the manner in which wood grows, at varying rates depending on time of the year amongst other variables, density will vary significantly within timber samples [11, 33-35]. On small scales, density variation will be very large, with variations being "averaged out" over larger samples. For the values referenced in Table 2, the coefficient of variation is plotted against sample volume in Figure 4. This provides a useful starting point for estimating the density variability when modelling at different scales. Density is known to effect charring rate [2, 4, 11, 29, 35-55] and mechanical properties [42], and thus uncertainty in the sample density can have an effect on the uncertainty in charring rate and structural analyses.

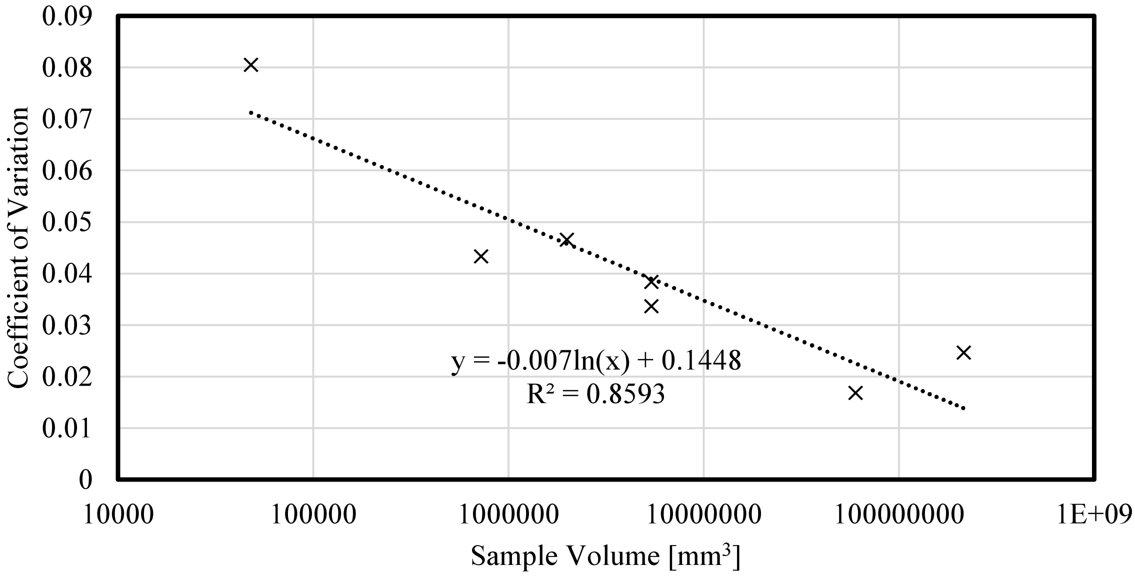

Figure 4: Coefficient of Variation of density as a function of sample size

14. Moisture Content

Moisture content affects the mechanical properties of timber [56]. Values from the University of Edinburgh and SP of moisture content at various places within a sample found coefficients of variation from around 0.034 to 0.040, showing good agreement between the two laboratories for different samples. Frangi and Fontana [19] found significantly higher variation of 0.12 for glued-laminated timber beams, although these were taken from a wider range of different samples.

15. Adhesive Strength

The adhesive properties, particularly at elevated temperature, have a significant effect on the failure mechanism of a timber sample [57], and the effects of different adhesives are currently not fully understood. This makes estimation of the uncertainty associated with adhesive bond strength at elevated temperatures impossible to estimate. In order to understand this, testing of adhesive properties at fire temperatures should be prioritised in order to be able to better predict a wider range of failure modes. Without detailed knowledge of temperature-dependent adhesive properties, certain failure modes (such as rolling shear) may go unpredicted, resulting in significant errors in predicted failure load.

4. Conclusions and Future Work

The report has identified and described 34 parameters whose uncertainties can influence the results of tests or models of timber elements subjected to fire. Where available, data has been analysed to provide coefficients of variation for these parameters. Where the information is not available, the approach should be the same – if a parameter is likely to influence the outputs, then values should be recorded during tests and the data analysed to find coefficients of variation.

From coefficients of variation, the standard deviation can be calculated, and then error bounds placed on each parameter according to the confidence limits required (e.g. 95% within 2 standard deviations from the mean).

A model based on the data collected in this study is being prepared in collaboration between the University of Edinburgh and SP based on SP's uncertainty quantification method, which will be the subject of a future joint publication.

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