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HEAT INDUCED DELAMINATION OF LAMINATED TIMBER

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Master thesis submitted in the Erasmus Mundus Study Programme

International Master of Science in Fire Safety Engineering

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To my Parents.

मेरा आमा बुवाको निम्ति ॥

Declaration

This thesis is submitted in partial fulfilment of the requirements for the degree of The International Master of Science in Fire Safety Engineering (IMFSE). This thesis has never been submitted for any degree or examination to any other University/programme. The author(s) declare(s) that this thesis is original work except where stated. This declaration constitutes an assertion that full and accurate references and citations have been included for all material, directly included and indirectly contributing to the thesis. The author(s) gives (give) permission to make this master thesis available for consultation and to copy parts of this master thesis for personal use. In the case of any other use, the limitations of the copyright have to be respected, in particular with regard to the obligation to state expressly the source when quoting results from this master thesis. The thesis supervisor must be informed when data or results are used.

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Abstract

The thesis studied the delamination in laminated timber structures at elevated temperature with an aim to investigate the influence of degradation of adhesive properties on the reduction of the strength of the glued timber joints at elevated temperature. Bond strength test of single lap-joint timber specimens bonded with polyurethane adhesive were performed at elevated temperature under varied loading percentage of the average bond strength capacity at ambient temperature along with the Dynamic Mechanical Thermal Analysis of the polyurethane adhesive. Clear delamination failure of the single lap-joint timber specimen were observed at elevated temperature for higher loading percentage of the average bond strength capacity while at lower loading percentage diverse results were obtained including delamination, failure at timber and no failure of the single lap-joint over the entire duration of heating until the temperature reached a steady state. Similarly, Dynamic Mechanical Thermal Analysis of the adhesive showed wide range of glass transition temperature. The work carried out helped in quantifying the range of failure temperature of the single lap-joint timber at various loading percentages of the bond strength capacity. The thesis also signifies the occurrence of delamination and degradation of adhesive strength at elevated temperature in laminated timber and the need for it to be accounted for fire safety design of laminated timber structures.

सारांश (Abstract in Nepali)

उच्च तापमानमा टाँसिने विशेषताहरुको क्षतिको कारण हुने प्रभावले टाँसिएका काठका जोइन्टहरुको क्षमतामा आउने न्यूनीकरणको अनुसन्धान गर्ने उद्देश्यका साथ यो शोधपत्रले उच्च तापमान लेमिनेटेड काठ संरचनाहरुमा हुने डिलेमिनेशनको अध्ययन गरेको थियो । वातावरणको तापमानमा औसत टाँसिने शक्तिको क्षमता विभिन्न भार प्रतिशत र पोलिउरेथेन एडेसिभको डाइनामिक मेकानिकल थर्मल विश्लेषण अन्तर्गत उच्च तापमानमा पोलिउरेथेन एडिसिभले जोडिएका एकल काठ ल्याप-जोइन्टहरुको नमूनाहरुमा गरिएको टाँसिने क्षमताको परीक्षण गरिएको थियो । औसत टाँसिने शक्तिको क्षमताको उच्च भार प्रतिशतका लागि उच्च तापमानमा गरिएको एकल काठ ल्याप-जोइन्टहरुका नमूनाहरुमा स्पष्ट डिलेमिनेशन विफलता अवलोकन गरिएको थियो भने कम भार प्रतिशतमा विभिन्न प्रतिफलहरु आएका थिए जसमा डिलेमिनेशन, काठमा विफलता र तापमान एक स्थिर विन्दूमा नपुग्दासम्म तताउँदाको सम्पूर्ण समयमा एकल ल्याप-जोइन्टमा कुनै विफलता नदेखिएका जसता प्रतिफलहरु समावेश छन् । त्यसैगरी, एडिसिभको डाइनामिक मेकानिकल थर्मल विश्लेषणले विभिन्न स्तरको ग्लास ट्रान्जिसन तापमान प्रस्तुत गरेको थियो । टाँसिने शक्तिको क्षमताका विभिन्न भार प्रतिशतमा एकल ल्याप-जोइन्टका काठको विफलताको तापमानको दायरालाई परिमाणित गर्न यस कार्य सहयोग सिद्ध भएको थियो । यस शोधपत्रले उच्च तापमानमा लेमिनेटेड काठमा हुने डिलेमिनेशन हुने सम्भावनालाई पनि महत्व दिएको छ र लेमिनेटेड काठका संरचनाहरुको सुरक्षित डिजाइनका लागि यी कुरा उत्तरदायी हुन आवश्यक रहेको छ ।

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Introduction

1.1 Background

Wood is an excellent building material. It is light weight, renewable, easily available and easy in fabrication and has a relatively high strength to weight ratio [3], making it a competitive modern building construction material. However, being a naturally produced material, wood may have significant variation in its properties. It is vulnerable to deterioration caused by decay, insects and fungal attack, swelling and shrinkage with changing atmospheric humidity and its strength in the perpendicular direction to the grain is low, compared to the parallel direction, which sometimes results in situation where shear resistance parallel to the grain becomes critical [44]. And the presence of knots and splits reduces the strength and stiffness of the timber members considerably and deteriorates the load-bearing capacity of the structure over time [42].

Given the aforementioned deficiencies and the lesser availability of larger wood for construction led to the development of engineered wood products (EWP). These are wood-based products manufactured by bonding together wood strands, fibers and veneers into new lumber, panel and other construction products, which have relatively high uniformity and well-defined performance properties [10]. Laminated timbers are the excellent examples of engineered wood products, which are manufactured by gluing together smaller lamella of timber.

Glued laminated timber (Glulam) and cross laminated timber (CLT) are two predominant types of laminated timber products. Glulam is manufactured by gluing various layers of timber lamellae longitudinally with the grains running along the length of the lamellae, whereas CLT is manufactured by gluing different layers of orthogonally oriented sawn timber lamellae against adjacent layers. Softwood is generally used for the construction of laminated timber products and among the various types of glues used for the bonding of the lamella two adhesives, namely melamine urea formaldehyde (MUF) and polyurethane (PU), are being used in the recent times extensively [20]. The gluing of smaller layers into one massive product means that the defects of the single timber layer (e.g. knots,

shrinkage, swelling, wrapping) become negligible given the combined performance of the multiple smaller layers of timber. Moreover, these elements provide higher in-plane and out-of-plane strength and stiffness properties and improved dimensional stabilities allowing for prefabrication of floor slabs, walls and other load-bearing structural systems [4]. These advantages have made CLT a very popular construction material around the world.

According to the United Nations [38], 66% of the world population will be living in urban space by the end of 2050. Hence, with a growing environmental awareness and housing demand for the world population, a need for more sustainable construction material has been realized in recent years more than ever. And wood for its renewable properties can be considered the material that could fulfill the criteria of a green construction material that could meet the demand of building sustainable houses for the future world population and laminated timber products have a major role to play in that [24].

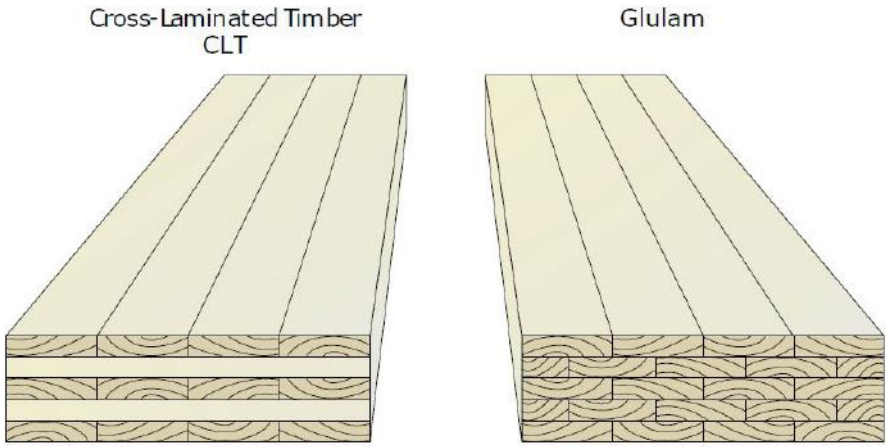


Figure 1.1: Example of Glulam and CLT [4]

Despite the apparent popularity of timber, fire safety considerations are a major concern for laminated timber products. Together with the combustibility of wood, delamination of the lamellae and degradation of the adhesive are another major issues with laminated timber products. Although there is fair knowledge on the interaction of timber in fire in general, the understanding of the behavior of laminated timber products when exposed to fire is very rare. And for these products to be used as the solution for sustainable construction, it is very important to have a significant knowledge on how would these products interact with fire.

1.2 Research Objectives

The current knowledge on the performance of laminated timber is comparatively better at ambient temperature than at elevated temperature. Recent research [39] on the failure mode change of bonded timber joints at elevated temperature investigated the potential shift in the failure mode of adhesively bonded lap joint from timber failure to bond line failure at elevated temperature. The work described herein aims at quantifying the temperature range at which laminated lap jointed timber fail in varied mechanical loading conditions. Single lap shear samples will be used to conduct the tests for this research, with the samples being loaded to different stress levels since in reality the structural elements have certain stressed induced on them during any case of fire. The research will be performed within two stages;

i Study the strength of lap jointed timber and its deterioration at elevated temperature

ii Study the degradation of mechanical properties of adhesive at higher temperature

The results of both the studies will be compared to investigate the correlation between degradation of the mechanical properties of the adhesive at higher temperature have a direct influence on the deterioration of the strength of laminated timber joint at elevated temperature.

The objectives of the work presented herein are;

- Study the reduction of strength of adhesively joined laminated timbers at elevated temperature.
- Study deterioration of mechanical properties of glue at elevated temperature.
- Examine the influence of degradation of glue properties on the reduction of strength of the glued timber joints at elevated temperature.

1.3 Outline of Chapters

This thesis report is comprised of five chapters, the contains of which are described here in brief.

Chapter 1 Introduction
A background on timber as a building material and the advantages of engineered wood products including laminated timbers is presented. The research objectives are formulated followed by the relevant literature reviews necessary to have a better understanding of the problem and the solutions required. The literature reviews includes the understanding of the structural performance of laminated timber products in general context and under fire scenario, along with the understanding of the behavior of the single lap

joint and the variation of the properties of the adhesive used at elevated temperature.

Chapter 2 Methodology
As this is a research based thesis, variety of experiments are required to be conducted. This chapter presents the procedure followed in the preparation of the samples and the types and procedures of the various tests need to be conducted to achieve the research objectives.

Chapter 3 Results
The results of the the different experiments conducted are presented in this chapter.

Chapter 4 Discussions and Analysis
This chapter consist of the analysis of the results obtained and the discussion made on them along with the reasoning behind the nature of the results.

Chapter 5 Summary and Conclusion
The summary of the thesis is presented here with the conclusions drawn from the results and the discussions. And recommendation for further research in the field were drawn.

1.4 Literature Review

1.4.1 Structural Performance of Laminated Timber

The strength of solid timber may vary significantly depending upon various factors acting independently or together with others, affecting the strength and the workability adversely, the factors that affect the mechanical strength of timber are moisture content, density, slope of grain and defects in timber [29].

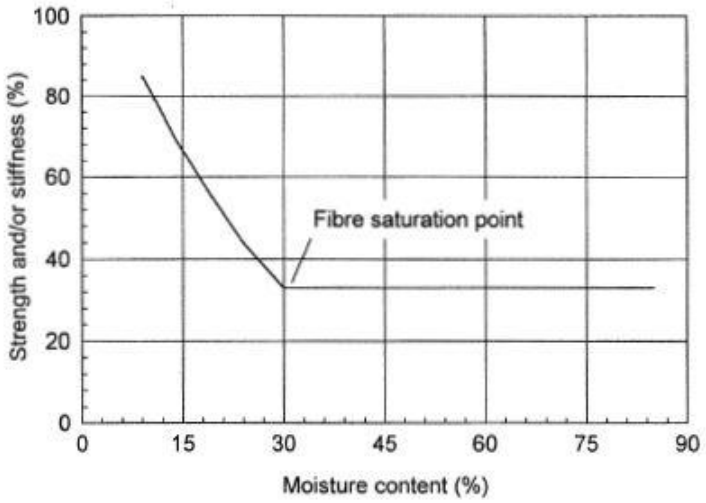


Figure 1.2: Relationship between strength/stiffness and moisture content of timber [29]

Besides the defects, production of sawn lumbers are limited in cross-sectional dimensions and lengths by the size of the tree as well, thus for larger span and loads the use of sawn lumber becomes unsuitable and structural laminated timber can be used in such circumstances. In the production of laminated timber, laminating stocks of higher quality can be used by excluding the growth characteristics and by dispersing the strength reducing defects like knots throughout the member, this provides excellent structural properties of laminated timber against sawn lumber. Since the different laminating timber blocks have different modulus values,

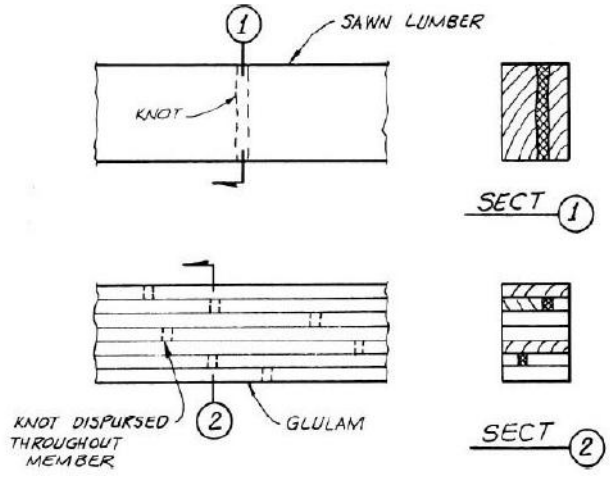


Figure 1.3: Dispersion of growth defects in glulam [2]

laminated timber product are considered as a composite member [2]. The adhesives used in the construction of laminated timber products includes resorcinol-formaldehyde (RF) and phenol-resorcinol-formaldehyde (PRF), which have been used for decades for the bonding of the load-bearing timber elements, however, recently one-component polyurethane (1-C PUR) has gained popularity [22].

In a glulam beam shorter lamellas are finger-jointed at the end of each timber bit to produce the required span, which may or may not be the case for the cross laminated timber products. The finger jointing can be done in different ways as shown in figure 1.4

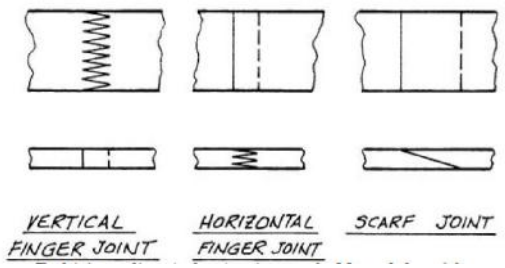


Figure 1.4: End-joint splices in laminating timber [2]

The process of laminating the timbers by bonding in the glulam beams results in increased strength of the lumber laminates compared to their strength when tested by standard procedures. This is known as laminating effect and is what contributes in the increased strength of the laminated timber structure than the sawn lumber [18]. Based on the results from the examination of the lamination and beam test, [18] suggests that the apparent increase in strength due to the laminating effect is collectively because of separate physical effects which includes the effect of testing procedures, a reinforcement of defects and an effect of dispersion.

Clearly, it can be said that the lamination of smaller plies of timber into massive solid timber elements increases the strength and stiffness of the member compared to sawn timber of similar dimensions, however, the selection of appropriate lamina with adequate strength and less defects influences the strength and performance of the laminated timber products. This was illustrated by Lee and Kim [32] in a study to determine the optimum modulus of elasticity (MOE) value as an input variable for the estimation of the strength properties of structural glued laminated timber (see Figure 1.5). The study showed that the evaluation methods of the MOE for lamina governs the accuracy of prediction for the performance of glulam, along with that, the study also showed that failure in glulam beams mostly develop in the vicinity of knots and the growth defects, the failure development is more influenced by these defects rather

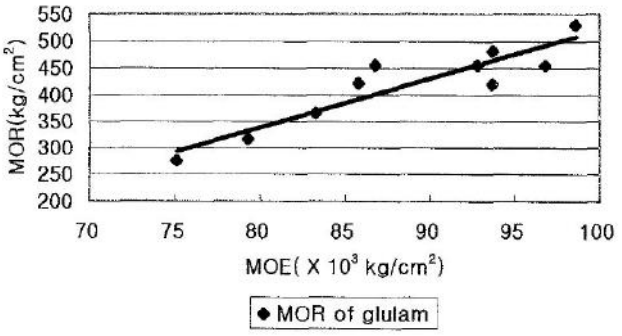


Figure 1.5: Relation between predicted modulus of rupture (MOR) of glulam and measured MOE of lamina [32]

than the strength factors like MOR and MOE.

In addition to the failure of the timber lamina, debonding or delamination is another major mode of failure in the laminated timber structure. In a study of the interfacial stresses in the plated beam carried out by Smith and Teng [40], debonding failure was found to be largely dependent upon the interfacial shear and normal stresses between the beam and the bonded plate. In the adhesive layer, the interfacial shear stresses relate to the difference between the longitudinal displacement of the lower and upper layers and the interfacial normal stresses relates to the vertical deformation compatibility between the two layers. Interfacial shear and normal stresses along the adhesive layer have been described in detail in Section 1.4.3, whereas, debonding in laminated timber has been explained in Section 1.4.2.

Provided that the individual lamina has adequate strength and stiffness, the overall performance of the structures constructed with laminated timber elements can be enhanced significantly by reinforcing the joints. This was demonstrated by Kasal et al. [28] in a study of the performance of laminated timber frames with fibre-reinforced joints in seismic loading. Full scale shake table tests of the glued laminated timber frames were conducted, the result demonstrated that wood structures exhibit capacity to dissipate large energy due to increased equivalent/total structural damping, which is due to the hysteretic behaviour of mechanical connectors under cyclic loading. The structure used in this research withstood strong levels of horizontal deformation and stresses, which can be inadmissible even for reinforced concrete or steel frames.

Figure 1.6: Seven-storey CLT building on the 3D shake table [7]

In another full scale test, a 7-storey cross laminated timber building (see Figure 1.6) was tested on top of a 3D shaking table [7]. The research project was called "SOFIE - Sistema Costruttivo Fiemme", where the 7-storey CLT building as shown in Figure 1.6 was subjected to different earthquake loading on a 3D shake table in the sequence of 22 tests. After the 22 tests the buiding still remained standing and just required some simple restoring interventions. The technique used for the construction was self-centring and sustained no significant damage up to a peak ground acceleration (PGA) of 0.82g (maximum PGA of JMA kobe earthquake). Furthermore, the inter storey drift was found not to be critical for the structural integrity of the building and no residual inter storey drift was observed. In addition, the maximum seismic forces were found to be within the acceptable level and the failure mode observed were ductile with fastener bending and embedment.

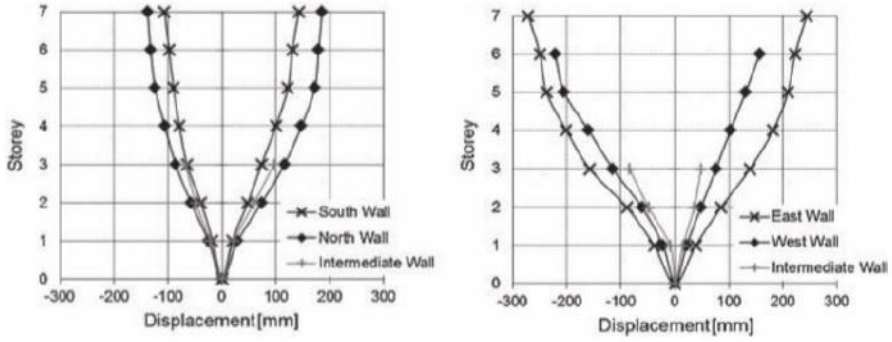


Figure 1.7: Maximum inter storey drift during test 18: long direction (left) short direction (right) [7]

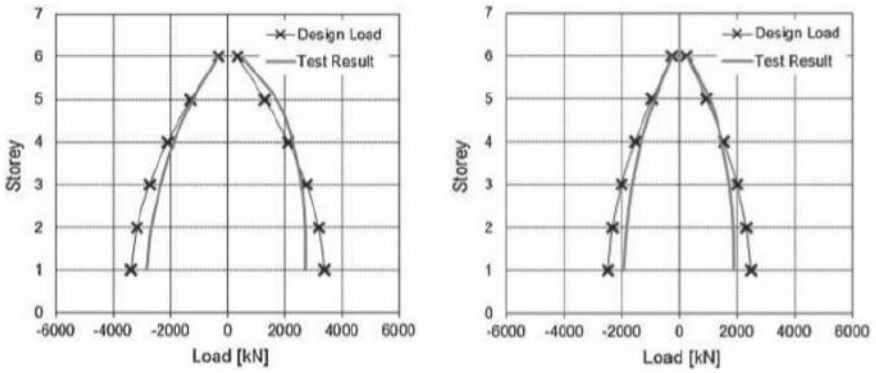


Figure 1.8: Seismic forces per storey during test 18: long direction (left) short direction (right) [7]

Figure 1.9: Fasterner failure of hold-downs (left) pulling-out of nails (mid) wood failure in compression perpendicular to the grain (right) [7]

This research demonstrated the excellent performance of cross laminated timber structure in seismic loading condition and the effectiveness of the construction system adopting the technology.

1.4.2 Laminated Timber Performance in Fire

The fire performance of timber buildings have always been a concern, however, a large scale compartment fire test carried in the full scale six storey timber frame building at BRE Cardington, UK demonstrated the adequate fire performance of timber buildings in essence of meeting the functional requirements of Building Regulations for England and Wales and the Building Standards for Scotland [33]. The test was a part of Timber Frame 2000 (TF2000) project and was performed with a primary objective of evaluating the fire resistance of a medium rise 6 storey timber frame building when subjected to a severe natural fire exposure. It assessed the structural integrity and compartmentation aspects of fire safety of a timber frame building subjected to a fully developed post-flashover fire. The fire test was conducted on the single flat at level 3 of the building with timber cribs providing the fire load necessary and ignition started in the living room. The termination of the test occurred at 64 minutes from ignition when the fixity of the ceiling plasterboards in the living room of level 3 were lost and the joists were directly exposed to the fire for approximately 8 minutes. One of the major observations of the test was that both the compartmentation and structural integrity of the building were maintained at the time when the test was stopped.

This test provides a strong base for the argument towards the use of medium-rise timber frame buildings and the better fire performance of such constructions globally. However, in context of engineered timber constructions, the performance of the individual structural elements needs to be assessed properly as the charring and the temperature variation within the element may affect the properties of the adhesive used in the manufacturing of the element, which indeed would influence the structural performance of the member. The following section illustrates the performance of laminated timber in fire scenario.

Charring Rate

Wood is a combustible material, this disadvantage of timber means that the fire safety design of timber structures requires additional precautions. To understand the structural performance of timber structures, including laminated timber structures, in fire it is necessary to understand the behaviour of timber in fire. When a timber surface is exposed to fire or elevated temperature the different constituents that make up the wood start to decompose and release volatiles, this process is called pyrolysis, at different temperatures as presented below [16].

Hemicellulose	200-260°C
Cellulose	240-350°C
Lignin	280-500°C

The ignition of the surface occurs when the temperature reaches 350-360°C which begins the formation of the charring layer [36]. The low thermal conductivity of the char layer protects the interior of timber cross section against heat and the increasing char depth shields the amount of heat transferred from the surface burning in towards the inner unburnt part of the wood, however, cracks formed in the char layer increases the heat penetration into pyrolysis zone [19].

Numerous prior studies have been done on investigating the charring rate of wood, among such researches Mikkola [36] studied the dependence of charring rate on the moisture content and external heat flux, the result for which are presented in Figure 1.10.

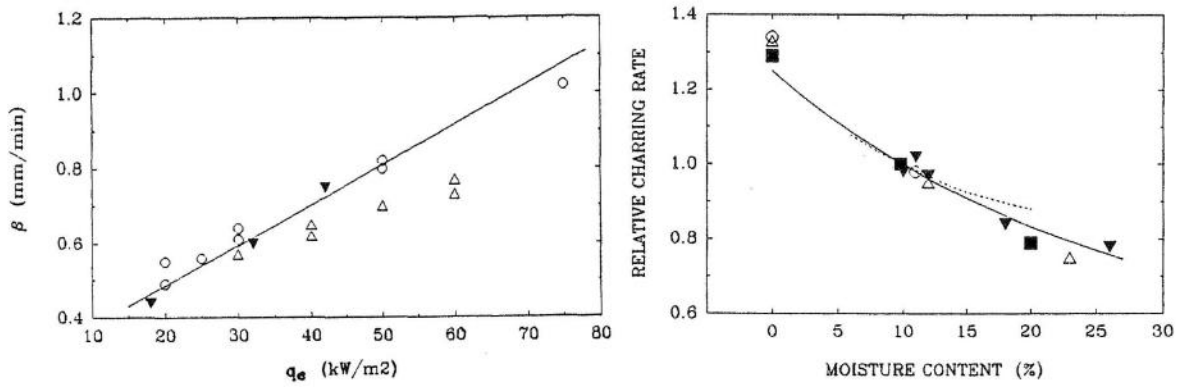


Figure 1.10: Charring rate as a function of: external heat flux (left) and moisture content (right) [36]

Frangi and Fontana [19] in a study measured the charring rates and the temperature profiles within the wood section. The research tested solid or glued laminated timber beams and timber slabs made of nailed timber planks or hollow core timber elements under standard ISO fire exposure where after the charring rates and the temperature profiles were measured in the wood sections (see Figures 1.11 and 1.12). The beams were exposed to ISO-fire on three sides while the slabs were exposed on one side.

The charring rates measured in [19], 0.67-0.70mm/min showed a good agreement with the basic values given in Annex A of ENV-1995-1-2 [11]. And the temperature profile exhibit steep gradient through the timber member exposed to fire, this is because the char layer exhibit good insulating behaviour. An important criterion that describes the temperature profile in the timber member exposed to fire is the 'thermal penetration depth', which is the distance from the char-line to the portion of timber at room temperature. Different values of thermal penetration depths have been measured in different studies, for instance Lache [31] measured the thermal penetration depth of around 25mm whereas Mikkola [37] gives it to be around 40-50mm.

Although most literature provide the charring rate and the charring depth of solid timber

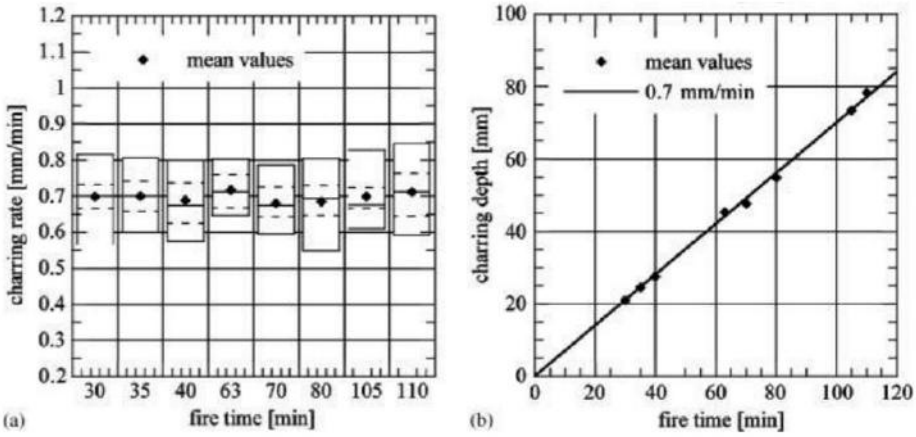


Figure 1.11: Measured charring rates (a) and charring depths (b) as a function of time of the fire tests [19]

for exposure to standard fire, laminated timber members are considered to char at the same rate [6]. An analysis conducted by Bartlett et al [5] on the charring rate of CLT upon exposure to non-standard heating conditions concluded that the average charring rate of CLT under exposure to simulated standard fire agrees strongly with the existing literature values. Bartlett et al [5] investigated the charring rate of CLT samples of different sizes under various heating exposures. Three different heating scenarios were studied i.e. 1) simulated standard fire exposures, 2) constant heat fluxes and 3) quadratically increasing heat fluxes (see Figure 1.14). The results from the analysis showed that the charring rates depends upon the heating rate, test setup, and the sample size and orientation and that there exists initial peak charring before it drops off to a lower quasi-steady value. The key finding of the analysis was that the average charring rate over the test duration is not an accurate representation of charring and consideration must be made of the effects of peak charring given the typical duration of compartment fires. Figure 1.15 shows the comparison between the results of the study.

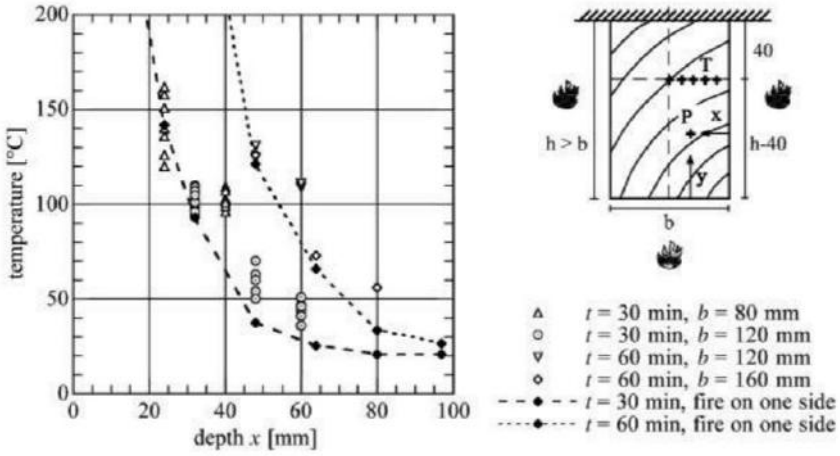


Figure 1.12: Measured temperatures after 30 and 60 minutes for timber beams exposed to standard fire on three sides and timber slabs exposed to fire on one side [19]

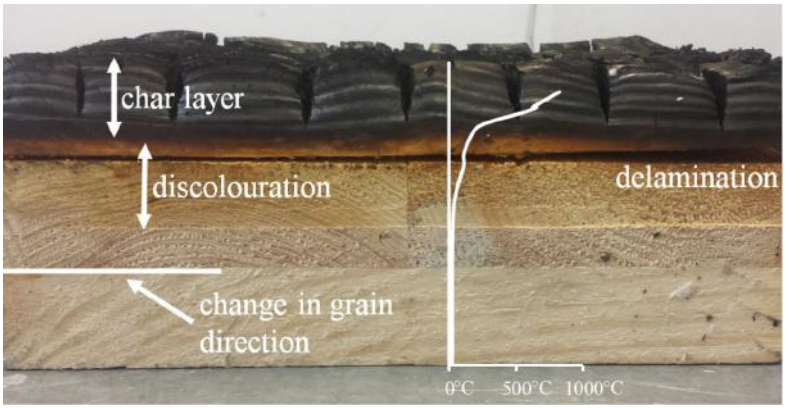


Figure 1.13: Char layer, temperature profile, delamination in a CLT sample after 60 minutes of exposure to quadratically increasing incident heat flux [5]

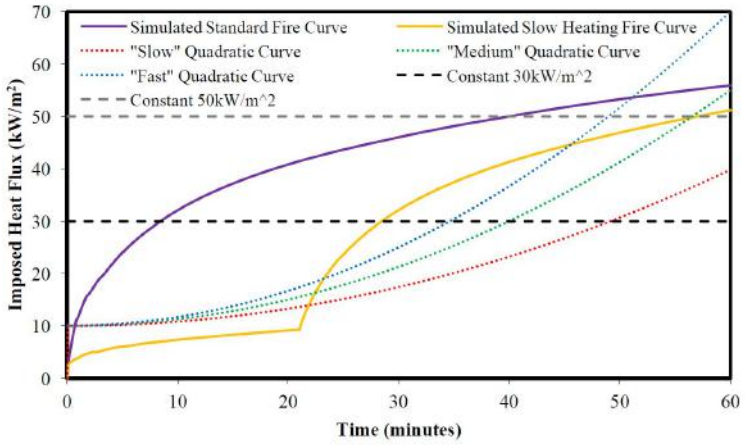


Figure 1.14: Heating scenatios test in the work [5]

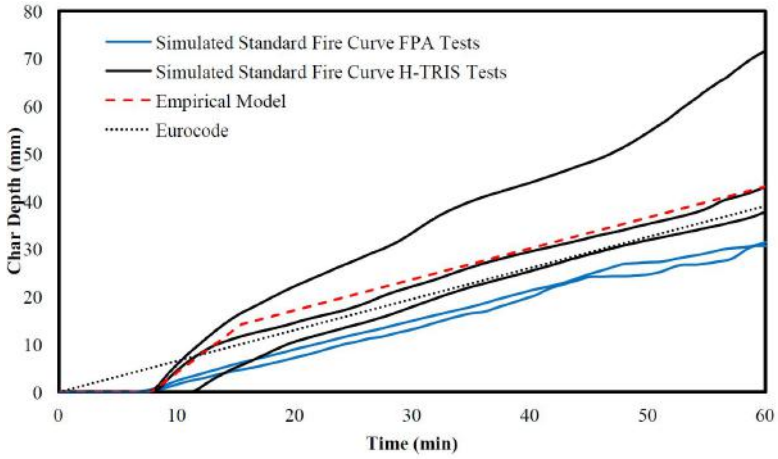


Figure 1.15: Comparison of Standard fire H-TRIS tests with Eurocode and empirical model [5]

Eurocode 5 [11] provides a following generic temperature profile as a function of distance from the char front, x;

$$T = T_i + (T_p - T_i)(1 - \frac{x}{a})^2 \tag{1.1}$$

where,
T = temperature (°C)
T_i = initial temperature (°C)
T_p = char front temperature (300°C)
x = distance from the char front (mm)
a = thermal penetration depth (40mm)

Janssens and White [27] provides a better fit to the Eurocode 5 generic temperature profile for pine with a=33mm as shown in Figure 1.16. The figure shows a steep gradient in the profile below the char front. However even until 25mm deep the temperature profile remains relatively high, which could be a concern for the strength of the adhesive used in manufacturing of the engineered wood product. The temperature profile is shown up to the thermal penetration depth, beyond which the temperature within the timber section stays at ambient i.e. 25°C.

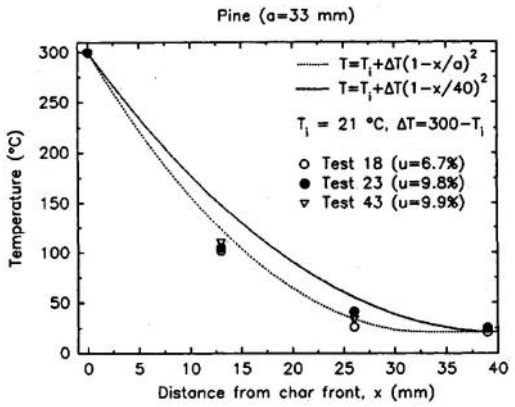


Figure 1.16: Temperature profile for pin below char front [27]

Adhesive Degradation and Delamination

Frangi et al. [21] studied the fire behaviour of CLT wall and floor assemblies experimentally and numerically. It was observed that the falling off of the charred layer was less pronounced in the vertical structural members (walls) compared to the horizontal members (slabs), which resulted in better performance of the vertical members in case of fire. In addition, the falling off of the charred layer was found to be influenced by the behaviour of the bonding adhesive layer at high temperature.

Prior studies have found that degradation of the adhesives used as glue for engineered timber products has an influence in the fire performance of these elements. Emberley et al. [17] studied the failure mode change of CLT at elevated temperature. Two series of tests were conducted, the first series focused on bondline failure mode at elevated temperature while the second series of tests were focus on studying the appearance of the failure modes in large CLT samples. The result of the first series of tests showed bond line failure of single lap shear test about certain threshold temperature (between 80°C-110°C). Likewise, in the second series of tests the transfer of failure mode from timber failure at ambient temperature to bond line failure at elevated temperature was observed. Figure 1.17 shows the result of the second series of test from [17].

The failure observed in [17] was through the propagation of delamination as shown in Figure 1.19. The failure initiated with a shear crack formation in a ply, which then

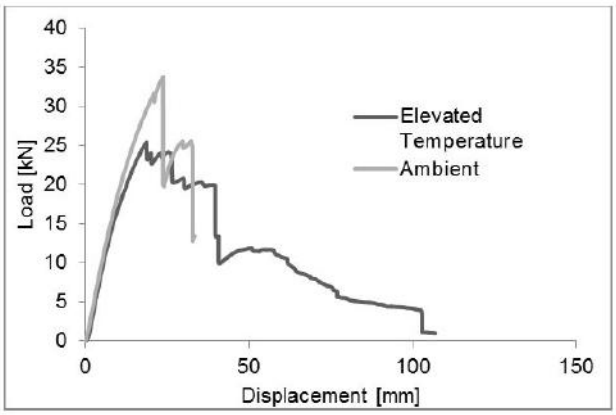


Figure 1.17: Load vs Displacement curve of CLT beam tests [17]

was directed towards the bonded interface due to increased stresses around the area of discontinuity. Afterwards, the crack continued down the beam length along the bond line as it was the weakest portion in the test. Until the crack reaches the end of the beam or the area where the glue becomes stronger than the adjacent timber, debonding is seen to continue.

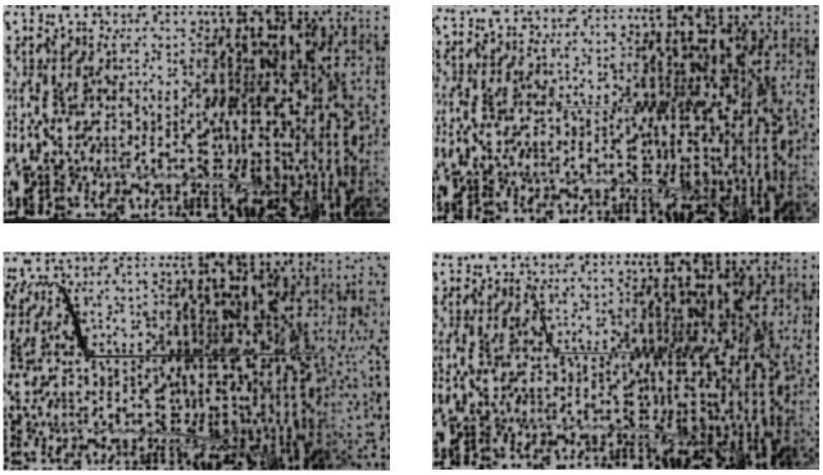


Figure 1.18: Delamination failure progression (clockwise from top left) between lamellas [17]

Figure 1.19: CLT beam after elevated temperature test: Beam centre with failure initiation location (left) Beam after failure (right) [17]

However, in another study Klippel et al. [30] investigated the influence of adhesive on the load carrying capacity of glulam timber members in fire. The study showed that for the glulam timber members temperature-dependent material properties of the adhesive have a small influence on the shear resistance of the member and the failure of the beams occurred mainly due to exceeding the bending moment resistance. The study also showed that the temperature of the inner regions of the timber beams were relatively low given the steep gradient of temperature during fire exposure, thus the shear capacity between the adjacent lamellas in the bondline was still adequate. Whereas, for the glulam timber beams with finger jointed lamellas, the influence of the adhesive that were used for finger jointing were significant at elevated temperature. The results are shown in figure 1.20.

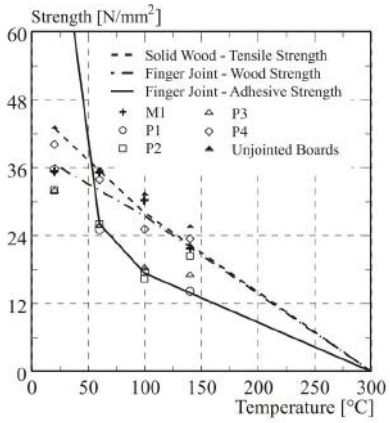


Figure 1.20: Results of tensile tests on specimens with finger joints pre-heated in an oven [30]

Considering the results from [17] and [30], it can be said that the delamination of the individual plies is more critical in cross laminated timber member than in glued laminated timber member.

1.4.3 Glued Single-lap Timber Joint

Single-lap joint is among the simplest of joints where an adhesive layer is sandwiched between two bonding adherent members. The simplicity and efficiency of the joint makes it a popular test specimen for the determination of the mechanical properties of the adhesive [26]. The free body diagram in figure 1.21 shows the forces acting in each components of the loaded single lap joint.

For the adherents, the equilibrium equations become [9]

$$\frac{dT_i}{dx} = \tau;\ \frac{dV_i}{dx} = \sigma;\ \frac{dM_i}{dx} - V_i + \tau\frac{t_i}{2} = 0 \qquad (1.2)$$

Here T_i, V_i, M_i are the tensile force, shear force and bending moment respectively where i = 1 or 2 representing the upper or lower adherent and t is the thickness of the adherents. σ and τ are the normal and shear stresses respectively given by following equations;

$$\tau = G\frac{(u_1 - u_2)}{\eta}; \sigma = E\frac{(v_1 - v_2)}{\eta} \qquad (1.3)$$

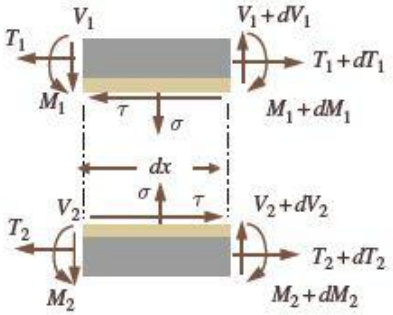


Figure 1.21: Internal forces acting on single lap joint [9]

where G and E are the Shear Modulus and Modulus of Elasticity of the adhesive respectively, u_i and v_i are axial and transverse displacement of the upper and lower adherents and η is the thickness of the adhesive layer.

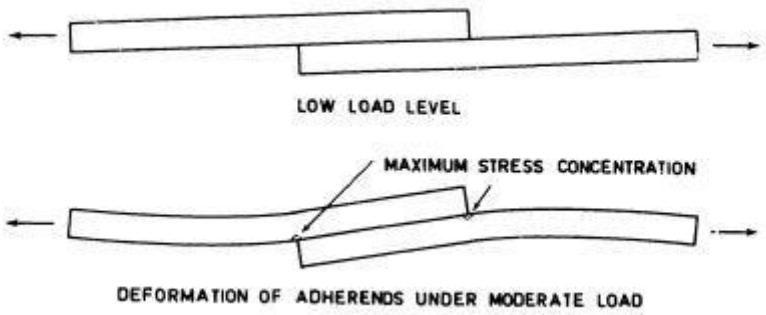


Figure 1.22: Deformation of single-lap joint at different level of load [25]

The adhesive layer sandwiched between the adherents transfers the load from one adherent to another. Figure 1.22 shows the deformation of the lap joint during loading, at low loading there is not much deformation of the joint. However as the load is increased the eccentric loading path induces bending deflection and joint edge moment at the free end of the overlap and the failure of the joint occurs due to high concentration of stress (shear and peeling stresses) at the free ends of the overlap [26]. The joint fails in shear when the maximum shear stress or strain in the adhesive reaches it allowable value and the associated bond strength is the bond shear strength, similarly if the adhesive reaches maximum allowable tensile stress or strain then there is peel or tensile failure and the corresponding strength is bond peel strength [43].

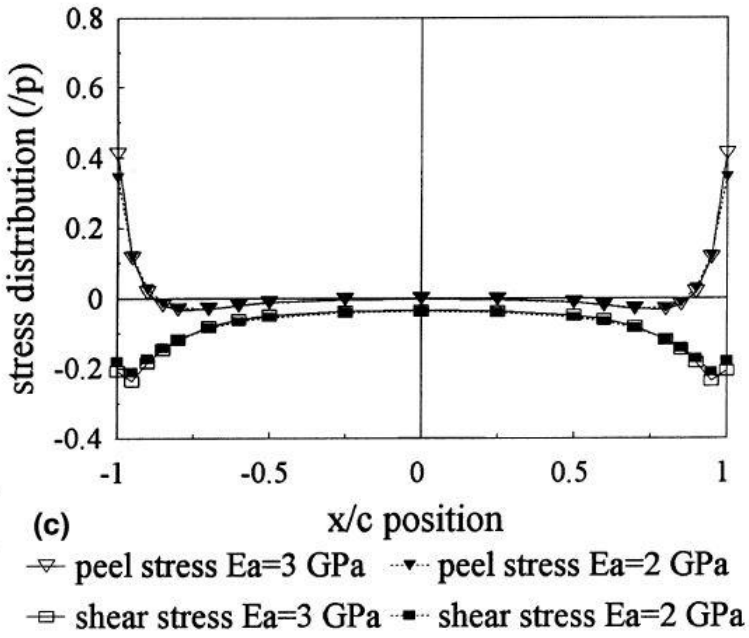
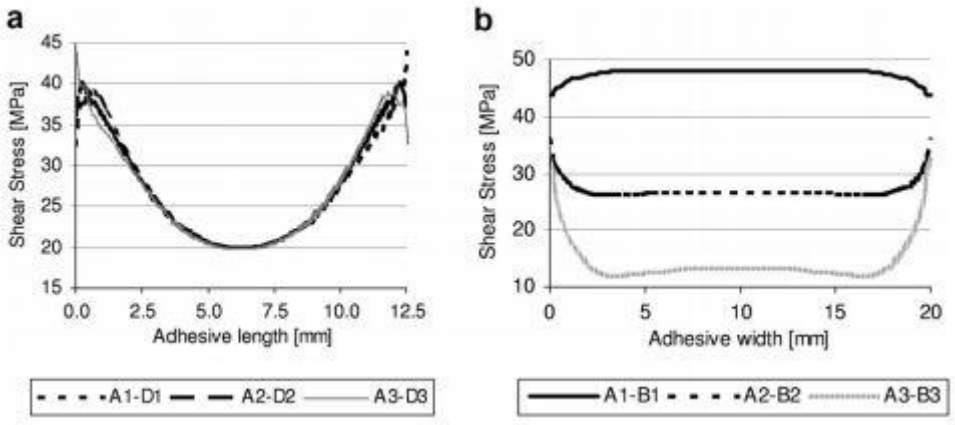


Figure 1.23: Stress Distribution along the bondline [34]

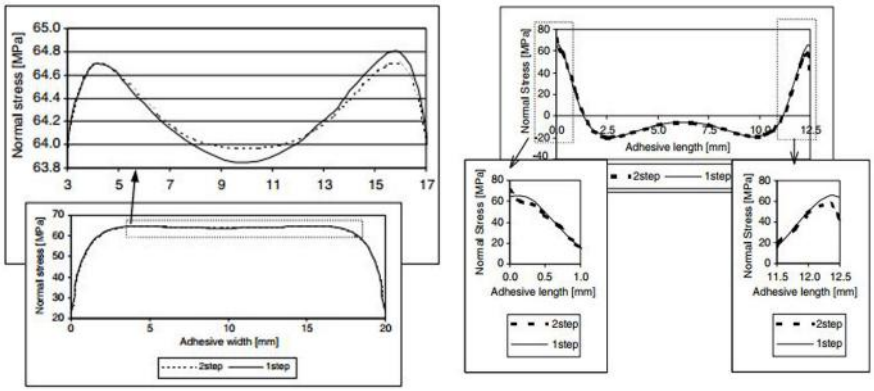
Figure 1.23 shows the nonlinear finite element modelling (FEM) analysis result of distribution of shear and peeling stresses at the middle of the adhesive thickness along the bondline of the lap joint. The result shows that the peeling stress is extremely high at the ends of the bondline and tends to zero as it moves towards the centre of the joint. Whereas, the shear stress is maximum at the points slightly inside the ends and becomes minimum as it moves towards the centre of the joint[34].

In another study, Derewonko et al. [12] compared the distribution of the shear stress and normal stress along and across the bondline thickness using numerical modelling with one-step and two-step loading schemes. The results for the study are presented in figure 1.24. In the figure for the shear stress distribution the subscript 1,2 and 3 represent the lower, middle and upper portion of the adhesive thickness. Not much difference was observed in the normal stress values for the one-step and two-step loading schemes, whereas, significant difference was observed for the normal stress.

Gleich [23] did the comparison of the shear stress and peeling stress distribution along the overlap from different classical single lap joint theories studies. The results of the comparison are shown in figure 1.25. The figure shows that all analyses except Allman (1977) ignored the variation of the normal stress through the adhesive thickness and thus predicted that the maximum adhesive shear stress occurs at the edge of the bondline, which doesn't comply with the stress-free boundary condition. Likewise, for the peeling stress, the prediction made by the Delale et al. (1981) has the largest normal



(a)



(b)

Figure 1.24: Results of (a) Shear stress and (b) Normal stress along and across the bondline [12]

stress (approximately 30% higher than other analyses) and Allman (1977) who did the consideration for the shear deformation has a normal value compared to other theories. The results of the single lap joint theories show that the static strength of the single lap joint could be improved by:

i Ductile adhesives with low modulus and shear modulus

ii High in-plane bending stiffness adherents

iii Orienting the fibres in outer adherent-adhesive layer along the joint length for composite materials

Two parameters influence the distribution of stress in the bonded region [26], namely, material parameter which includes the material the adherents made of and shear modulus of adhesive and geometric parameter including thickness of the adhesive layer, thickness of the adherent and the overlap length. The influence is such that with the increase

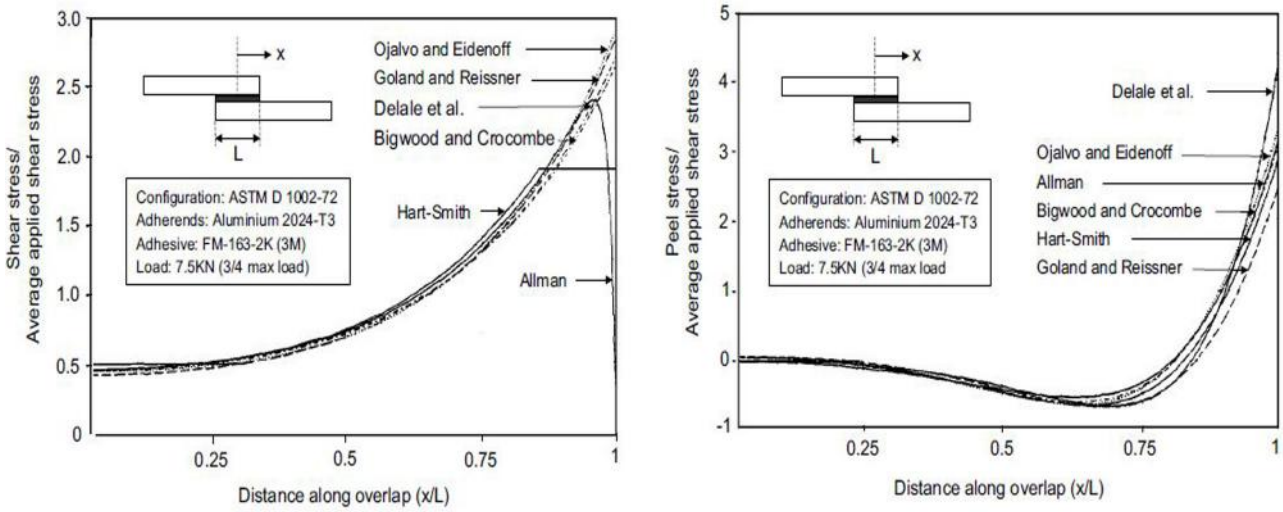


Figure 1.25: Comparison of shear (left) and peel (right) stresses results of classical theories [23]

in thickness of the adhesive layer the shear stress becomes lower i.e. thicker adhesive layer improves the strength if the adhesively bonded joint. For adherents with different stiffness, the shear stress is maximum at the free end of adhesive region that's near to adherent with higher stiffness and whereas for adherents of different thickness shear stress is maximum at the free end of adhesive region near to thinner adherent.

As for the mechanical properties of wood bonding adhesives, study using different testing methods Stoeckel et al. [41] shows that there is large variation in the properties depending upon the type of adhesive and the testing method as well. Figure 1.26 show the elastic modulus of different wood bonding adhesives for solid wood bonding (left) and panel production (right) determined using nanoindentation inside bondline (top), on adhesive films (middle) and by using macroscopic testing methods (bottom). The result shows large variation of the elastic modulus in different adhesive types and within the same adhesive type as well for different testing method. For example the modulus values for MUF, as an adhesive for solid wood, range from 3.5 to 7.5 GPa when tested as an adhesive films, whereas the values reached up to 12 GPa when tested by the means of nanoindentation on film fragments and in-situ bondlines. However, PUR which is the adhesive being used for this project has modulus values between 0.1 to 5 GPa for all testing methods making it among the groups of wood adhesives with highest flexibility.

In a study carried out by Luedtke, Amen, van Ofen and Lehringer [35] on influence of processing parameters of 1C-PUR on hardwoods for engineered wood products, they showed that primering of the gluing surface prior to application of the glue significantly enhances the bonding quality. Delamination and shear strength tests were carried out

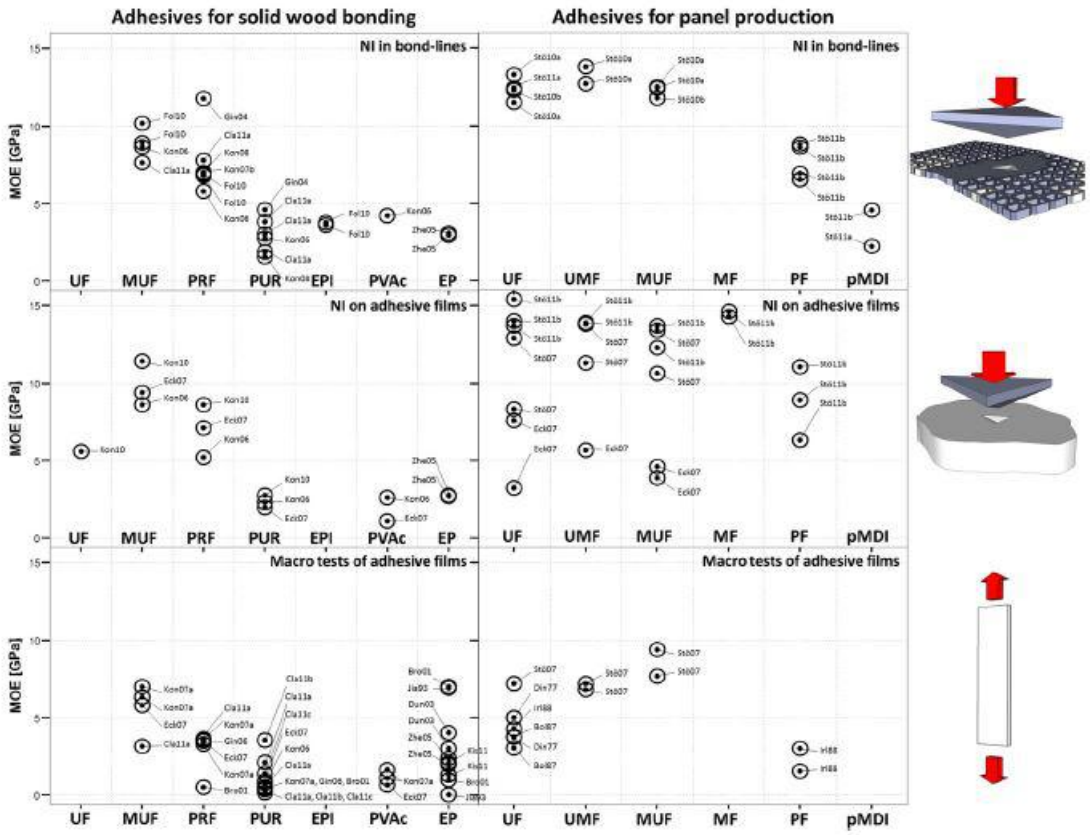


Figure 1.26: Elastic Modulus of different wood adhesives [41]

in the study, the results for which are presented in Figure 1.27. The shear test was done focusing on dry bonding quality which shows low impact of the treatment used on the shear strength values, however both the surface machining technique used and the primering of the surface before application of the glue seems to have significant influence on the delamination of the joint.

The behaviour of single-lap joint at high temperature has also been studied with different adhesives. Clauss, Joscak and Niemz [8] tested the thermal stability of different commercially available adhesives. The research studied the bonding strength of the adhesives in a wide range of temperature. Figure 1.28 shows the comparison of the shear strength of different adhesives at 20°C and 220°C. From the graph it can be seen that all the adhesives show sufficient strength well above 10MPa but at 220°C all the adhesives showed significant drop in the shear strength. The result shows high variation in the strength of the three different 1C polyurethane adhesives used, which shows that with different chemical composition PUR adhesives have large diversity in their thermal behaviour.

In another study carried out, [22] studied the shear behaviour of the bond line of 5

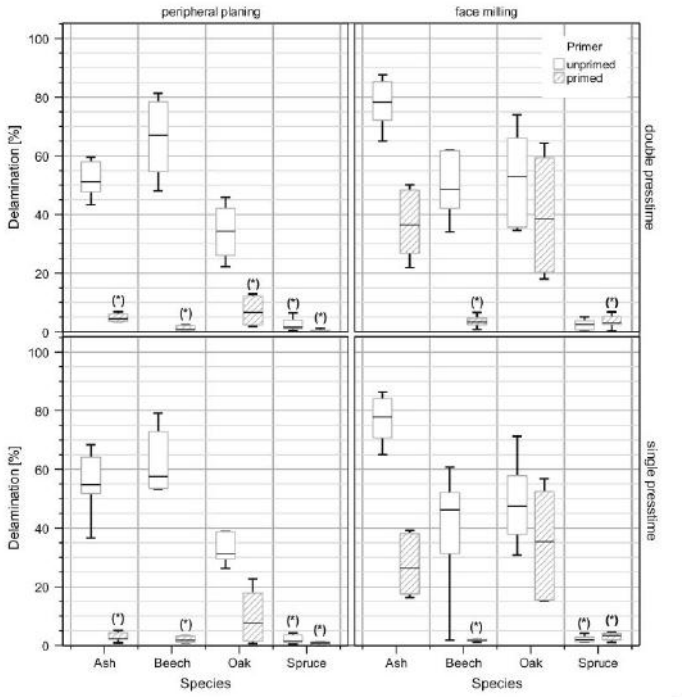
different polyurethane adhesives along with an epoxy and resorcinol-formaldehyde adhesives. For decades resorcinol-formaldehyde (RF) and phenol-resorcinol-formaldehyde (PRF) are being used in load-bearing timber elements, however, both RF and PRF never had concern about failure of the bond lines during the fire tests conducted [22], [13], [14], [15]. Figure 1.29 shows the reduction in the shear strength of the different adhesives at high temperature. [22] observed different failure modes i.e.

i Failure by loss of cohesion in bond line

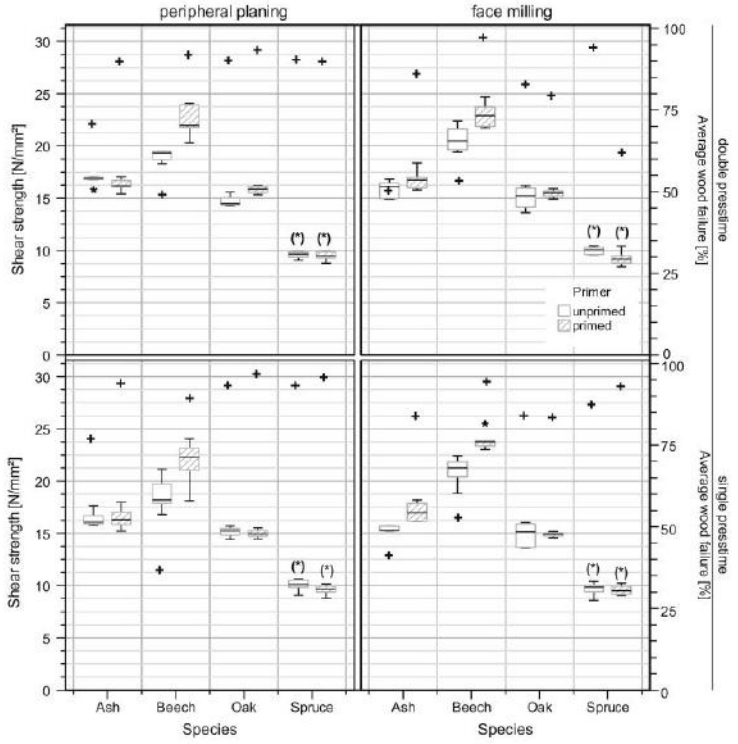
ii Adhesion failure between adhesive and timber

iii Timber failure outside the bond line

Also the shear behaviour of different 1C-polyurethane adhesives were observed to be dependent on the composition of the adhesive and the test result for one 1C-PUR cannot be used for another 1C-PUR adhesive.



(a)



(b)

Figure 1.27: Results of (a) Delamination tests and (b) Shear tests [35]

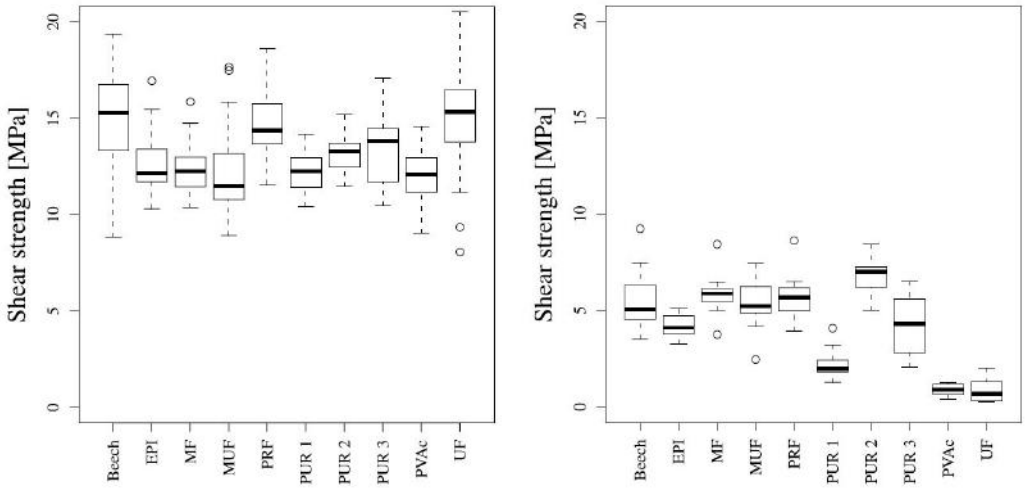


Figure 1.28: Comparison of Shear strength of adhesive bonds at 20°C (left) and 220°C (right)[8]

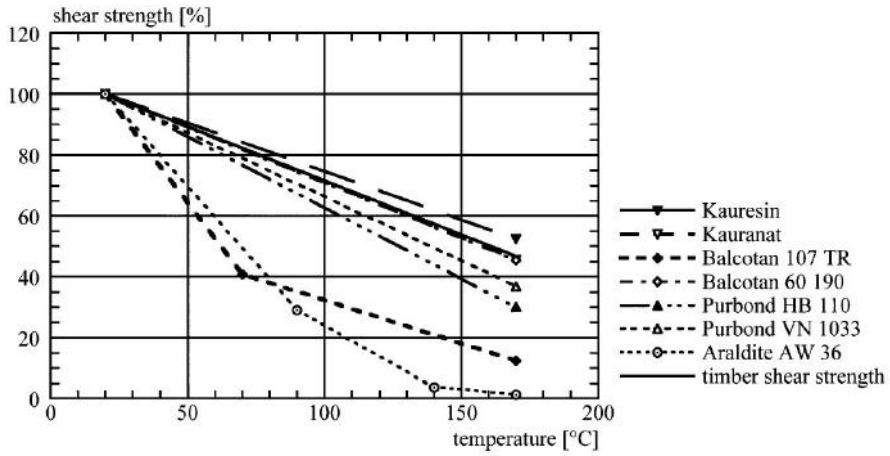


Figure 1.29: Reduction of shear strength for different adhesives at high temperature [22]

2

Methodology

This section presents the methodologies followed in the preparation of the test samples and the procedures of tests for the fulfilment of the work presented herein. The tests performed were:

i Bond Strength Tests- test of single lap-jointed timber at ambient temperature.

ii Thermal Penetration Test- heating tests measuring temperature variation along the bonded interface of single lap-jointed, unloaded samples

iii Bond Strength Test- heating tests on single lap-jointed samples under sustained mechanical load.

iv Dynamic Mechanical Thermal Analysis (DMTA)- performed on the adhesive.

2.1 Materials

2.1.1 Timber

The timber species used for the preparation of the samples was Radiata pine and were purchased from Bunnings Warehouse. Radiata Pine is a native species to west coast of North America but is also a major plantation species now around the world. It is a medium density softwood, with a density ranging from 350 to 550 kg/m^3. The density and moisture content of the particular Radiata pine used in the experiments for the this thesis were determined to be 441kg/m^3 and 12.7%, in average, respectively. The size of one piece of timber ply bought from Bunnings Warehouse was 2.4m×89mm×19mm. Radiata pine has a wide range of application from engineering, construction, decorative and others. It is used in the manufacturing of laminated beams, structural plywood, particleboard, medium density fibreboard among others.

2.1.2 Adhesive

The adhesive used for the gluing of the laminates was a one-component (1-C) polyurethane adhesive. The reason behind using that particular adhesive was it is among the most used adhesive for the production of engineered wood products specifically CLT. The adhesive is a Isocyanate Prepolymer and has the viscosity of approximately 24,000 MPa.s. The application temperature for the adhesive is +15°C to +30°C (which was mostly maintained in the Structures Lab of The University of Queensland) and the wood moisture content for the load-bearing application has to be around 8% - 15%. The spreading rate of the adhesive is between 150g/m^2 to 200g/m^2 and the processing time is maximum 70 minutes. The pressure needed to be applied for the load-bearing application is between 0.6N/mm^2 to 1N/mm^2 and for non load-bearing application is at least 0.3N/mm^2 and the pressing time is minimum 175 minutes.

2.2 Test Samples Preparation

The test samples were designed with the dimensions shown in Figures 2.2 and 2.4. The length of the sample was 1520mm, with 600mm of bonded length and 140mm long timber blocks glued at the end for clamping with the 1MN MTS machine, width 89mm and thickness was 38mm (thickness of single adherent being 19mm). The reason behind choosing the length was such that the bonded length would cover the entire length of the environmental chamber (650mm in height) so as to make the maximum used of the bonded length such that the full development of stress across the bond line could be achieved (see Figure 2.1). Likewise, the width was chosen to ensure proper gripping of the sample and to avoid overhanging as it would cause differential stressing. The following sections provides the details on the preparation of the samples for individual tests.

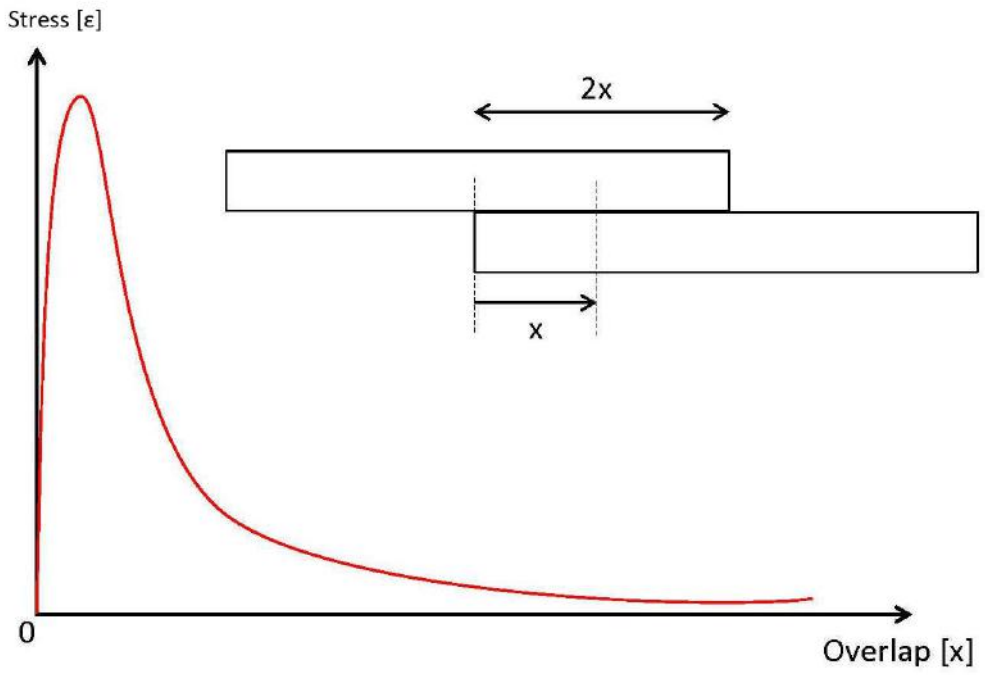


Figure 2.1: Expected stress distribution over the bondline

2.2.1 Single Lap-joint samples

The timber bought from Bunnings Warehouse were stored and cut into sizes in the Fire Lab of the University of Queensland. The length of the single adherent was 1060mm and 140mm for the end blocks which were glued to the edges of the adherent. The timber pieces were then transported to the Structures Lab for pressing. Five samples were prepared at a time, one of the adherent was placed in the clamping jig, cleaned and the gluing surface were moist with a wet cloth since the glue is moisture curing. Then the glue was applied uniformly over the entire bonding surface of another adherent through a plastic scrapper and placed on top of the adherent in the clamping jig, the process was repeated for next four samples. Afterwards the steel block weighing 400kg was placed on top of the samples followed by the hydraulic loading jack. A pressure of 0.9MPa was applied through the jack and hold for 3 hours (see figure 2.6). The whole process starting from the spreading of the adhesive on the timber surface until the application of the desired pressure was completed within 30 minutes which was well under the allowable processing time of 70 minutes for the polyurethane adhesive being used. To ensure the adequate spread of the adhesive over the entire surface of the joint the adhesive was applied in such was that there was certain amount of adhesive being squeezed out of the bond line during the pressing of the sample. Afterwards the samples were taken out of the pressing system and stored for at least 48 hours, for full curing of the adhesive, before testing. In couple of samples, the glue didn't spread all over the surface and there

appeared small gap between the two adherents at one edge of the joint (see Figure 2.3), those samples were used for the thermal penetration tests.

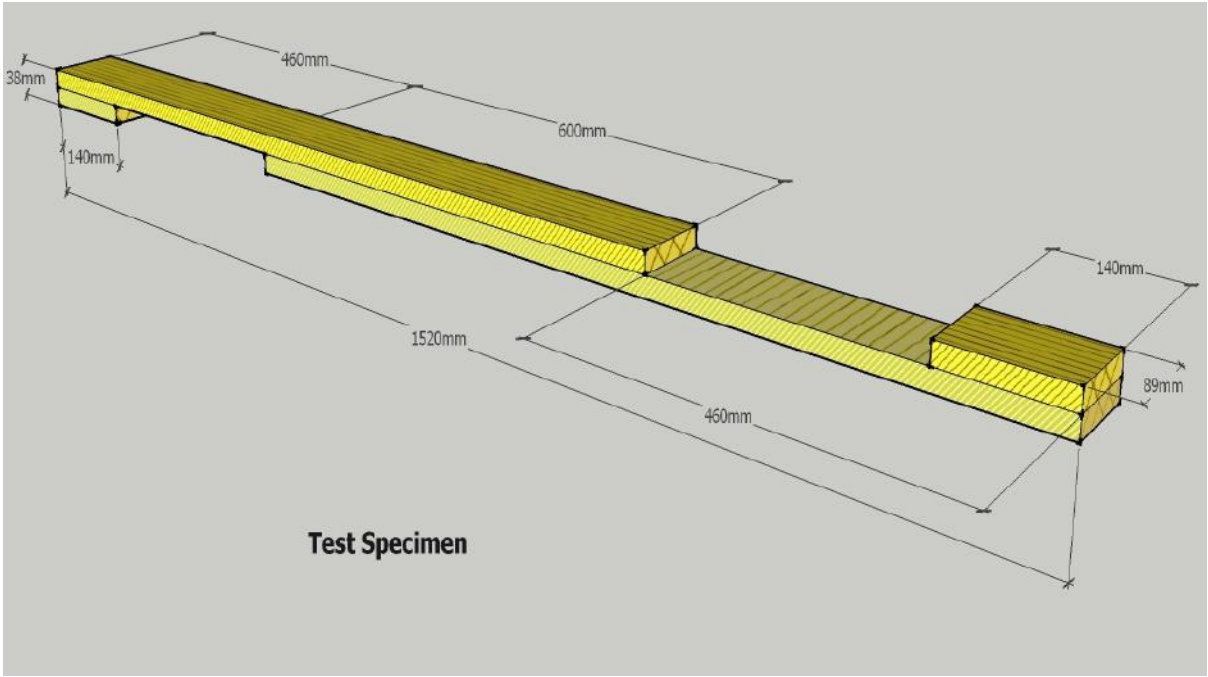


Figure 2.2: Sketchup drawing of sample

Figure 2.3: Gap between adherents due to uneven spread of glue

Figure 2.4: Prepared sample

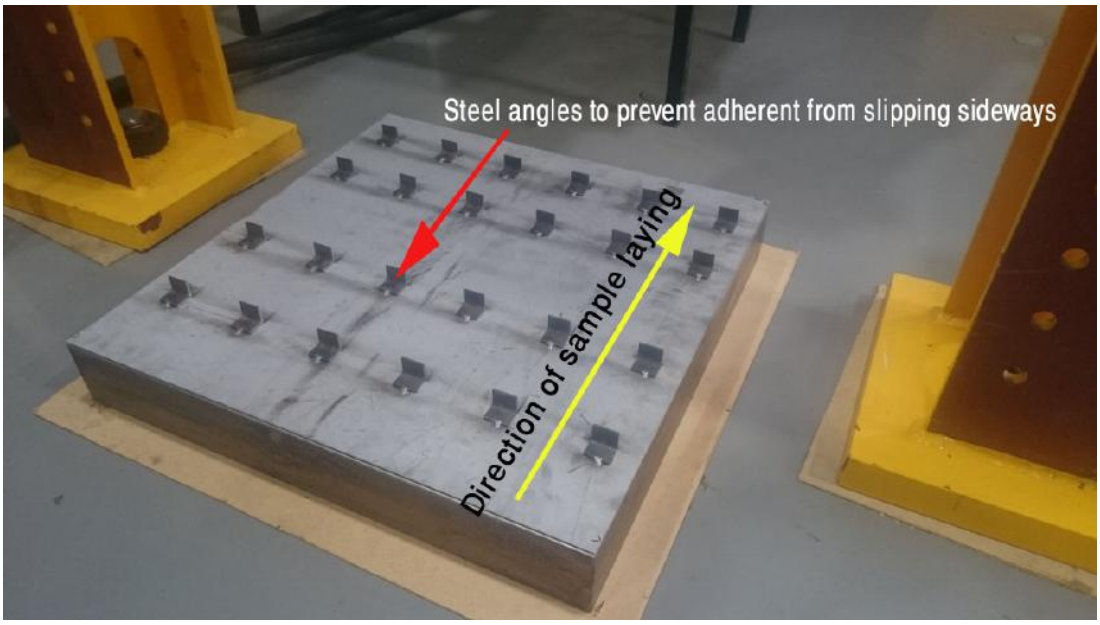


Figure 2.5: Jig for holding samples for pressing

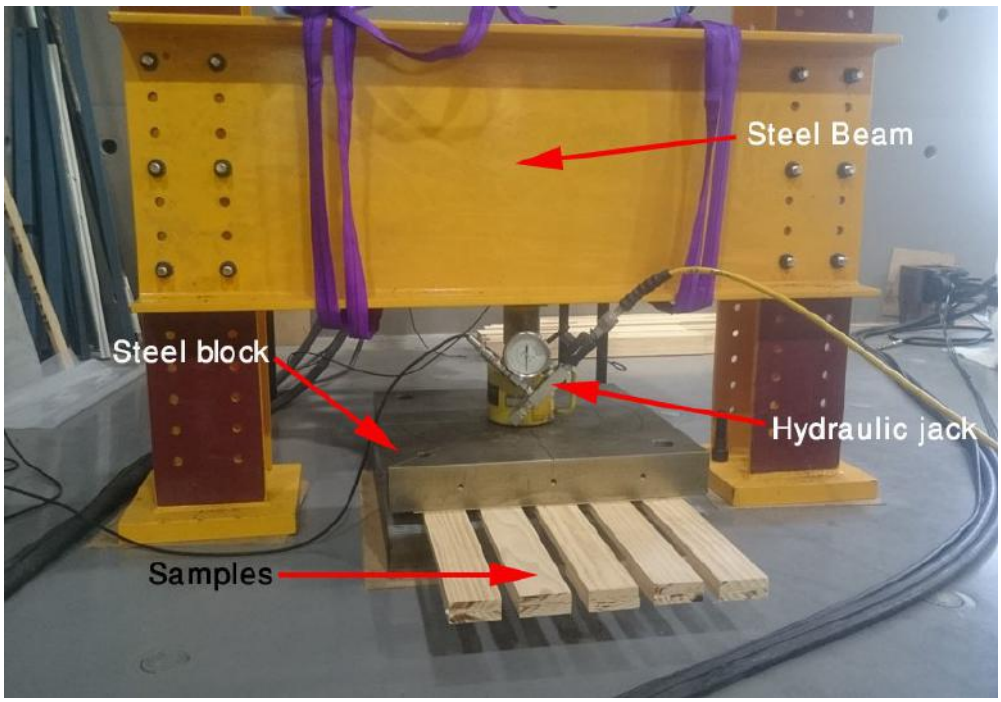


Figure 2.6: Setup for pressing the samples

2.2.2 Single Lap-joint samples for Thermal penetration test

The samples used for the thermal penetration test were of same dimensions. Since the bonded area was rectangular, it was divided into 4 quarters and only one quarter was used to record the change of temperature of the bonded area. Eleven thermocouples were placed within the specified quarter at staggered position as shown in Figure 2.7. The holes at the edge were drilled 5mm inward from the edge and the rest were drilled at equal distance in a staggered position as shown in Figure 2.7. The holes had diameter of 1mm and were drilled from the face of the lap joint up to the bondline interface so that the temperature of the adhesive can be recorded and the thermocouples used for the recording of the temperature were type K thermocouples. The staggering positioning was chosen so as to get as much uniformity and coverage of the whole bonded interface. Position 11 lies right at the middle of the bondline interface and the rest are placed equidistance from that.

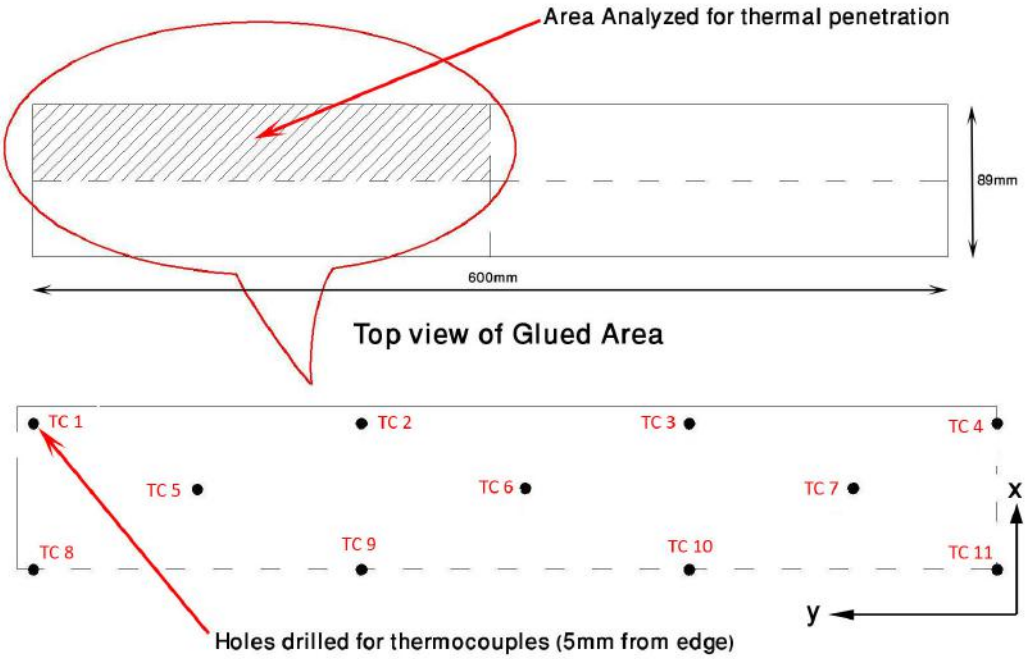


Figure 2.7: Staggered positioning of holes for thermocouples for thermal penetration test

Table 2.1: Measurements of thermocouples positioning

Position of thermocouples	Distance from centre*	
	X (mm)	Y (mm)
TC 1	295	39.5
TC 2	196.67	39.5
TC 3	98.3	39.5
TC 4	0	39.5
TC 5	245.83	19.75
TC 6	147.5	19.75
TC 7	49.17	19.75
TC 8	295	0
TC 9	196.67	0
TC 10	98.3	0
TC 11	0	0

*centre is the middle of adhesive interface (see figure 2.7)

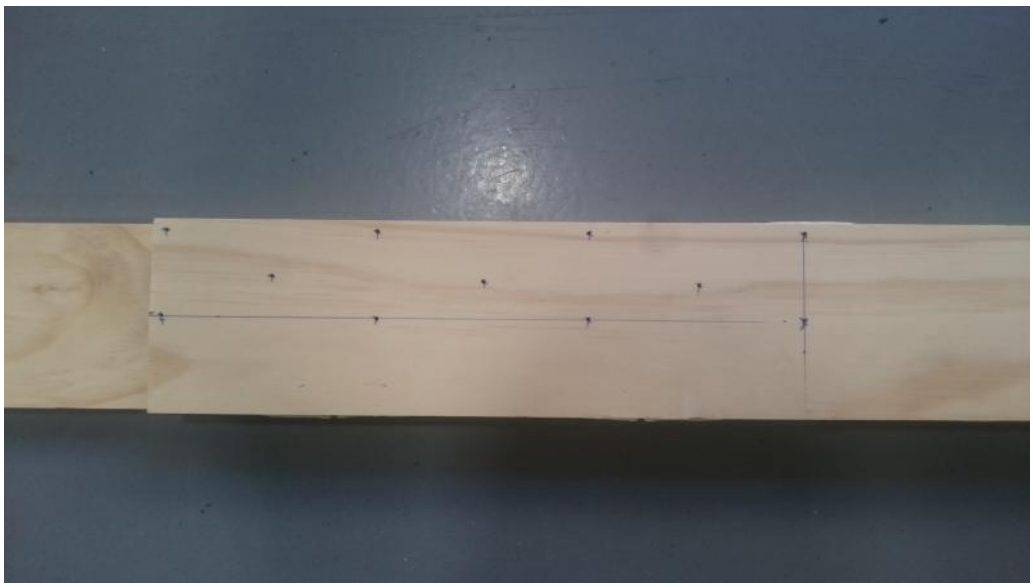


Figure 2.8: Drill holes for thermocouples to measure thermal penetration at bondline

2.2.3 DMTA Samples

The adhesive being tested 1-component polyurethane foams up under atmospheric curing, so precaution needed to be taken during the preparation of the sample for the DMTA test. A small drop of polyurethane adhesive was sandwiched between two Teflon blocks, weights were placed on top of the blocks then in order to squeeze out the air and prevent the adhesive from forming. The size of the samples was around 30mm×10mm×1mm and are shown in figure 2.9. The size of the sample was governed by the clamping length of the dynamic mechanical analyser and the mode of testing i.e. 3-point bending test.

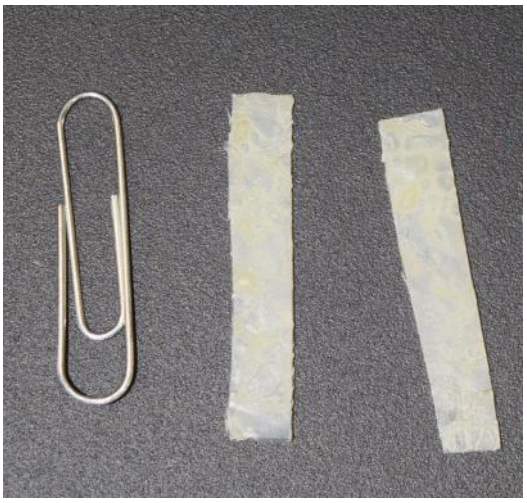


Figure 2.9: Samples for DMTA test

2.3 Testing Procedures

As described in the introduction, the objectives of the project are to study the reduction of strength of laminated timber and deterioration of mechanical properties of the glue. In order to achieve those objectives series of different tests as listed below need to be carried out:

- Thermal penetration measurement tests.
- Bond strength (at ambient and elevated temperature) tests of single lap-joints.
- Dynamic Mechanical Thermal Analysis.

2.3.1 Thermal Penetration Measurement Test

The purpose of the thermal penetration test was to determine the variation of the temperature with time along the bonded interface, so that the result can be used for the prediction of the bondline temperature at failure of the bond strength test at elevated temperature. In order to check the consistency of the temperature variation along the bonded interface, three test were conducted to observe the repeatability of the results. Similar methodology was followed for all three tests, as explained in the following paragraph.

The setup of the environmental chamber was done in such a way that the holes on either ends (top and bottom) of the chamber would align with the clamping jaws of the 1MN MTS machine. The sample prepared for the test was then placed, centred and clamped in the 1MN MTS machine through the environmental chamber. The thermocouples, which were connected to the data logger prior to the setting up, were then placed in their labelled positions and the holes between the sample and the chamber were filled with mineral wool and shielded. Afterwards, the environmental chamber was closed and the gas temperature of the chamber was set to 200°C. Then the data logger and the environmental chamber were both started simultaneously. In order to assure the entire bonded interface reaches a homogeneous, even temperature the tests were run for 2 hours, after which the environmental chamber was turned off and the recording of the data in the data logger was stopped. The sample was then removed from the chamber and the chamber was left to cool for 30 minutes. After the chamber has cooled down another sample was placed in and the whole procedure was repeated again.

2.3.2 Bond Strength Lap-joint Tests

The Bond strength lap jointed tests consisted of two different sets of experiments. Firstly, the bond strength tests at ambient environment were done and then the bond strength tests at elevated temperature were conducted. The procedures followed for both sets of testing methods are explained in the relevant section below.

Figure 2.10: Sample with thermocouples placed for thermal penetration test

Ambient Temperature Tests

The bond strength test of the lap joint in ambient environment was done to get the reference value of average bond strength capacity of the lap joint which would be used to determine the different loading percentages to perform the bond strength tests at elevated temperature. The samples were first placed in the 1MN MTS machine, in between the clamping jaws, then two 10mm thick steel plates (see Figure 2.12) were placed on either sides of the sample between the sample and the clamping jaws. The purpose for the steel plates were to get maximum gripping of the sample since the clamping jaws of the 1MN MTS machine were not long enough. After the sample has been centred, the jaws of the MTS machine were closed slowing and the sample was gripped until a cracking sound of timber compressing was heard, to ensure maximum possible grip without breaking the sample. Then the sample was loaded at constant displacement rate of 3mm/min until failure, since the MTS machine had its own data logging system not external data logger was used during the ambient test.

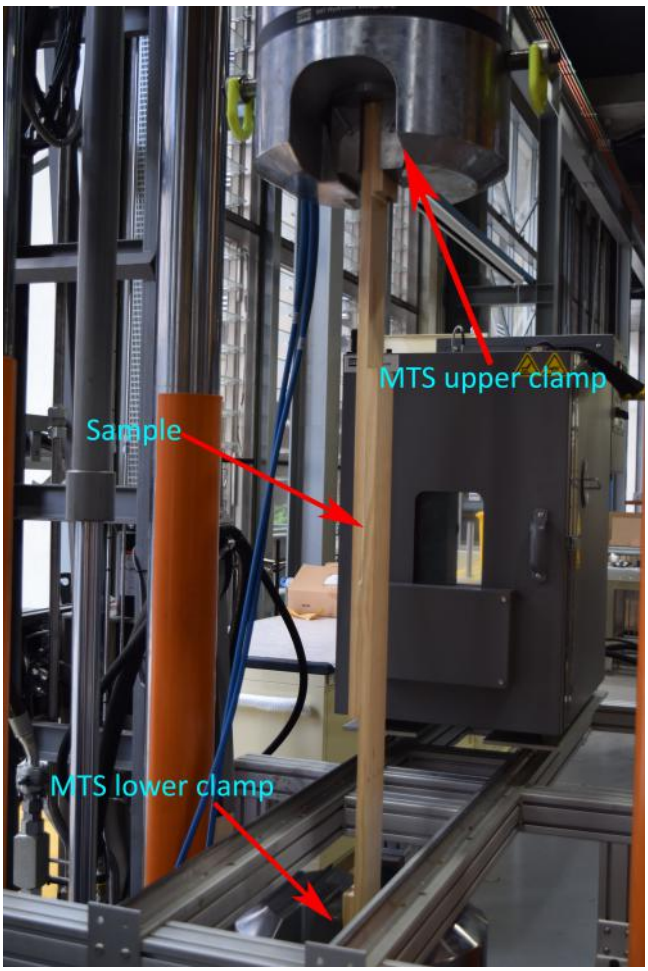


Figure 2.11: Bond Strength Test at Ambient Temperature setup

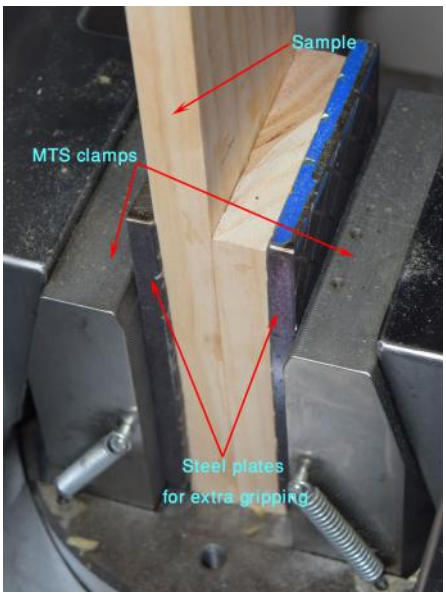


Figure 2.12: Steel plates placed between clamps and sample for extra gripping

Elevated Temperature Tests

In the second set of bond strength tests of the lap joints were performed to determine the delaminating temperature of the bond line at different loading percentage of the average bond strength capacity at ambient temperature. The procedure for set of tests is explained in the following sections.

The thermal tests of the samples were carried out with different loading percentage of the bond strength value determined from the ambient temperature strength test, the loading percentage used were 30%, 50% and 70% of the bond strength at the ambient temperature. The placing of the samples followed the same procedure as in the ambient test expect that after the samples were clamped to the 1MN MTS machine, the environmental chamber was positioned in such that the entire bonded length of the sample was enclosed within the chamber. Then the gaps and holes in the chamber were shield with mineral wool and the chamber door was closed. Since the experiment was force controlled, external data logger was used as the data logger in the MTS machine was not able to record the force and displacement values for the force controlled testing mode. The sample was then loaded to a desired loading percentage, until that point the loading was displacement controlled with 1mm/min displacement rate and then the system was changed to force controlled and the load was held for 5 minutes to ensure that the load stabilizes and the stress distribution over the bonded interface is consistent. After holding the load for 5 minutes, the environmental chamber was switched on and the sample was allowed to heat. If the sample failure before the temperature in the bonded interface reaches the steady value the experiment was stopped, the sample was removed and the chamber was allowed to cool for a minimum of 15 minutes. However, if the sample didn't

fail even after the bonded interface temperature reached a steady value the load was then increased until the sample failure.

In order to determine the failure temperature of the bonded interface, the plots between the failure load, displacement and the temperature variation over the interface against time are compared against one another as shown in figure 2.14. The top and middle plot shows the variation of the applied load and displacement over time and the bottom plot shows the variation of temperature across the bonded interface over time which starts at the mark of 5 minutes of holding up of the load. The displacement starts to increase gradually and at the failure load it reaches to a maximum value and the temperature corresponding to that load and large displacement point is the failure temperature.

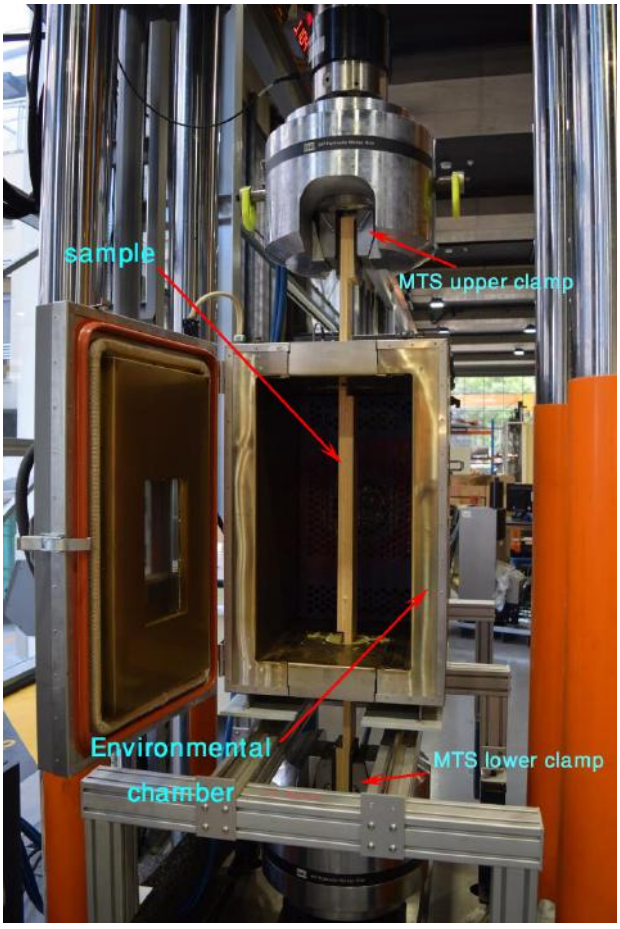


Figure 2.13: Sample placed inside the environmental chamber right before the door being closed

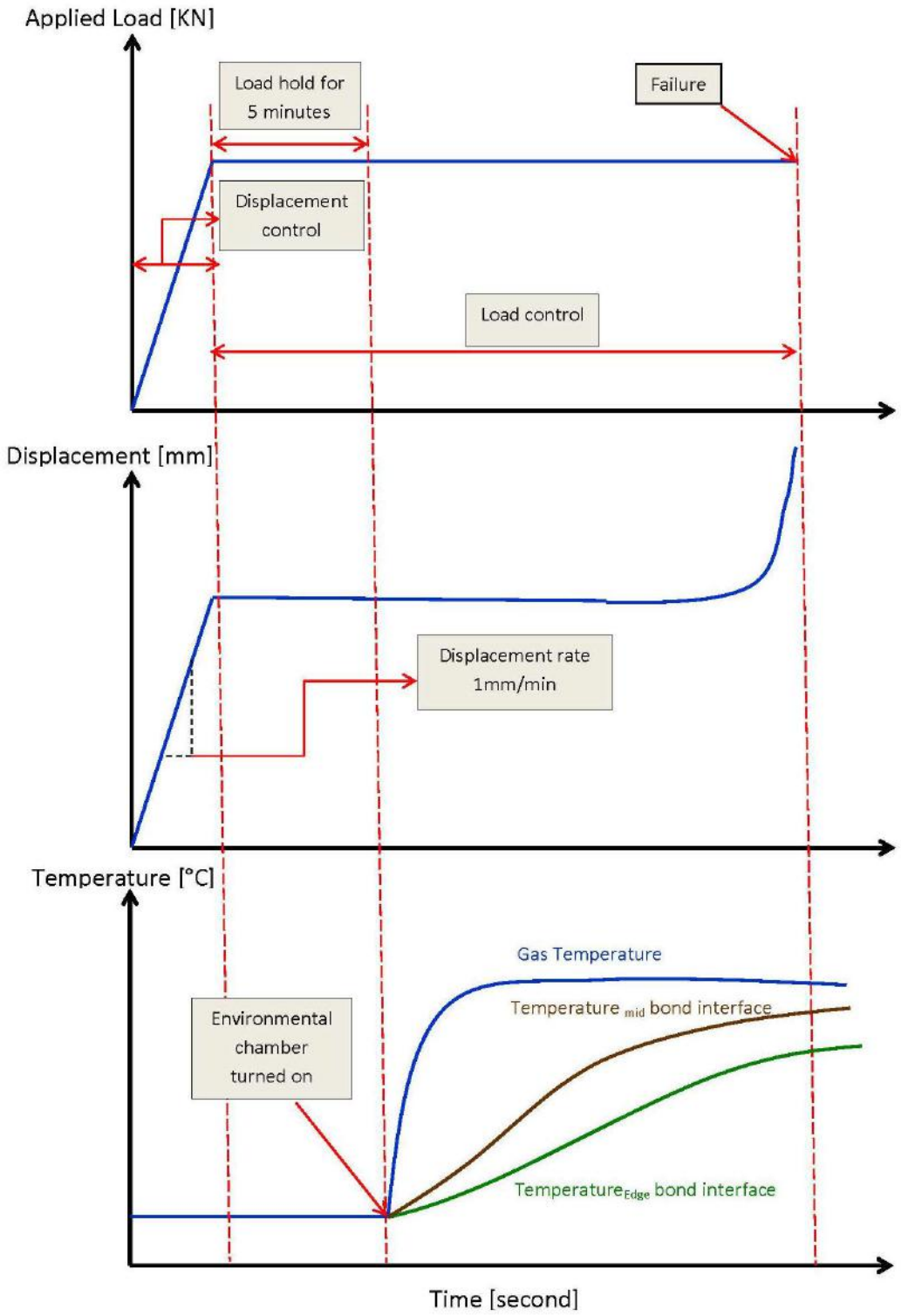


Figure 2.14: Comparison of Applied load/Displacement/Temperature Vs Time curves during Transient Bond Strength Tests to determine temperature at bonded interface at failure

2.3.3 Dynamic Mechanical Thermal Analysis (DMTA)

The purpose of performing the Dynamic Mechanical Thermal Analysis (DMTA) is to investigate the reduction in the storage modulus (E') of the 1-C polyurethane adhesive, used as the gluing material, at elevated temperature. The testing procedure followed was as specified in the ASTM D7028 "07" "*Standard Test Method for Glass Transition Temperature (DMA Tg) of Polymer Matrix Composites by Dynamic Mechanical Analysis (DMA)*". The apparatus used for the analysis is the Dynamic Mechanical Thermal Analyser DMTA V from the Rheometric Scientific, Inc. Three-point bending testing module was used for the investigation of the reduction of the modulus of the polyurethane adhesive. The installation of the sample, calibration and the operation of the test was done in accordance to the DMTA V Instruction Manual. The testing fixture appropriate for three-point bending test was selected and assembled, the sample was then loaded in the assembly (see Figure 2.15). The test was conducted with the standard heating rate of 5°C and Frequency of 1 Hz as specified in the ASTM D7028-07.

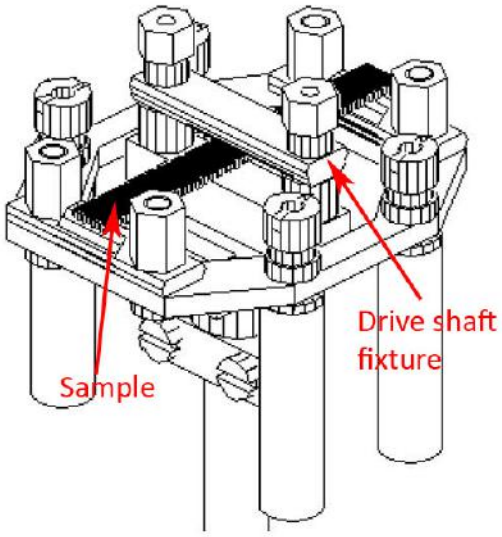


Figure 2.15: Three Point Bending Test Fixture with Sample Loaded [1]

3

Results

Single lap-joint bond strength test at elevated temperature for samples glued with polyurethane adhesive was carried out at various loading percentages along with the dynamic mechanical thermal analysis of the polyurethane samples. This section presents the results of the elevated temperature strength tests and the DMTA along with the results of the tests carried out in support of the aforementioned tests.

3.1 Thermal Penetration Test

The thermal penetration test was done in order to determine the variation of temperature across the bonded interface. It was necessary to have the understanding of the variation of the bondline interface temperature over time and to have a repeatable result as there were no thermocouples placed within the sample during the transient bond strength test. Three tests were carried out in total, the average temperature variation across the bonded interface for the 11 thermocouples are shown in figure 3.1.

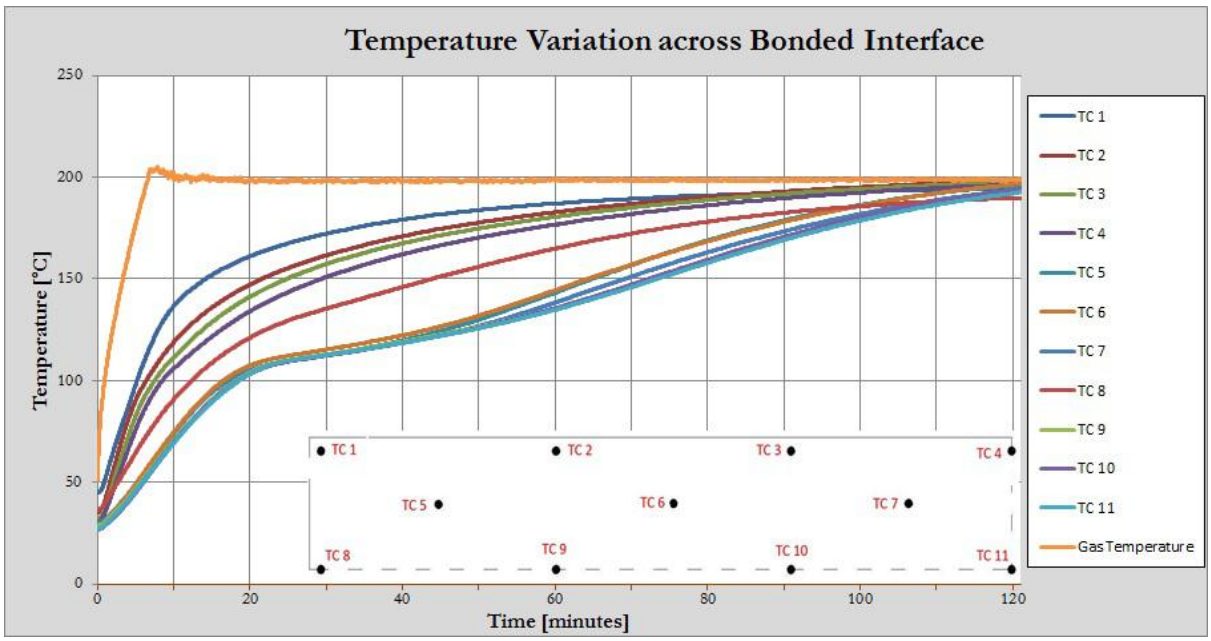


Figure 3.1: Result of Thermal penetration Test over the bonded interface

In the figure, TC1 (placed at the corner) shows steep rise in the temperature followed by TC2, TC3, TC 4 and TC8 respectively. TC 2, 3, 4 were placed near the side which was closer to the fan of the chamber which could be the reason why the temperature rise in those thermocouples were higher than TC8 which was placed at the top of the joint. For the thermcouples placed at the inner section of the interface i.e. TC5, TC6, TC7, TC9, TC10 and TC11, all of them show rather similar temperature gradient over time. The graph for those thermocouples starts to plateau at around 20 minutes to 40 minutes, the reason for this is that most of the thermal energy entering the timber is being used to evaporate the moisture and the temperature only starts to rise again after majority of the moisture has been evaporated. Test 3 for TC9 showed a steeper rise in temperature, this must be because of the displacement of the thermocouple from its position. TC1, TC2, TC3, TC4 and TC8 all took around 100 minutes to reach to a steady temperature, while TC 5, TC 6, TC6, TC9, TC10 and TC11 took almost 2 hours to reach steady temperature. Neither of the thermocouple reach the gas temperature of 200°C even after the duration of 2 hours of heating, so the test was stopped afterwards and the results until 2 hours were considered. As the tests were conducted with the environmental chamber at the temperature slightly higher than the ambient temperature, all the thermocouples shows starting temperature higher than the ambient temperature and similar procedure was also followed during the strength test at elevated temperature. The individual results of the different thermocouple positions are presented in appendix A.

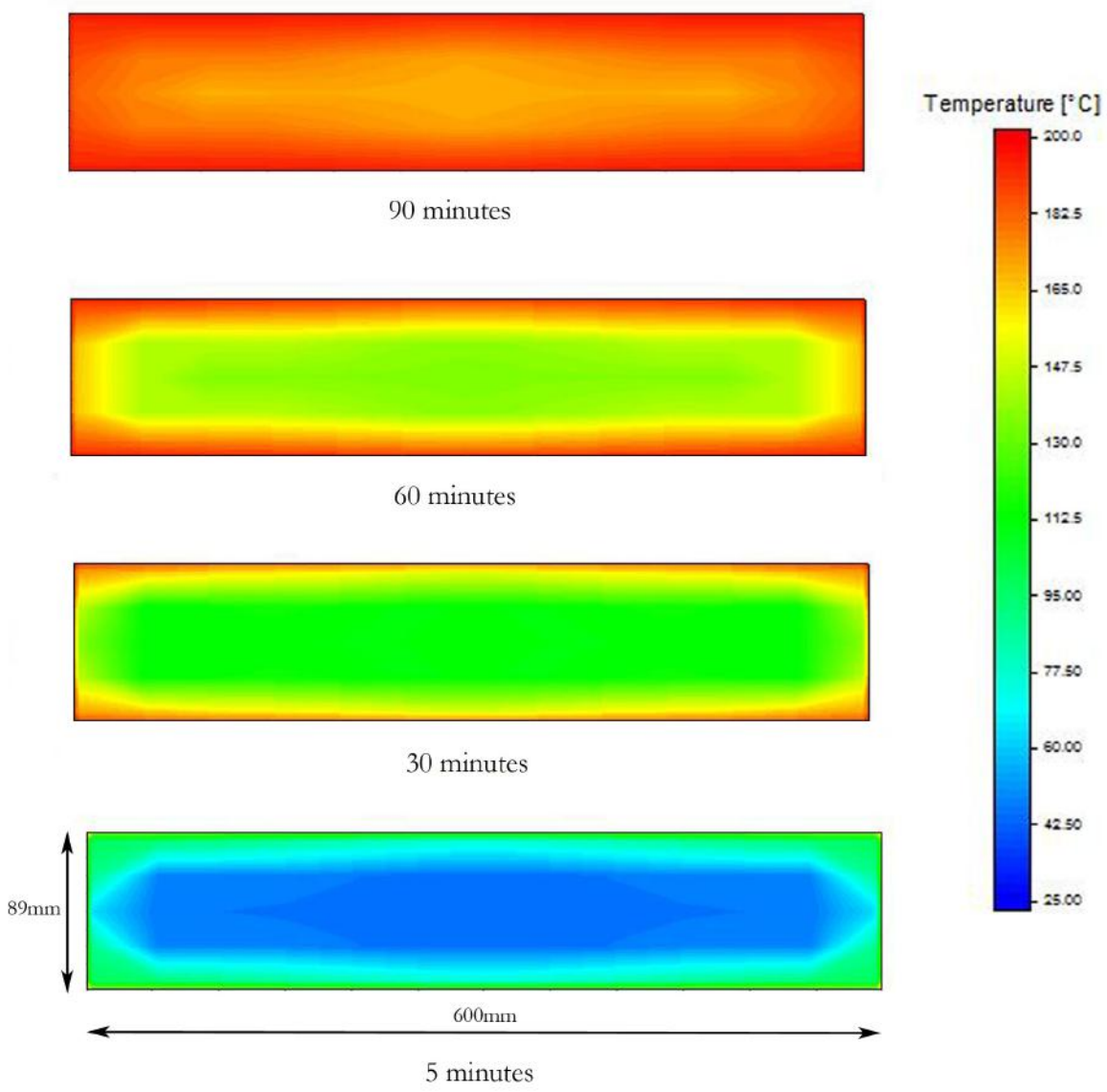


Figure 3.2: Temperature distribution across the bonded interface over time

Figure 3.2 illustrates the development of temperature distribution across the bonded interface over the duration of the thermal penetration experiment. During the first 5 minutes of the experiment the temperature in most of the bonded interface remained around 60°C whereas by 30 minutes the temperature reached over 112.5°C all over the interface. Within the hour mark of the start of the experiment, the temperature at the middle portion of the bonded interface was around 147.5°C while at the edge of the interface the temperature reached around 182.5°C. After 90 minutes, the temperature of the whole interface was over 182.5°C.

3.2 Bond Strength Lap-joint Tests

3.2.1 Strength Tests at Ambient Temperature

The purpose of bond strength test at ambient temperature was to obtain an indicative value to be used for determination of forces for different loading percentage. Table 3.1 shows the results for the bond strength test at ambient temperature. In total 4 samples were tested among which, test 2 had highest failure load of 81.02KN followed by test 1 with 69.75KN and test 3 and 4 had failure loads of 58.02KN and 57.50KN respectively of the four. Thus from the four test an average bond strength at ambient temperature was determined as 66KN. Figure 3.3 shows results of the tests and Figure 3.4 shows the failure of the samples tested at ambient temperature.
In the figure it can be seen that the load increases linearly against the cross-head displacement of the MTS and the starts to plateau at around 5mm displacement for all the tests. The plateauing continues until the failure of the sample and the failure mode for all those test was timber failure. Test 1, 2 and 3 showed larger displacement than test 4.

Table 3.1: Results of Bond Strength Tests at Ambient Temperature

Test	Failure Load (KN)	Cross-head Displacement (mm)
AT_ 1	69.75	30.18
AT_ 2	81.02	31.98
AT_ 3	58.02	36.92
AT_ 4	57.50	11.80

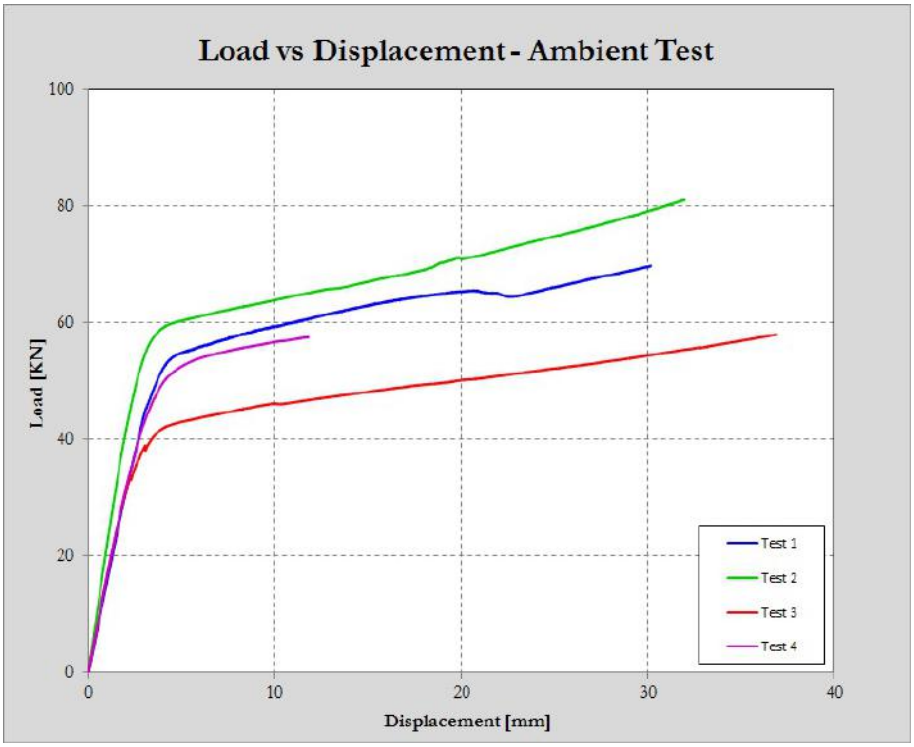


Figure 3.3: Load Vs cross-head displacement graph for ambient temperature single lap-joint bond strength tests

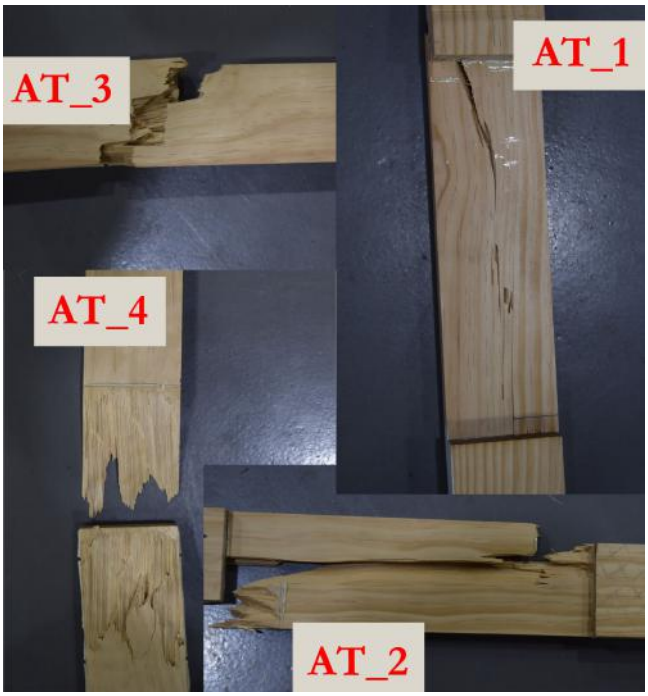


Figure 3.4: Failure of samples considered for strength of lap joint at ambient temperature

3.2.2 Strength Test at Elevated Temperature

The bond strength tests of the lap joint were performed with different loading percentage compared to the average bond strength calculated from the ambient test. The different loading percentage with the corresponding values are presented in Table 3.2. The tests were started with 70% loading ratio followed by 50% and 30% respectively. Two samples were tested for 30% neither of which didn't fail until 2 hours of heating so afterwards the load was gradually increased until failure. Then one sample with 40% was tested which didn't fail until 2 hours of heating as well, thus a higher loading percentage of 45% was selected instead. Table 3.3 shows the results of the 45%, 50% and 70% of the average bond strength capacity at ambient temperature, mid refers to the area of the bonded interface from and inside of the thermocouple TC5 (see Figure 2.7) and edge refers to the area outside of that.

Table 3.2: Loading ratios corresponding values and stresses induced across the bonded interface

Loading Percentage [%]	Loading Values [KN]	Stress Induced across Bonded Interface [N/mm^2]
30	20	0.37
40	26	0.49
45	30	0.56
50	33	0.62
70	45	0.84

Figure 3.5 and Figure 3.6 presents the results of the tests where delamination failure at the bonded interface was obtained. The failure temperatures were determined according to the procedure explained in Figure 2.16 and the graphs for the individual loading percentage are presented in Appendix B. The results for each loading percentage are explained in detail below.

45% load capacity of average bond strength

5 samples were tested for the 45% load capacity of average bond strength, among which test 1, 3 and 5 failed with delamination of the lap joint while test 2 and 4 didn't fail until 2 hours of heat after which the load was gradually increased until failure. Both test 1 and 5 lasted just over 25 minutes before the joint failed in delamination, whereas test 3 lasted around 80 minutes before failing in delamination. The range of failure temperature observed were 119.4°C - 174°C and 103.9°C - 160.3°C for the edge and mid of bond interface respectively. Figure 3.7 shows the failure of the test samples, test 1 and 5 had clear delamination failure while in test 3 although the initiation of the failure was through delamination of the bond at the edge the crack propagated into the timber as well.

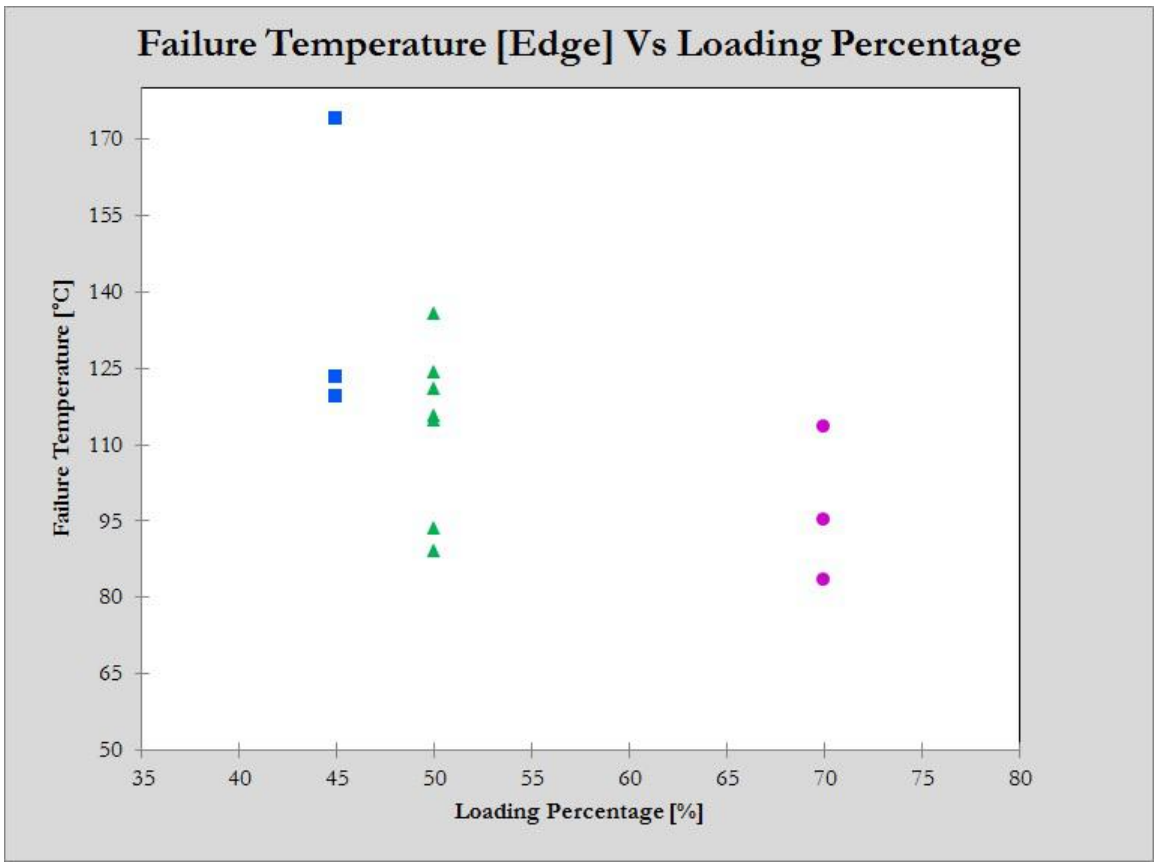


Figure 3.5: Failure Temperature at the edge of bonded interface for different loading percentage

50% load capacity of average bond strength

For the 50% load capacity of average bond strength in total 11 samples were tested among which test 1, 4, 5, 6, 7, 10 and 11 failed with delamination of the bonded interface. Whereas, test 2 and 9 didn't fail for the whole heating period of 2 hours, afterwards the load was increased until failure. Test 3 and 8 however had a premature timber failure and so the results were not included for those tests. Figure 3.8 and 3.9 shows the failure of the samples, among which test 1, 5 and 11 failed with clear delamination and test 4, 6, 7 and 10 had failure initiated through delamination with some timber failing as well. The range of failure temperature observed were 89.1°C - 135.9°C and 71.8°C - 113°C for the edge and mid of bond interface respectively.

70% load capacity of average bond strength

For the 70% load capacity of average bond strength 3 samples were tested and all 3 of them failed in delamination. In figure 3.10 the delamination failure of all the three samples are showed. The figure shows some timber failure as well in the samples but that is due to the complexity of the stresses induced which propagates from the bondline

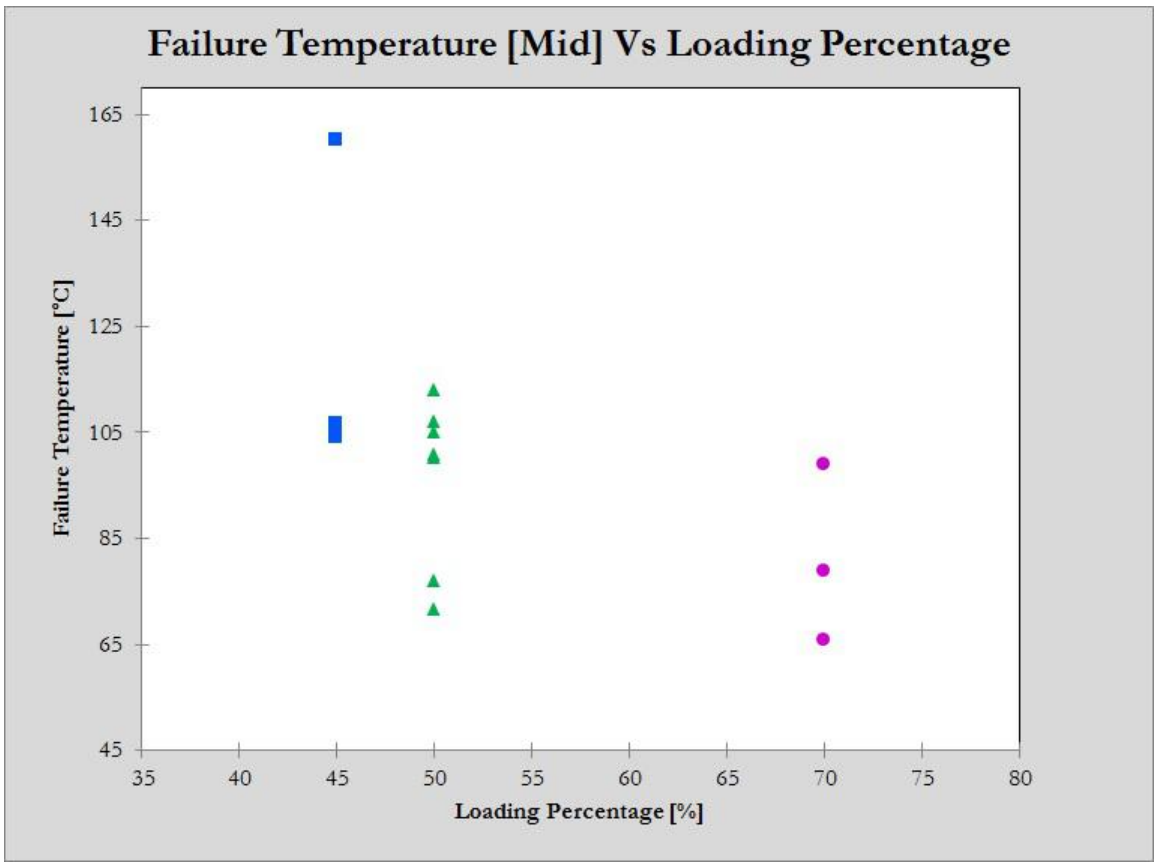


Figure 3.6: Failure Temperature at the mid of bonded interface for different loading percentage

towards the weaker portion of timber during the time of failure. The range of failure temperature observed were 83.3°C - 113.3°C and 65.8°C - 98.8°C for the edge and mid of bond interface respectively.

3.3 Dynamic Mechanical Thermal Analysis

The dynamic mechanical thermal analysis of the polyurethane adhesive was performed in order to determine the glass transition temperature (T_g) of the polyurethane so that a correlation could be made between the reduction of the mechanical properties of polyurethane and the degradation of bond strength of the lap joint timber sample bonded with polyurethane. Two polyurethane samples were tested and the result of those tests are presented in figure 3.11.
The figure represents the curves of the normalized storage modulus (E') of the polyurethane samples, as it can be seen the reduction in the modulus starts after 30°C for both the samples. At around 60°C the modulus of sample 2 is reduced to 60% whereas for sample

Table 3.3: Results of Bond Strength Tests at Elevated Temperature

Loading Percentage [%]	Test Number	Failure Temperature [°C]		Failure Mode
		Edge	Mid	
45	ET_45%_1	123.2	106.5	Delamination*
	ET_45%_2		>200	No failure**
	ET_45%_3	174	160.3	Delamination*
	ET_45%_4		>200	No failure**
	ET_45%_5	119.4	103.9	Delamination*
50	ET_50%_1	115.7	100.9	Delamination*
	ET_50%_2		>200	No failure**
	ET_50%_3		-	Timber failure***
	ET_50%_4	89.1	71.8	Delamination*
	ET_50%_5	135.9	113	Delamination*
	ET_50%_6	124.3	107.1	Delamination*
	ET_50%_7	114.9	100.3	Delamination*
	ET_50%_8		-	Timber failure***
	ET_50%_9		>200	No failure**
	ET_50%_10	121	105.1	Delamination*
	ET_50%_11	93.7	77.1	Delamination*
70	ET_70%_1	113.3	98.8	Delamination*
	ET_70%_2	95.1	78.7	Delamination*
	ET_70%_3	83.3	65	Delamination*

* Delamination refers to the failure at bonded interface.
** Sample didn't fail until 2 hours of heating.
*** Sample failed in timber prematurely during testing.

1 it was about 70%. However, both the samples had 50% reduction in their modulus at around 70°C and were reduced to 30% at around 120°C. The samples showed wide range of glass transition temperature starting from 25°C to 200°C, where the modulus of the samples were reduced down to around 10%.

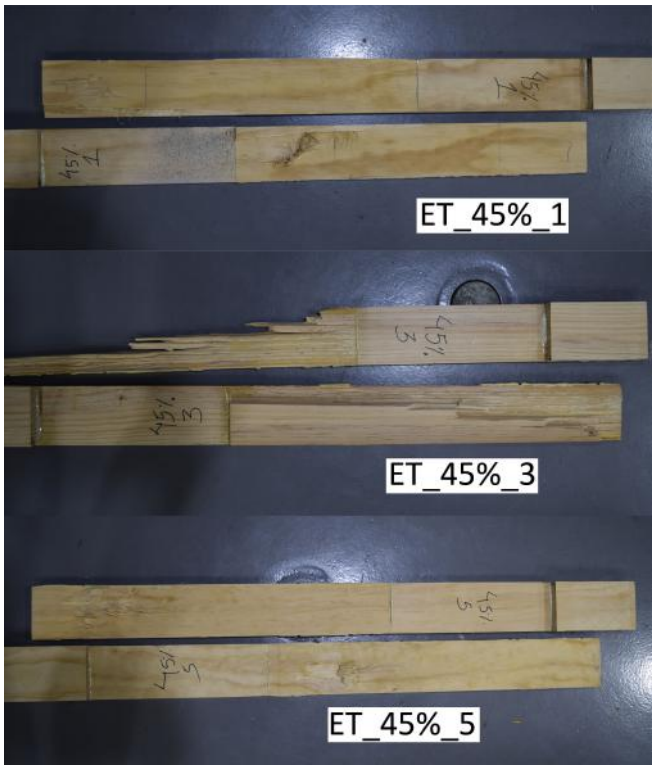


Figure 3.7: Delamination of samples at 45% loading

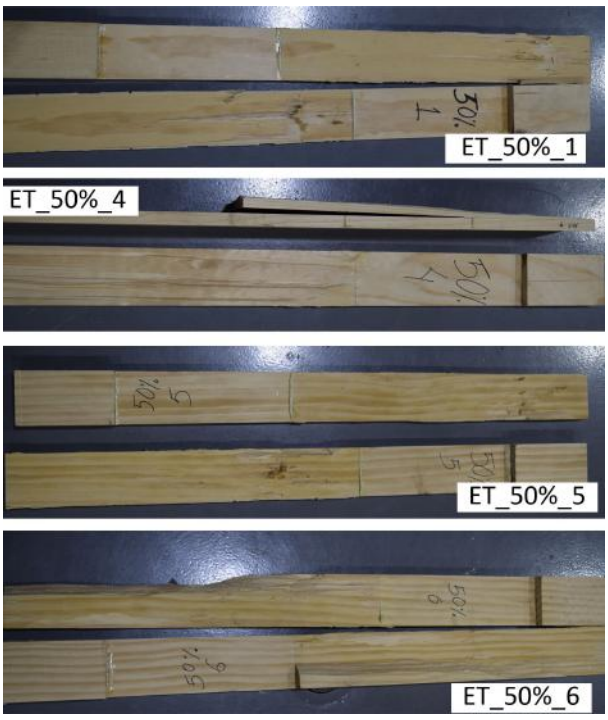


Figure 3.8: Delamination of samples at 50% loading

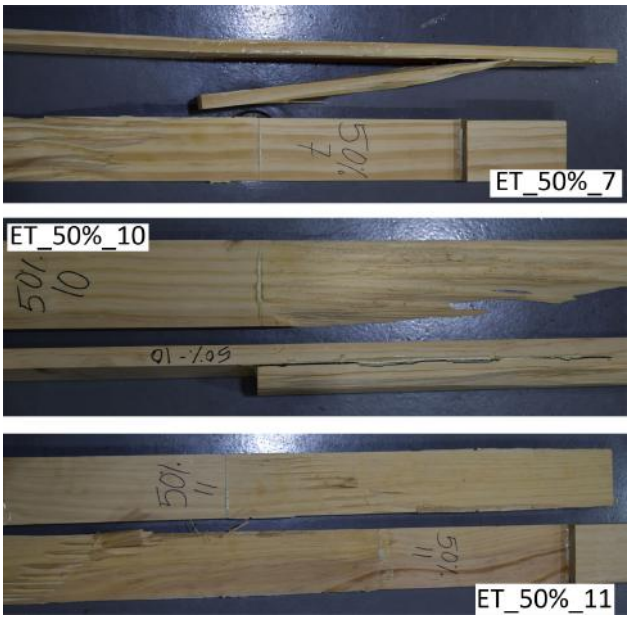


Figure 3.9: Delamination of samples at 50% loading

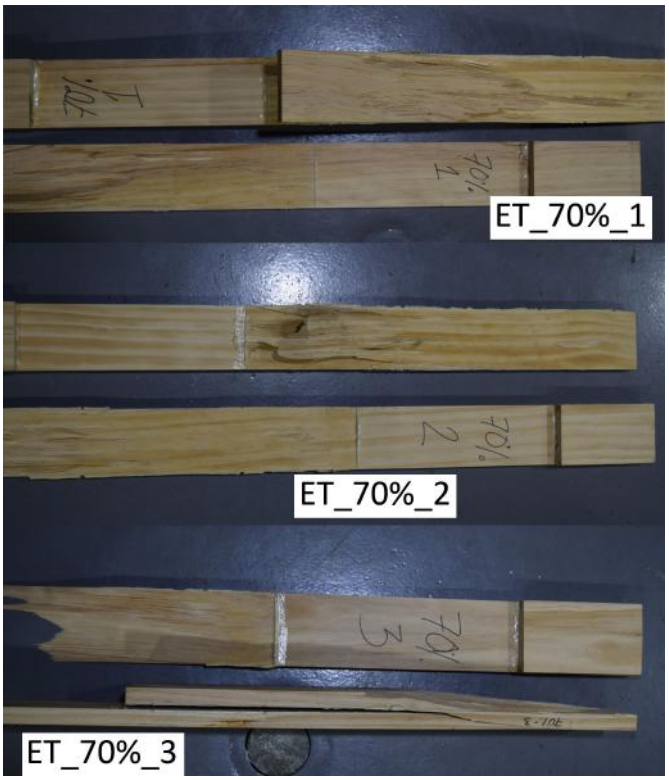


Figure 3.10: Delamination of samples at 70% loading

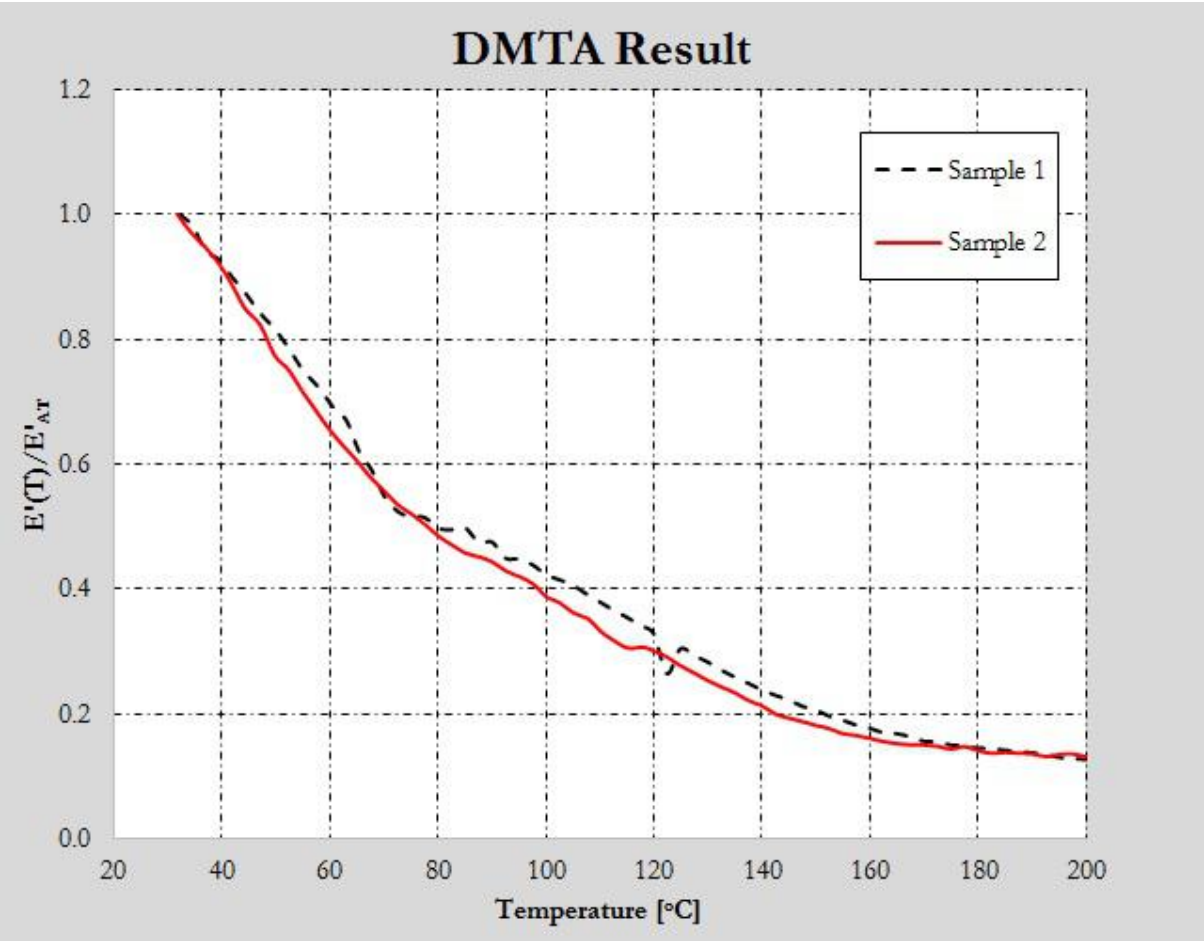


Figure 3.11: DMTA results of Polyurethane adhesive samples

4

Analysis and Discussions

The previous section presented the results obtained from the experiments performed in context of meeting the objectives of this thesis. This section presents the analysis, interpretation and discussions on the obtained results. Single lap-joint timber specimens were tested for bond strength at elevated temperature. The tests were carried out at various loading percentage of the average bond strength capacity at ambient temperature. Different failure mechanisms were observed during the entire sets of experiments, as listed below:

i Failure at the bonded interface (Delamination)
Here the failure was observed at the bonded interface because of the reduction in the strength of the adhesive which leads to clear delamination of the lap-joint

ii Failure at the timber
The failure observed here was at the timber rather than at the bonded interface.

iii No Failure
Here no failure either at the bonded interface or the timber was observed for the sample during the entire heating period of 2 hours.

Among the failure mechanism presented above, only the delamination failure of the single lap-joint specimens were observed at 70% loading of the average bond strength capacity at ambient temperature. While for the 50% loading, diverse failure mechanisms were observed. Among the 11 samples tested, 7 of them failed with delamination of the single lap-joint and for 2 samples timber failure was observed whereas 2 samples did not fail at all during the entire heating period of 2 hours. This was observed for 2 samples tested with 45% loading of the average bond strength as well, while the remaining 3 samples failed with delamination of the lap-joint. However, no timber failure was observed for any samples test with 45% capacity of the average bond strength. Apart from that, for the two lower load capacity (i.e. 30% and 40%) tested no failure of the single lap-joint was observed at all for the entire 2 hours heating duration, the numbers of samples tested for these load capacities were 2 and 1 respectively.

The interpretation of the figure demonstrating the failure temperature against the loading percentage shows that at lower load capacities there is a larger scatter in the results and the range of failure temperature is wider as well. However, as the load capacity increases the result begins to converge to a narrower range of failure temperature with less scattering of the result. As the loading percentage increases, the failure mechanism was found to be more consistent.

The Dynamic Mechanical Thermal Analysis of the polyurethane adhesive was also performed and the result showed a wide range of glass transition temperature. The result obtained from the DMTA shows correlation with the results obtained from the bond strength tests of the single lap-joints. The DMTA result shows 30% reduction in the strength of the adhesive at around 60°C and the failure is observed to begin at around 65°C at the mid of the bonded interface for the single lap-joint loaded with 70% of the average bond strength capacity. Likewise, the temperature corresponding to 50% reduction in the strength of the adhesive for the DMTA result is over 70°C and the failure at 50% loading initiates from over 71°C at the mid of the bonded interface. For 45% loading of the average bond capacity, the failure initiates at temperature above 103°C at the bonded interface whereas the DMTA result for the temperature corresponding to 55% reduction in the adhesive strength is around 90°C. However having said that, as polyurethane forms up at atmospheric condition, there were some issues during the casting of the samples. As a result of which the polyurethane adhesive samples used for the DMTA were not perfectly homogeneous and there were some air gaps within the specimens. The influence of these air gaps in the results obtained from the DMTA is unknown and it might be possible that the presence of these air gaps may have affected the results and the glass transition temperature range for the particular one-component polyurethane adhesive could otherwise have been different from what has been obtained. This can be taken as one major draw back of this thesis and in order to verify the findings of the DTMA in this work more tests need to be done on more homogeneous specimens of the one-component polyurethane adhesive used.

In the interpretation of the failure temperature correlation with the DMTA result, the reason for choosing the temperature at the mid portion of the bonded interface is that during the entire testing duration (until failure), of all the specimens, the proportion of temperature distribution is higher at the mid portion of the bonded interface i.e. the temperature of the mid portion is more uniform and covers larger sector of the bonded interface at any given instant of time which can be observe in the Figure 3.2 of Section 3.1, this distribution of temperature across the bonded interface stays consistent until the entire bonded interface reaches a steady temperature after 90 minutes of heating.

However, the steep rise in temperature towards the edge of the bonded interface has an influence in the delamination of the lap-joint. This can be explained from the fact that the peeling stresses are high near the edge of the lap-joint (as shown in Figure 1.22 of the literature), it is this stress that causes the delamination of the joint. As the temperature

of the bonded interface increases, the strength of the adhesive starts to degrade which results in the loss of cohesion within the adhesive and the loss of adhesion between the adhesive and the timber, which results in the failure of the joint at the point of high stress concentration which then propagates inward along the bond line leading to the delamination failure of the joint.

As for the timber failure that was observed in 50% of the average bond strength capacity, with the increasing temperature there is a gradual reduction in the strength of the timber itself as well along with the adhesive. Given the non-homogeneity of timber and the presence of defects, the reduction of strength of timber with increasing temperature becomes critical and as the adhesive has a steady strength reduction, the failure progress through the weaker portion of timber. Meanwhile, no failure for the entire duration of heating, until the bonded interface temperature reached a steady state, was also observed in the 50% loading along with the 45%, 40% and 30% of average bond strength capacity. This performance is expected of the lower loading percentage as the stress induced in the bonded interface is low at those loading percentage and that might not be enough to initiate the failure of the interface for the range of temperature investigated. Executing the experiment at higher temperature range might yield delamination failure of the lap-joint for lower loading percentage of average bond strength capacity.

The delamination of the adhesively joined single lap-joint timber have been observed to occur at relatively lower temperature for a higher loading percentage. The critical temperature for failure of the bond line is lower of high stress level induced and much higher for lower stress level. With that in mind, the consideration that needs to be made is "Does the degradation of the adhesive reduce the load carrying capacity of laminated timber members faster than the weakening induced by loss of cross-section associated to charring under fire scenario?". For a certain laminated timber structure, depending up on the material properties there will be a certain rate of charring . And the temperature profile below the char front will be such that the temperature right ahead of the char front will increase and will follow a steep gradient towards the inner section of the member. For a bond line at a certain depth, the applied load will induce certain stress along this line. If the stresses in the bond line are high then only a small increase in temperature is required to cause failure of the bond line. If the stresses induced in the bond line are lower then much higher temperature is needed to cause failure of the bond line. The propagation of the lower temperature range at the end of the thermal profile is much faster than the propagation of the higher temperature range. Therefore for a heavily loaded structure, the degradation of the adhesive strength becomes more critical than charring since the bond line will reach its critical failure temperature before the char front approaches the bond line. For a lightly loaded structure, the propagation of the higher temperature range is similar to the velocity of charring rate, then cross-section reduction failure induced by charring and degradation of adhesive strength failure appear simultaneously.

5

Conclusions

5.1 Conclusions

Delamination in laminated timber structures at elevated temperature was studied. The aim was to investigate the influence of degradation of adhesive properties on the reduction of the strength of glued timber joints at elevated temperature. Necessary methodologies were developed for the fulfilment of the objectives. Bond strength test of single lap-joint timber specimens bonded with polyurethane adhesive were performed at elevated temperature under varied loading percentage of the average bond strength capacity at ambient temperature. Dynamic Mechanical Thermal Analysis of polyurethane adhesive was also performed to investigate the degradation of the adhesive strength at elevated temperature.

For all the samples tested at higher loading percentage, the failure mechanism observed was clear delamination of the single lap-jointed timber specimens. However, for the samples tested at lower loading percentage diverse failure mechanism were observed including delamination failure of the lap-joint, failure of timber and no failure observed for the entire duration of heating. The results clearly revealed the eminent degradation of bond strength of single lap-joint timber at elevated temperature. Wide range of failure temperature along with higher scatter of result regarding the failure mechanism was observed for samples tested with lower loading percentage. For the samples tested with higher loading percentage the failure temperature had narrow range with smaller scatter and consistent failure mechanism. The Dynamic Mechanical Thermal Analysis of the polyurethane adhesive also showed a wide range of glass transition temperature for the particular one-component polyurethane adhesive under study. The results obtained from the Dynamic Mechanical Thermal Analysis of the polyurethane adhesive show correlation with the results obtained from the bond strength tests of single lap-joints.

Clear delamination failure of the single lap-joint was observed at lower temperature range for higher stress levels. From this a conclusion that could be made is, for a heavily loaded structure the degradation of the adhesive strength becomes more critical than charring since the bond line will reach its critical failure temperature before the char

front approaches the bond line. While for a lightly loaded structure, the propagation of the higher temperature range is similar to the velocity of charring rate, then cross-section reduction failure induced by charring and degradation of adhesive strength failure appear simultaneously.

5.2 Recommendation for Future Work

The following recommendation for future research could be drawn from the findings of the work performed herein:

- In the bond strength tests of the single lap-joint at elevated temperature carried out at lower loading capacity, inconsistent failure mechanisms were observed. This could be eliminated by determining the critical bond length, where the failure mechanism at ambient temperature shifts from timber failure to bond line failure, for the studied dimension of the bonded interface. This way delamination failure of the bonded interface at elevated temperature for the different loading capacities may be ensured.

- The polyurethane adhesive samples used for the Dynamic Mechanical Thermal Analysis were not homogeneous throughout the entire length, this might have affected the obtained results. Therefore, better results might be obtained for the glass transition temperature of polyurethane adhesive with a more homogeneous sample.

- As explained in the Discussion Section, the heat induced degradation of adhesive strength is critical than the propagation of charring for heavily loaded laminated timber structures, future research might be focused on quantifying the critical loading ratio above which the adhesive strength degradation becomes the governing factor for the load bearing capacity of the structural laminated timber member.

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Appendix A

Thermal Penetration Test Results

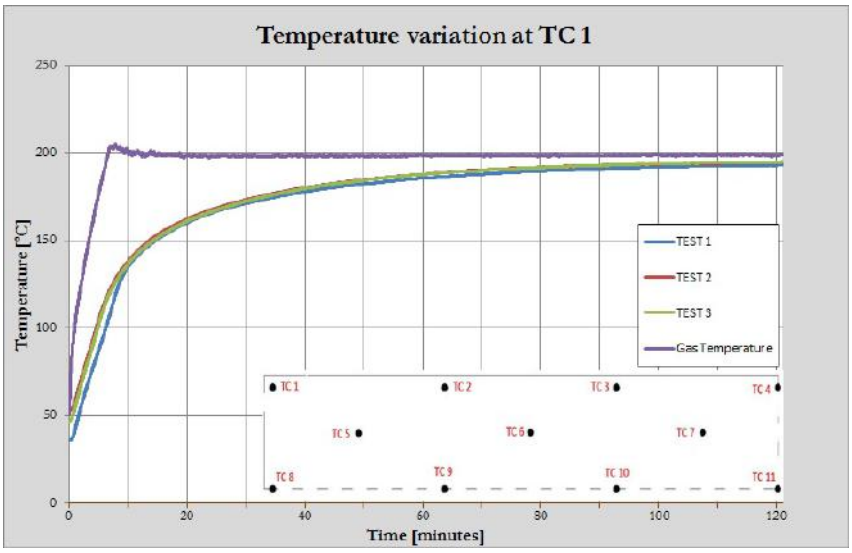

Figure A.1: Thermal penetration result at position 1

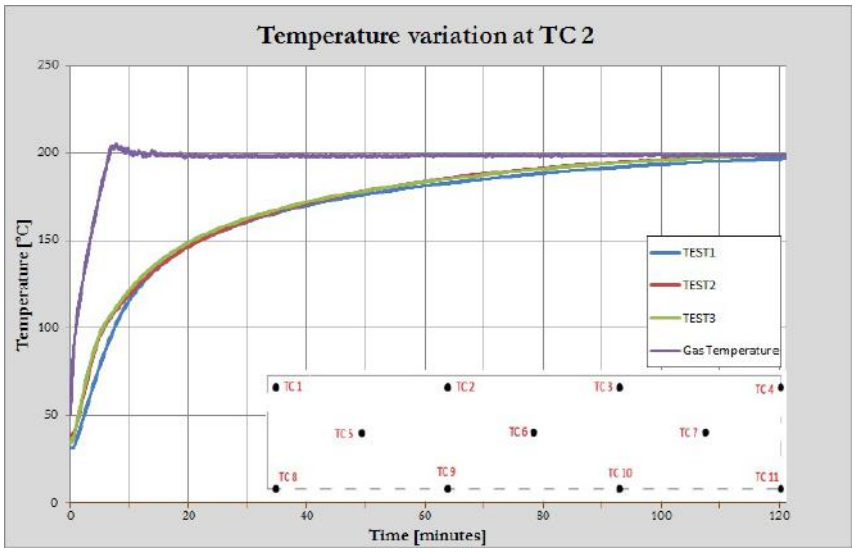

Figure A.2: Thermal penetration result at position 2

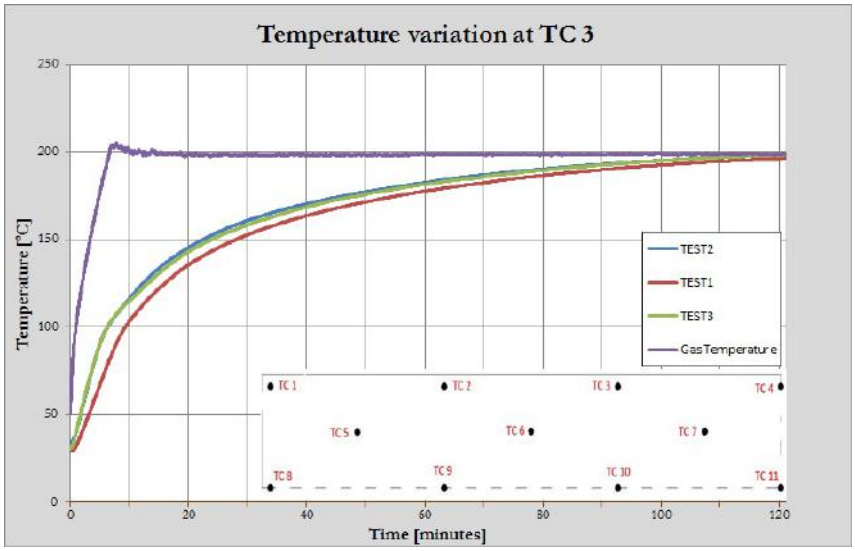

Figure A.3: Thermal penetration result at position 3

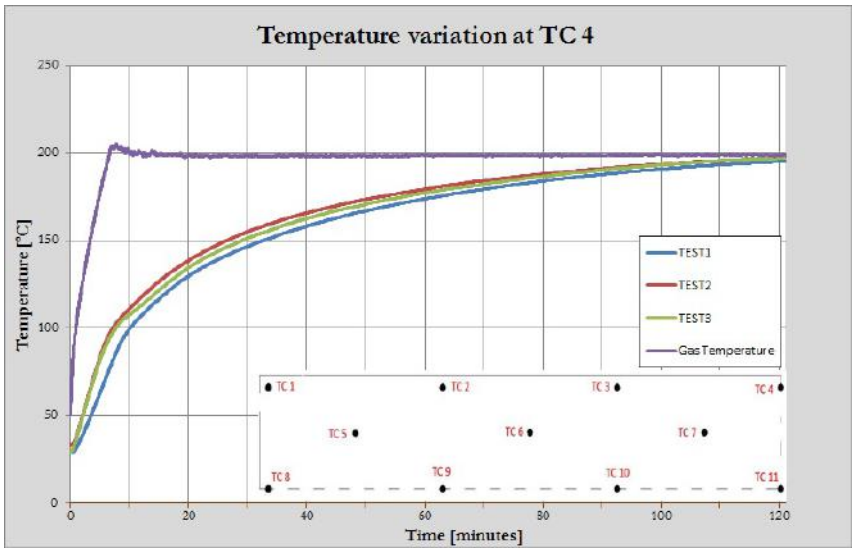

Figure A.4: Result of Thermal penetration test over the bonded interface

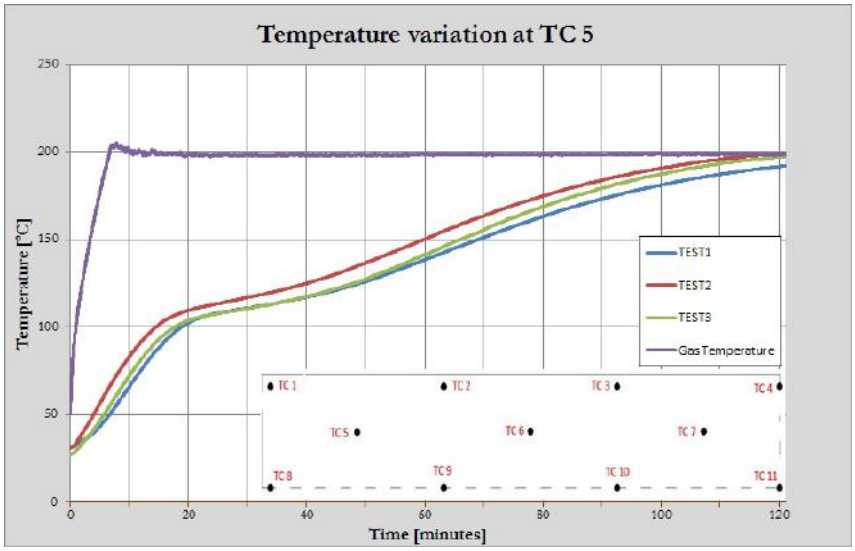

Figure A.5: Result of Thermal penetration test over the bonded interface

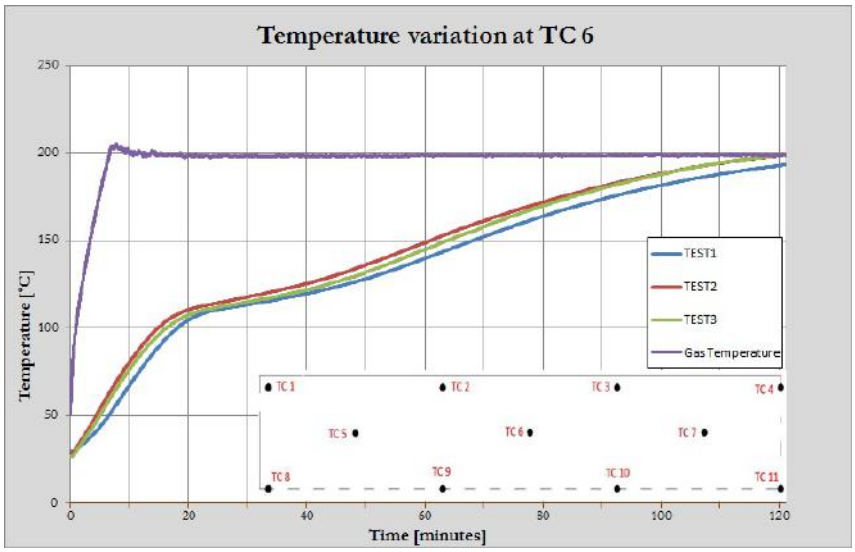

Figure A.6: Result of Thermal penetration test over the bonded interface

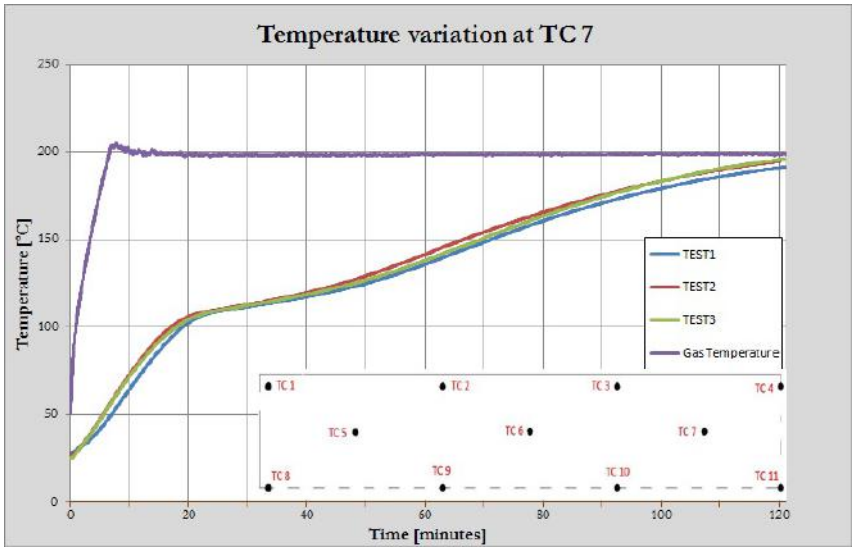

Figure A.7: Result of Thermal penetration test over the bonded interface

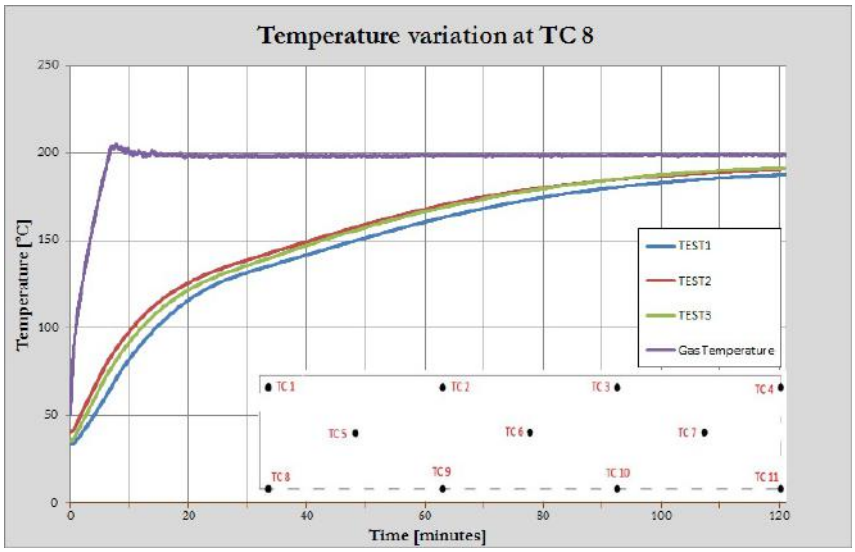

Figure A.8: Result of Thermal penetration test over the bonded interface

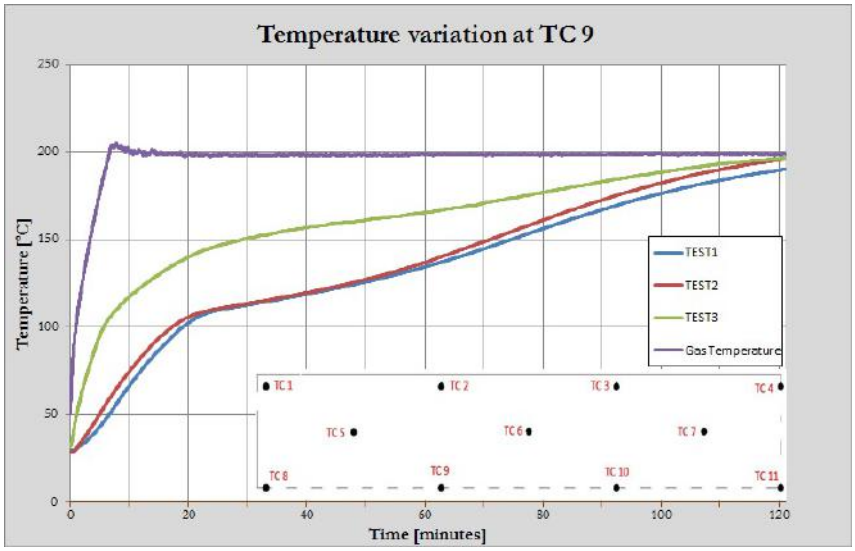

Figure A.9: Result of Thermal penetration test over the bonded interface

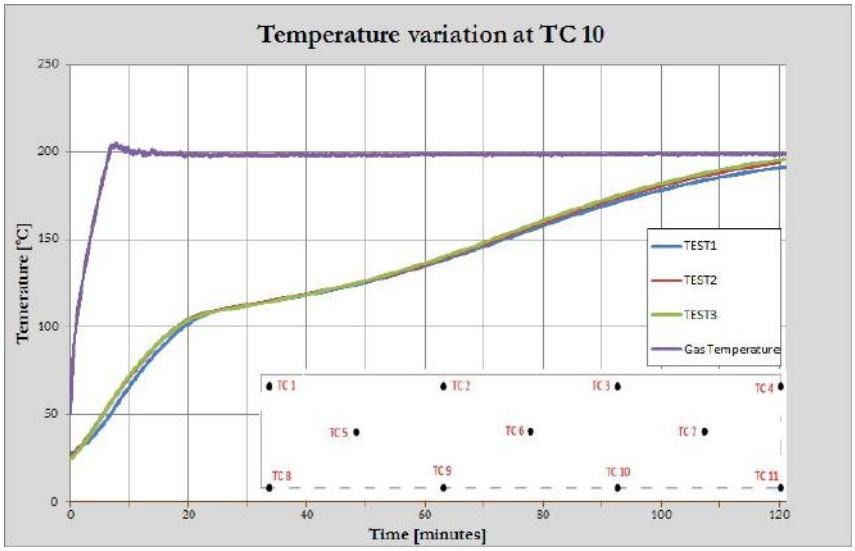

Figure A.10: Result of Thermal penetration test over the bonded interface

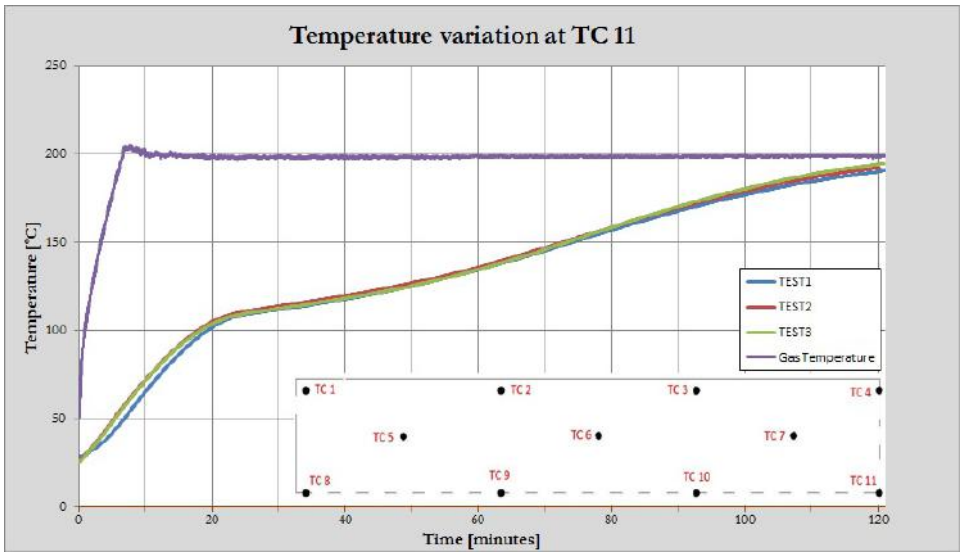

Figure A.11: Result of Thermal penetration test over the bonded interface

Appendix B

Bond Strength Tests Results

B.1 Elevated Temperature Test

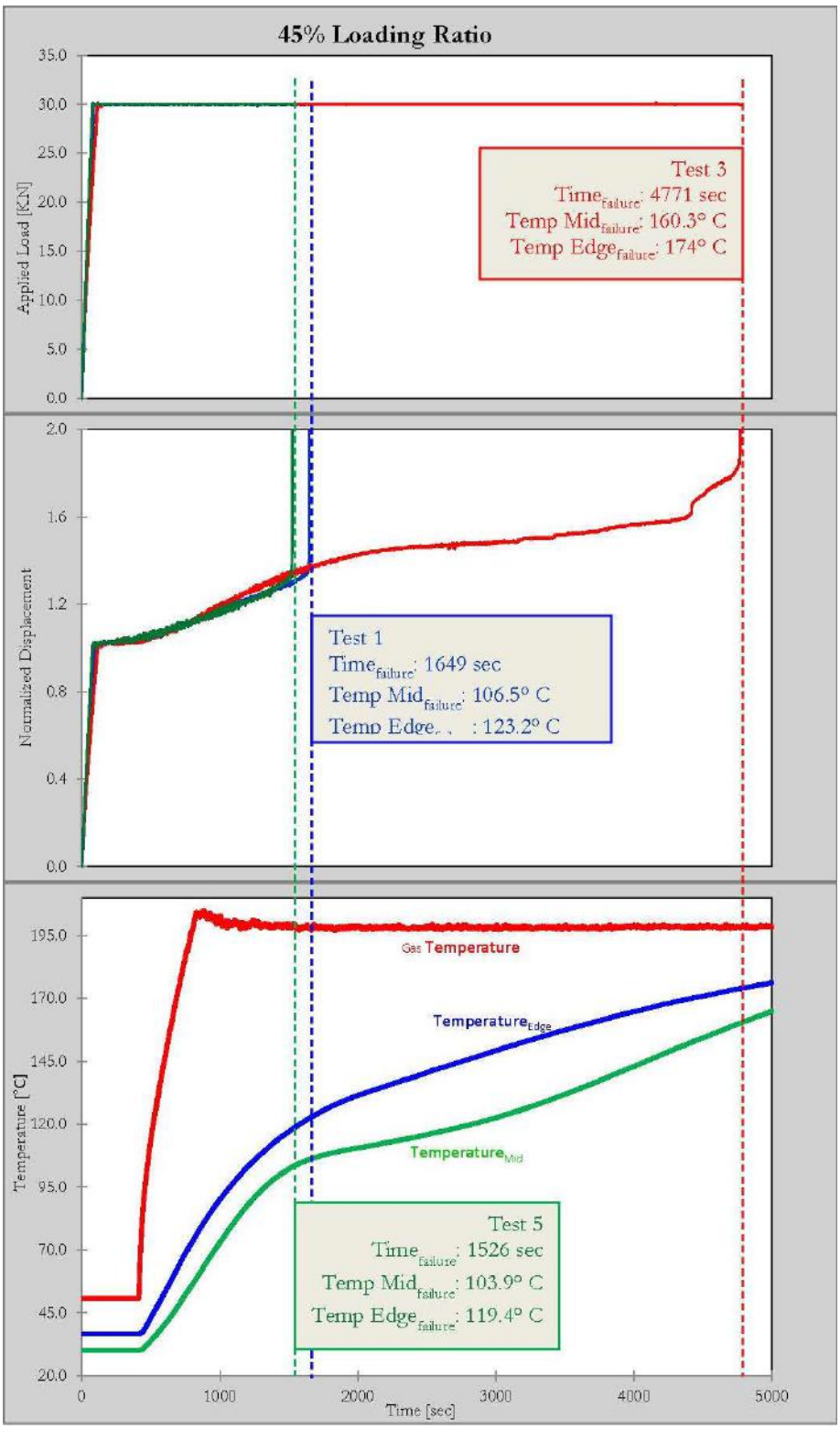

Figure B.1: Elevated Test at 45% loading

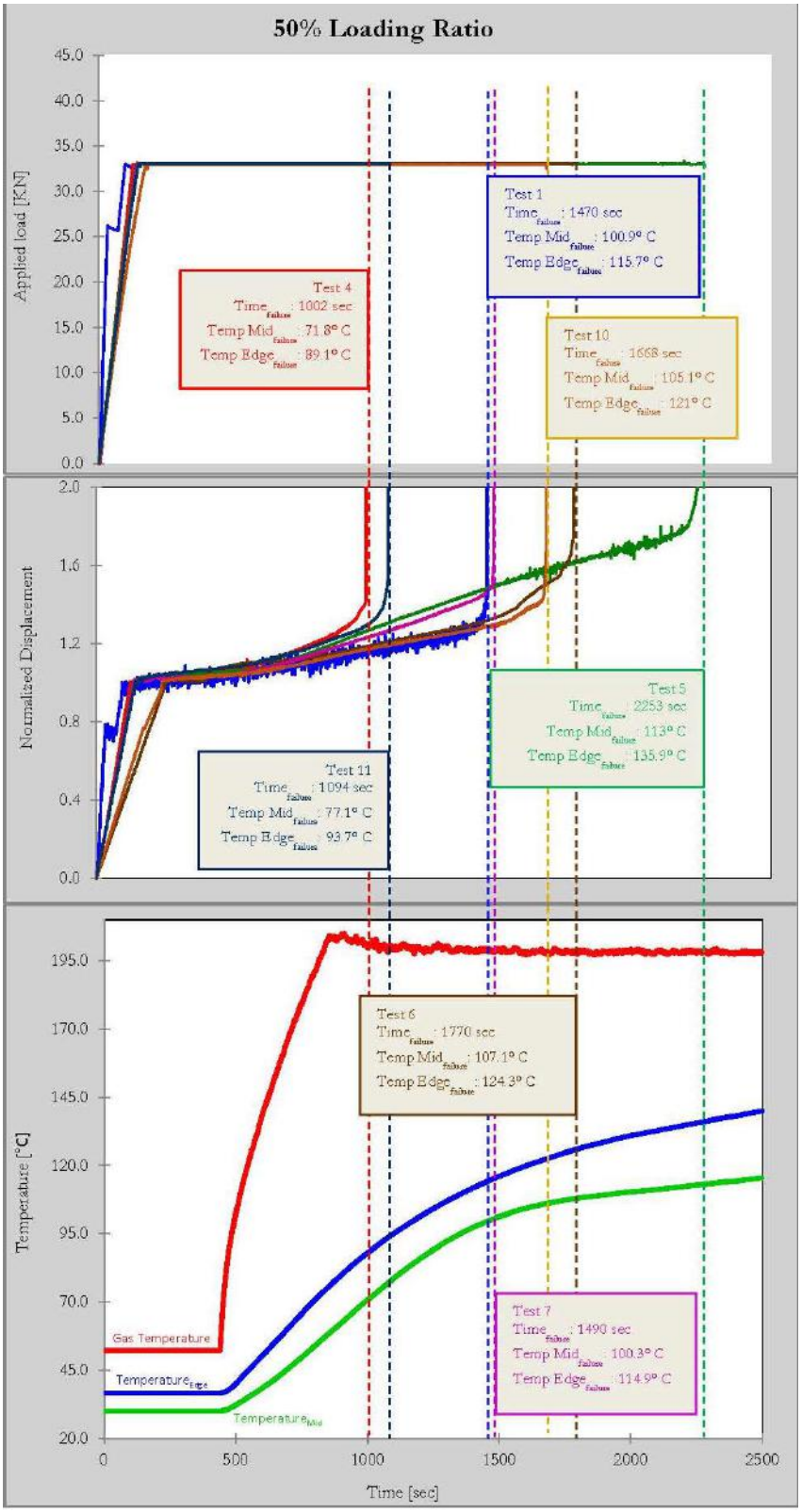

Figure B.2: Elevated Test at 50% loading

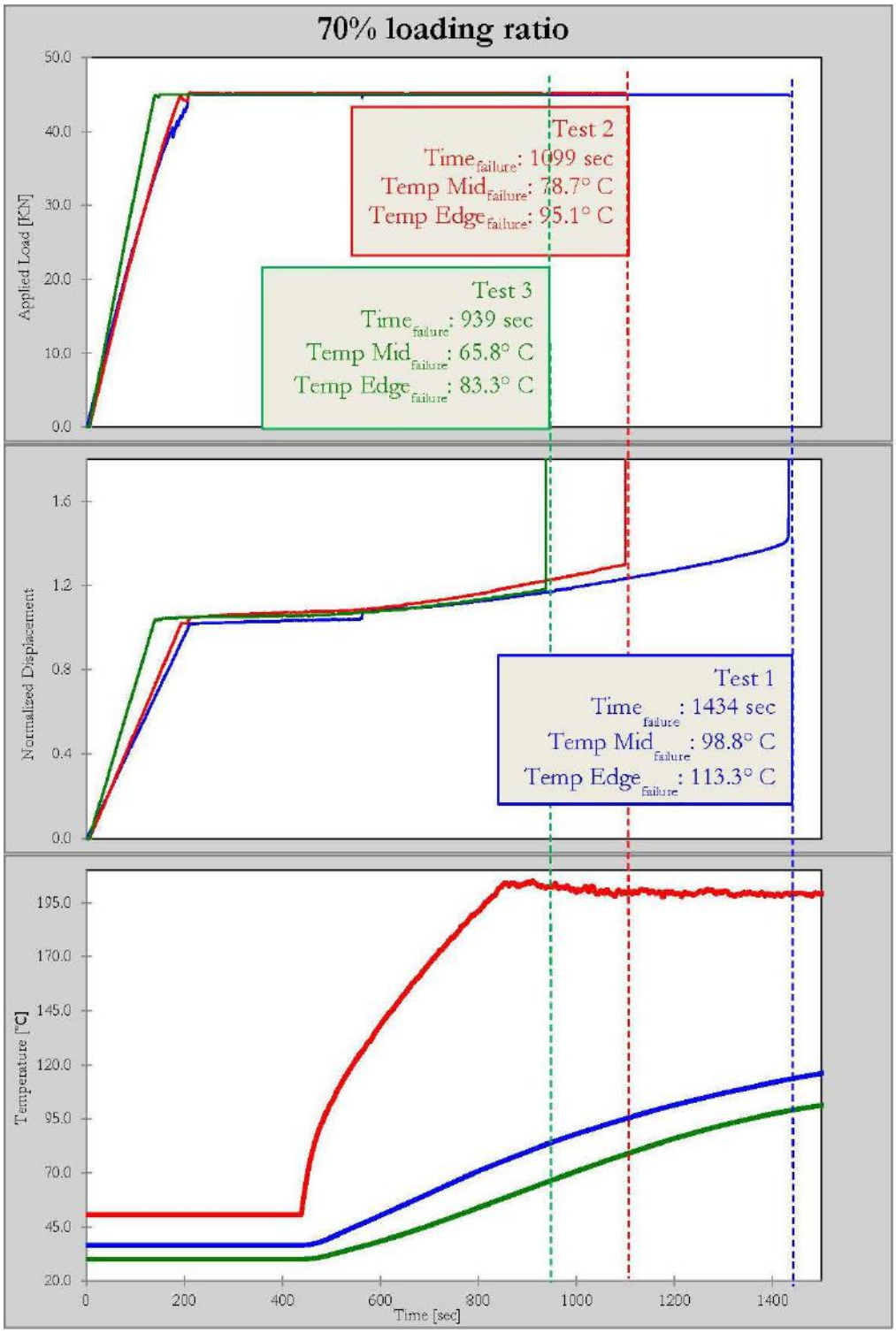

Figure B.3: Elevated Test at 70% loading