Forest&Wood Products Australia
Knowledge for a sustainable Australia

PRODUCTS & PROCESSING

PROJECT NUMBER: PNB036-0607 MAY 2009

Mechano-Sorptive Nailplate Backout in Nailplated Timber Trusses

This report can also be viewed on the FWPA website
www.fwpa.com.au
FWPA Level 4, 10-16 Queen Street,
Melbourne VIC 3000, Australia
T +61 (0)3 9614 7544 F +61 (0)3 9614 6822
E info@fwpa.com.au W www.fwpa.com.au

Mechano-Sorptive Nailplate Backout in Nailplated Timber Trusses

Prepared for

Forest & Wood Products Australia

by

P. Paevere, M. Nguyen, M. Syme, R. Leicester, K. Ho

Publication: Mechano-Sorptive Nailplate Backout in Nailplated Timber Trusses

Project No: PNB036-0607

This work is supported by funding provided to FWPA by the Australian Government Department of Agriculture, Fisheries and Forestry (DAFF).

ISBN: 978-1-920883-61-4

Researcher:
P. Paevere
CSIRO Sustainable Ecosystems
P.O. Box 56, Highett, Victoria 3190

Final report received by FWPA in March, 2009

Forest & Wood Products Australia Limited
Level 4, 10-16 Queen St, Melbourne, Victoria, 3000
T +61 3 9614 7544 F +61 3 9614 6822
E info@fwpa.com.au
W www.fwpa.com.au

Table of Contents

LIST OF FIGURES

LIST OF TABLES

1. Executive Summary

1.1. Introduction

Plated timber trusses have been used extensively and successfully for house construction in Australia over several decades. However truss problems were reported at a retirement village in 2002, and after a subsequent series of inspections, some of the nailplates in some roof spaces were observed to have separated from the parent timber. In some cases the nailplates appeared to have 'backed out' of over time. These examples of nailplate backout were predominantly observed in un-sarked concrete tiled roof spaces. Although it is well known that backout due to moisture cycling can occur in exposed nailplated joints, it is not thought to have been a problem within the building envelope.

Separation of nailplates from parent timber, for any reason, is of concern, because even a small amount of separation (1mm) can have a significant effect on structural capacity of nailplated connections (>25% strength loss). Separation of nailplates from parent timber can occur due to several different factors including:

- Backout over time due to repeated swelling and shrinkage of the wood under moisture/humidity variations in the roof space over time (mechano-sorptive backout)
- Lateral movement across the joint due to poor handling practices in the manufacturing plant, or during transport, storage and/or installation;
- Errors in manufacturing process resulting in plates that are not fully embedded;
- Overloading

These effects can occur singly or in combination, but this investigation is limited to an examination of the conditions that contribute to the mechano-sorptive backout due to moisture cycling effects. Mechano-sorptive backout is of particular concern, as this is potentially cumulative over time, and potentially hidden until failure.

This report presents the results of an extensive investigation into mechano-sorptive nailplate backout. The results have helped to facilitate understanding and prediction of the phenomenon, and has provided the basis for the development of methods to estimate the extent of the problem in the existing housing stock, and to test potential solution options.

The coordinated program of research activities developed to achieve these objectives are described in detail in the following sections.

1.2. Literature Review

Literature related to nailplate backout, as summarised in Nguyen and Paevere (2006), is scarce, and mostly consists of anecdotal observations of isolated cases, which are generally attributed to shrinkage and swelling due to moisture changes in timber. There is a larger body of literature on 'nail-pop', which is a very similar phenomenon, but the majority of this literature is also anecdotal. Recently, Paevere et. al. (2004) reported extensive nailplate backout in a series of 10-year-old retirement home complexes located along South-Eastern Australia. Common features of these houses were the uses of seasoned pine, a common brand of 1.2mm-thick nailplates (Steelfast – now obsolete), low pitch trusses with spans of about 10m, and un-sarked tiled roof construction.

1.3. Numerical Modelling

A suite of numerical models were developed to facilitate understanding and enable estimation of:

- roof micro-climate based on external climate and roof configuration
- cyclic wood moisture profile based on roof microclimate
- cyclic wood deformation based on wood moisture profile
- mechanical interaction between wood and nailplates under cyclic wood deformation
- mechano-sorptive plate backout based on cyclic wood deformation profile, nailplate characteristics, and joint loading

Hence for any location in Australia, using local met-bureau data and basic details of the roof and joint configuration, the models can be used to estimate the likely mechano-sorptive plate backout.

The numerical models were calibrated using data from laboratory experiments, field monitoring, and roof inspections, and then used to estimate backout under a range of different scenarios. It was shown that the models are capable of predicting nailplate backout behaviour under a wide range of moisture cycling regimes and loading conditions.

1.4. Laboratory Simulations and Experiments

A series of laboratory simulations and experiments were undertaken to help gain a fundamental understanding of nailplate backout, and to calibrate and reality-check the developed numerical models. The experiments and their outcomes are described briefly in the following.

1.4.1. Swell-Shrink tests

The objective of the swell-shrink tests was to simulate wood and nailplate movement under moisture cycling and to collect calibration data for the wood deformation and nailplate backout models. In these series of tests, nailplated joints were subjected to various moisture-cycling regimes and the deformation response of the wood and nailplates were measured very accurately. The effects of different joint loadings, the application of two different types of joint sealant, and some other factors were examined.

Key findings from these experiments were as follows:

- The amount of load on a joint has a profound effect on the rate of nailplate backout under moisture cycling
- Application of a sealant can potentially slow or stop mechano-sorptive nailplate backout from occurring under cycles of wetting and drying
- Highly loaded joints can potentially fail to rupture under a small number of cycles of wetting and drying (< 50 cycles). These tests were based on samples with only two rows of teeth per side, and hence failure may have been accelerated compared to full nailplate connections.

1.4.2. Press-Pull tests

The objective of the press-pull experimental program was to examine the ratio between the penetration (pressing) and withdrawal resistances of nailplates pressed into pine under a range of exposure conditions. This is important because it is this ratio which determines the rate at which cumulative nailplate backout occurs under cyclic wood swelling and shrinking.

In these tests, nailplates were pressed into timber with different grain orientations, and then subjected to different exposure regimes before being withdrawn and re-pressed. Key findings from these tests were:

- Ratios of penetration to withdrawal resistance ranged from 3.13 to 9.72. This indicates that cumulative nailplate backout under cyclic wood swell-shrink is possible under a wide range of exposure conditions, from dry to wet.
- No strong or consistent trends were observed for various grain orientations in the results. The only notable effect seems to be that the penetration to withdrawal resistance ratio for the pith-side specimens is higher than for quarter-sawn or bark-side specimens.

1.4.3. Joint capacity tests

The objective of the joint capacity test was to estimate the short-term capacity of the joints used in the swell-shrink experiments conducted under load. This was required so that the loaded swell-shrink tests could be loaded to a targeted proportion of the short-term capacity (30%, 70%, 90%, 100%). The short-term capacity was also used to estimate the backout versus load relationship for existing long-term joint test data so that this could in-turn be used for calibration of the mechanical backout model. The test result indicated that the short term joint capacity was 18kN.

1.5. Field Monitoring

The objective of the field monitoring program was to:

- Collect data for calibration of roof microclimate models
- Compare the different roof microclimates in sarked and un-sarked tiled roof configurations

1.5.1. Test houses

Two (single room) test houses were built at CSIRO Highett site. The houses were identical in dimension, configuration and materials used, except one was sarked with a moisture barrier under the tiles, and one was un-sarked. Measurements were made over a period of one year in both houses to collect data for external and in-roof climate.

The data collected was used to validate the models developed for estimation of the roof microclimate, and it was shown that model-predicted and measured temperature and humidity in the roofspace agree well.

Analysis of the measured data showed that the installation of the moisture barrier drastically reduced the humidity variation, and slightly reduced the temperature variation in the sarked roofspace. This results in a very significant (two-thirds) reduction in the computed wood surface equilibrium moisture content in a sarked roofspace compared to an un-sarked.

1.5.2. Field houses

Three field houses in South East Melbourne were monitored for external and in-roof climate:

- A 32-year-old house in Keysborough, VIC, with un-sarked, low-pitched, light red concrete tiled roof.
- A 28-year-old house in Keysborough, VIC, with un-sarked, low-pitched, dark red concrete tiled roof.
- A 2-year-old house in Springvale South, VIC, with un-sarked, low-pitched, black terracotta tiled roof.

The data collected was used to validate the roof microclimate models for real un-sarked roof spaces. It was shown that the model-predicted roof temperatures agree very well with the measured ones for all seasons. For the relative humidity in roof space, the model estimations are found to be very good for summer. The model is not quite as accurate for winter humidity predictions, mainly due to indoor moisture being neglected, however the results are more than adequate for predicting the number and the size of humidity fluctuations in the roof space, which are the main factors of interest for the purposes of this research.

Analysis of the monitoring data showed that indoor microclimates can have an impact on the roof-space microclimates, particularly in winter. It was also shown that the measured microclimates in the 3 roof-spaces were quite similar, suggesting that the variation is small between microclimates in different un-sarked tiled roof spaces

1.6. Roof Inspections

1.6.1. Roofs Inspected in Victoria

The objective of the random inspections was to get an estimate of the extent of occurrence of nailplate backout in a random selection of roof-spaces. A set of inspection checklists was developed, and deployed by a building inspector in 41 roof spaces in Southern Victoria. Houses were effectively selected at random, with a preference for softwood constructed roof trusses and buildings in the age range 5-30 years.

The inspection results showed that 25 of the 41 roof-spaces inspected had some gaps under the nailplates of more than 1.5mm, but that the majority of these could not be clearly attributed to moisture-related factors (many were manufacturing-related). Based on the data collected, it can be concluded that moisture-related backout does not appear to be a widespread and systematic problem in Victoria. It must be noted however that this conclusion is based on a very small sample size (less than 20 roofs with susceptible configuration of tiles and softwood trusses) and from one geographic region only (Victoria)

1.6.2. Problem roofs

A selection of ‘problem roofs’, where performance issues had been reported by occupants or owners, have been inspected by nailplate manufacturers and other consultants. Data collected from these inspections is used as an additional data source to examine similarities between situations where backout may be more likely to occur. Each documented ‘problem roof’ needs to be considered in its own context, however the following observations can be made:

- Many of the problems observed in South Australia related to Steelfast brand nailplates, which in many cases were under-designed and therefore carrying larger loads than appropriate.
- Many of the reported problem joints were in un-sarked concrete tiled roofs and/or in roof spaces with evidence of water penetration

1.7. Scenario Analyses

The objective of the scenario analyses was to estimate of the nailplate backout which is likely to occur under the following scenarios.

- 4 Cities: Adelaide, Melbourne, Sydney, Brisbane
- Joint loads: 0% 40%, 75% & 100% of design capacity
- Moisture regimes: humidity, wind-driven rain, roof leak
- Roof Construction: sarked and un-sarked

1.7.1. Humidity

Estimates of humidity-driven mechano-sorptive backout in roof spaces (based on model predictions) showed that:

- Very highly loaded joints in un-sarked tiled roofs could potentially be susceptible to structurally significant levels of backout (>1mm) under long-term (50 yrs) humidity fluctuations.
- Humidity-driven backout could be reduced by as much as 70% in sarked roof spaces compared to un-sarked.

It must be noted that the estimated values of backout in this analysis are considered a worst-case upper bound, and are based on models which have large uncertainties. Although the absolute value of the estimated backout has a low certainty, the ratio of the estimated backout between the different roof configurations is likely to have higher certainty, as the relevant factors in the models are based on more robust calibration data.

1.7.2. Roof Leak

Estimates of backout for joints subjected to leaking from rain (for example through cracked or broken tiles) were calculated for four different cities. The main conclusions that can be drawn from these estimates are that joints subjected to repeated wetting from roof leaks are highly likely to fail, and that highly loaded joints are more susceptible to significant backout under cycles wetting than are joints with small loads.

It should be noted that other durability issues resulting from leaks such as stains, odour, rot and corrosion could possibly become apparent before backout is an issue for joints with low loading. However for highly loaded joints, structurally significant backout (greater than 1mm) is potentially a shorter-term problem if moisture is allowed to penetrate the roofspace to the point where the roof truss joints are becoming repeatedly wet and dry.

1.7.3. Wind-driven rain

An analysis was undertaken to estimate the required level of resistance to wind-driven rain that a roof system would need in order to avoid structurally significant backout over its design life. Wind driven-rain can penetrate an un-sarked roofspace, especially if the tiles are loose-fitting or cracked/broken, and if prevalent, could potentially be a more significant issue than roof leaking in the context of backout. This is because often only a small amount of water will penetrate as a 'spray', and although this could be enough to cause significant wood swell-shrink, other indicators of moisture penetration such as staining and odours may not be apparent. The results of the wind-driven rain analyses showed that:

- For light rainfall wind-driven rain (<1mm rain in 30 min.), Adelaide has the highest number of potential occurrences per year (for >6 m/s gust), over a 50 year lifetime and Melbourne has the lowest. This would indicate that we would be more likely to see backout from wind-driven rain in Adelaide than the other cities examined.
- As the rainfall threshold increases above 1mm, the number of wind-driven rain events that occur simultaneously with high winds (>6 m/s) reduces rapidly, and it is therefore unlikely that wind-driven rain under heavy rainfall will be a cause of backout problems in any location over a 50 year lifetime.
- To prevent structurally significant backout over a 50 year design life, roofs should be able to resist water penetration from light rainfall (<1mm rain in 30 min.) being driven by windspeeds of at least
    - 10 m/s for Melbourne and Sydney
    - 14 m/s for Brisbane
    - 18 m/s for Adelaide

1.8. Key Conclusions & Recommendations

Nailplate backout can occur when cyclic mechano-sorptive swelling and shrinking of wood results in a ratcheting mechanism in which withdrawal deformations accumulate. Many of the reported examples of mechano-sorptive backout in ‘problem roofs’ have occurred in un-sarked concrete tiled roofs and/or in roof spaces with evidence of water penetration. However there are also many examples of general separation of nailplates from parent timber that can be most likely attributed to manufacturing and handling errors, warping of timber, and overloading. Some observed cases of gaps under the nailplates have no apparent explanation.

Based on data collected during a program of ‘random’ roof inspections, it can be concluded that moisture-related backout does not appear to be a widespread and systematic problem in trussed roofs. However numerical modeling has indicated that long-term humidity fluctuation, wind-driven rain, and roof leaking can all be a potential threat to the long-term performance of nailplated roof truss systems. Confidence levels for both of these findings are low due to limited availability of data.

Laboratory experiments in which joints were subjected to cycles of wetting and drying have showed that highly loaded joints can potentially fail to rupture under a small number of cycles of wetting and drying (<50 cycles), but that the application of a sealant material can potentially slow or stop nailplate backout from occurring under cycles of wetting and drying.

Field monitoring has shown that installation of sarking in a tiled roof will result in a drastic reduction in the amplitude of the daily humidity fluctuation compared to an un-sarked roof, and also reduced potential for backout caused by moisture penetration due to cracked or loose-fitting tiles

Based on the conclusions of this study it is recommended that :

1. Sarking or equivalent measures to prevent external moisture penetration should be adopted for all roof construction in Australia. Sarking of tiled roofs is already compulsory in Queensland, and the Building Code of Australia already specifies that a building is to be constructed to provide resistance to moisture from the outside. Universal adoption of sarking to prevent external moisture penetration would serve to minimize potential for mechano-sorptive backout, and will also result in other benefits such as more durable construction overall, and enhanced thermal efficiency. It should also be noted that there should be no water penetration into the roof space from mechanical equipment, and it may be prudent for enhanced long term performance to vent steam from kitchen and bathroom to the outside where possible rather than directly into the roof space.

2. Examine the feasibility of reducing assumed tooth capacities for permanently loaded joints to below 100% of current values. Given that highly loaded joints under permanent loads appear to be more susceptible to backout and premature failure than joints with lesser loadings, it may be prudent for plate manufacturers to examine the option of reducing specified tooth capacities by a factor which would not have a significant impact on overall truss cost. It is possible that this could lead to enhanced safety, and superior long term performance for very little cost penalty.

3. Explore sealant treatment on critical joints. The application of a sealant material can reduce susceptibility to moisture-related backout, and if an effective and low cost sealant treatment can be incorporated into the manufacturing process, then this could potentially reduce the risk of failures of critical joints due to moisture penetration through poor construction or maintenance practices.

4. Explore tooth profile redesign for increased withdrawal strength for future metal-plate products. This would reduce the potential for mechano-sorptive backout and all other types of nailplate separation cause by handling and installation. This could also potentially open up new applications for nailplated connectors in more exposed environments.

It should be noted that limiting moisture penetration into the building envelope (recommendation 1) should be considered as a higher priority in the prevention hierarchy than other recommendations. It should also be stressed that of-course quality control of manufacturing and installation is essential so that nailplates are fully embedded during manufacture, and are not be handled in a manner that will create lateral joint displacements

2. Introduction

Plated timber trusses have been used extensively and successfully for house construction in Australia over several decades. However after roof-truss problems were reported at a retirement village in 2002, a subsequent series of inspections showed many examples of an in-service performance issue, whereby some of the nailplates in some roof spaces appeared to have 'backed out' of the parent timber over time. Some examples of observed nailplate backout inside roof-spaces are shown in Figure 2.1.

These examples of nailplate backout have predominantly been observed in un-sarked (i.e. without a moisture barrier) concrete tiled roof spaces. Although it is well known that backout due to moisture cycling can occur in exposed nailplated joints (see Figure 2.2), it is not thought to have been a problem within the building envelope. These observations, although small in number, have caused some concern within the industry, because as shown in Figure 2.3, even a small amount of nailplate backout can have a significant effect on structural capacity of nailplated connections, due to the short embedment length of nailplate fasteners (may be as small as 8mm).

Separation of nailplates from parent timber can occur due to several different factors including:

- Backout due to repeated swelling and shrinkage of the wood under moisture/humidity variations in the roof space over time (mechano-sorptive backout)
- Lateral movement across the joint due to poor handling practices in the manufacturing plant, or during transport, storage and/or installation;
- Errors in manufacturing process resulting in plates that are not fully embedded;
- Overloading

These effects can occur singly or in combination, but this investigation is limited to an examination of the conditions that contribute to the backout due to moisture cycling effects. Mecahno-sorptive backout is of particular concern, as this is potentially cumulative over time, and potentially hidden until failure.

The appearance of the separation can also take many different forms, and this appearance can give some indication of the causes, as shown in Figure 2.4.

Nailplate separation caused by repeated swelling and shrinkage of the wood (mechano-sorptive backout) is of particular concern, as this is potentially cumulative over time, and can potentially remain hidden until failure. Hence an extensive investigation into mechano-sorptive nailplate backout was undertaken, with the following objectives:

- To facilitate understanding and prediction of nailplate backout due to moisture conditions in roof spaces
- To assess the extent of the problem in the existing housing stock
- To test potential solution options.

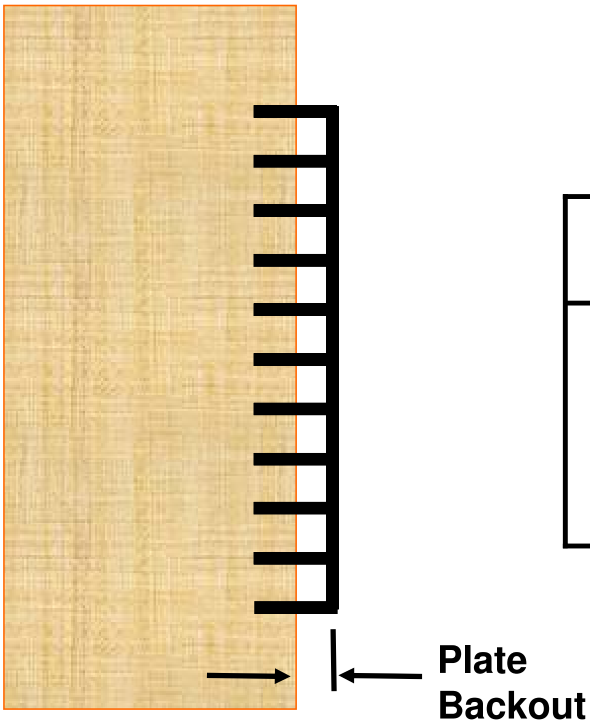
A research program was developed to meet these objectives, and comprised the following key activities:

- Literature review
- Numerical modelling
    1. For prediction of roof microclimate given external climate
    2. For prediction of wood moisture profile given roof microclimate
    3. For prediction of wood deformation given wood moisture profile
    4. Prediction of Nailplate backout, given wood deformation
- Laboratory simulations and experiments
    - Swell-Shrink tests under different moisture cycling, moisture treatment, and mechanical loading regimes
    - Mechanical load tests
- Field monitoring of roof microclimate
    - 2 x controlled, purpose-built test houses
    - 3 field houses
- Roof inspections
    - 41 inspections of random roofs in Victoria
    - Inspections of a range of problem roofs
- Scenario analysis
    - Adelaide, Melbourne, Sydney, Brisbane
    - Joint loads: 0, 40, 75,100% design capacity
    - Moisture regimes: humidity, wind-driven rain, roof leak
    - Sarked and un-sarked roof construction

A diagrammatic overview of the research program and supporting activities is given in Figure 2.5. The following sections of this report summarise the objectives, methodology and results of the different components of the research program.

Figure 2.1 - Examples of nailplate backout inside roof spaces

Figure 2.2 – Backout of nailplates exposed to the weather for 20 years



Effect on Strength

Gap	Strength Ratio (short tooth NP)
0	1.0
1 mm	0.75
2 mm	0.55
3 mm	0.30
4 mm	<0.1

Figure 2.3 – Indicitave effect of nailplate backout on joint strength

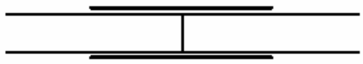
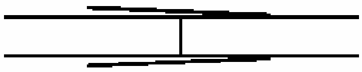
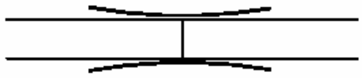
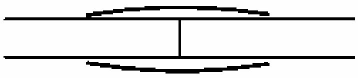
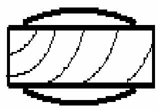
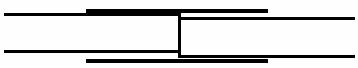
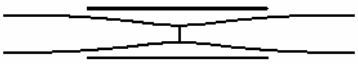
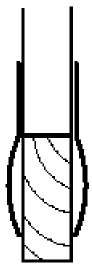
Type of Nailplate Separation	Possible Cause
Parallel 	Repeated Swell-Shrink
Taper 	Repeated Swell-Shrink
Curling Peeling 	Overloading Repeated Swell-Shrink
Thickness 	Manufacturing
Heaving 	Manufacturing (Gap Closure)
Doming 	Shrinkage
Alignment 	Manufacturing Warping
Cupping 	Shrinkage
Pear 	Manufacturing (Gap Closure)
Bulge 	Handling

Figure 2.4 – Classifications and causes of nailplate backout

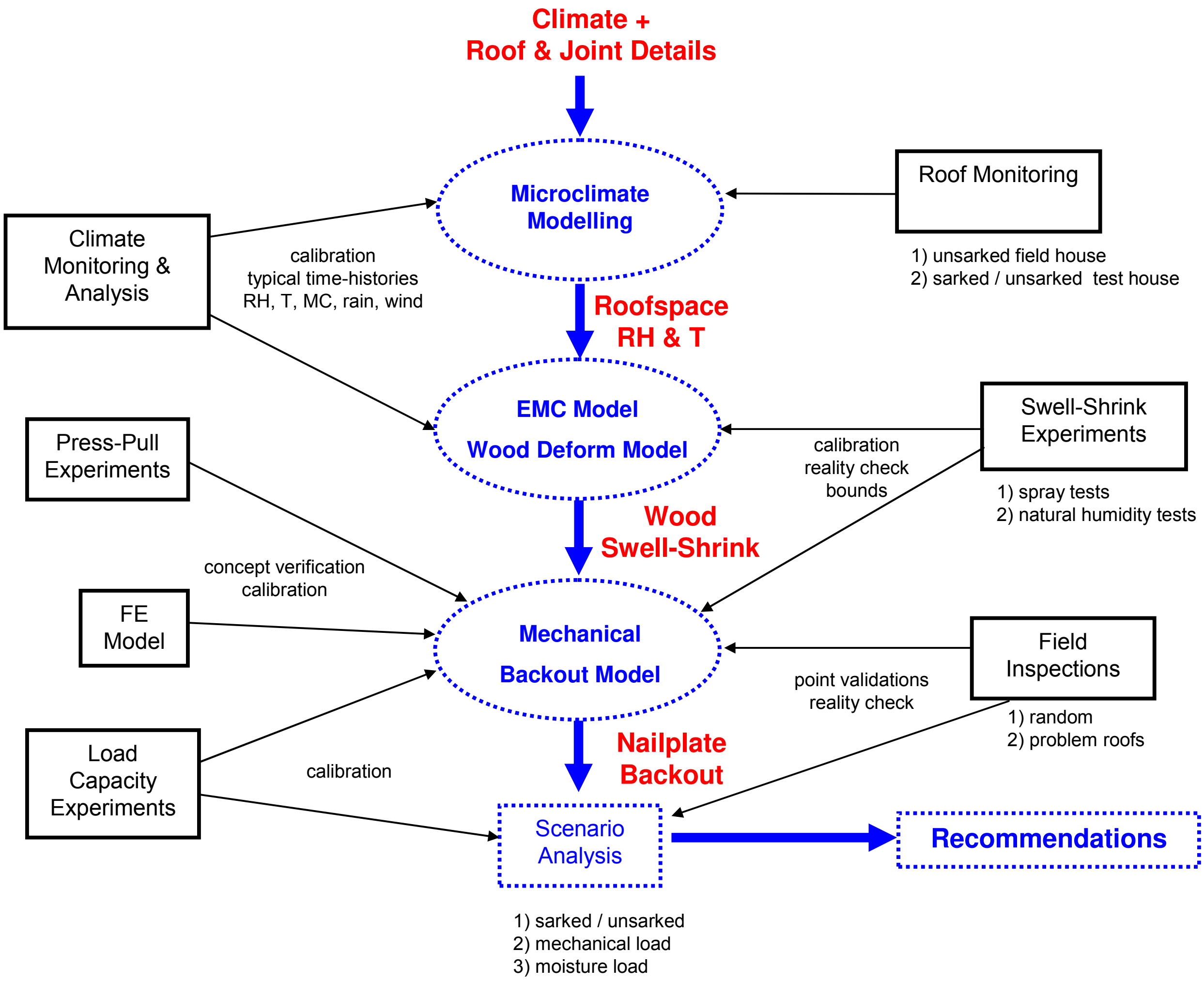


Figure 2.5 – Overview of research project activities

3. Laboratory Experiments

3.1. Swell-Shrink Tests

A program of 'swell-shrink' tests was designed and conducted to investigate the magnitude of wood swelling and shrinking, and associated nailplate backout, under different moisture cycling regimes, mechanical loadings and sealant treatments. Three different kinds of tests were conducted:

- Spray Tests: Specimens were subjected to water spray, and measurements of deformations were taken
- Steaming Tests: Specimens were subjected to large humidity changes through exposure to cold steam and deformations were measured
- Natural humidity tests: Timber specimens were subjected to natural cycles of humidity and temperature fluctuations. Wood deformation was measured in detail.

Details of these experiments and the results are provided in the following Sections.

3.1.1. Spray Tests (MiTek)

Objective

Two spray test programs were conducted at MiTek.

The main objective of these tests was to:

- determine the effectiveness of sealant coating products in reducing nailplate backout under cyclic wetting and drying
- investigate the effects of some parameters, including timber cutting patterns (back-sawn / quarter-sawn), timber species (Slash pine/ Radiata pine), and timber finished surface (plain / reed), on the nailplate backout.
- collect data for calibration of the CSIRO mechanical backout model

Test Method

The first MiTek test program had been carried out from Feb 2005 to Oct 2008. This test was primarily aimed at investigating the extent of nailplate backout due to wetting of Radiata timber joints with:

- Two different types of timber finished surfaces: plain finished surface and reed finished surface
- Non-coated or coated with a sealant product. Two types of 'Seal n Peel' sealant products were used, 'WB5000' and '660'.

Ten test specimens were fabricated using Radiata pine and MiTek® GQ75200 nailplates. Each test specimen has 2 nailplate joints, which were made by joining 3 pieces of 35x90mm Radiata pine, as depicted in Figure 3.1. Figure 3.2 shows the test specimens. In each specimen, one joint is non-coated, one joint is coated with a 'Seal n Peel' product. 'WB5000' were applied on plain finished surface timber specimens (named A1 to A5); '660' were applied on reed finished surface timber specimens (named B1 to B5).

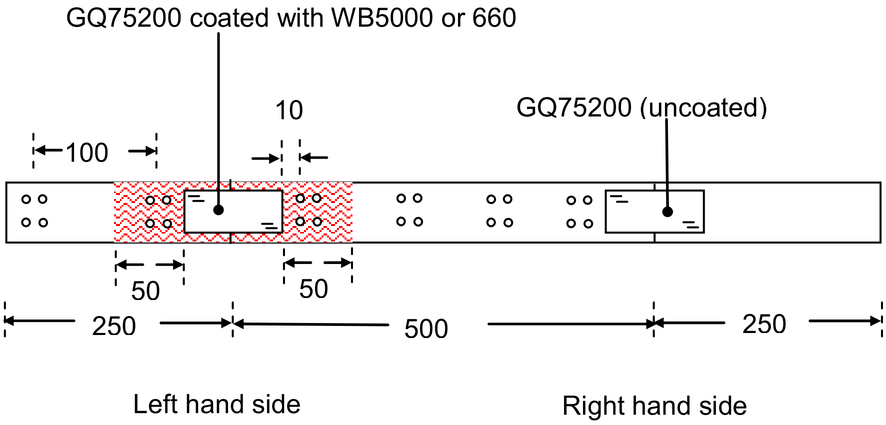


Figure 3.1 – Fabrication of test specimens with 'Seal n Peel' products.

Figure 3.2 – Test specimens: left are plain finished with 5 joints non-coated and 5 coated with WB5000; right are reed finished with 5 joints non-coated and 5 coated with 660 Seal n Peel

The second MiTek Test program had been carried out from Sep 2006 to Oct 2008. This test primarily aimed at investigating the extents of nailplate backout due to wetting on timber joints with:

- Two different species of timber: Radiata and Slash Pine
- Two different timber cutting patterns: back-sawn and quarter-sawn

Sixteen test specimens were fabricated using 1200mm length of Radiata and slash pine. Six MiTek® GQ75200 nailplates were pressed at 3 locations on each specimen, as depicted in Figure 3.3. Figure 3.4 shows 2 batches of 4 test specimens. Note that these joints are not real joints, as timber is continuous. All timber used is plain finished surface. All joints are non-coated.

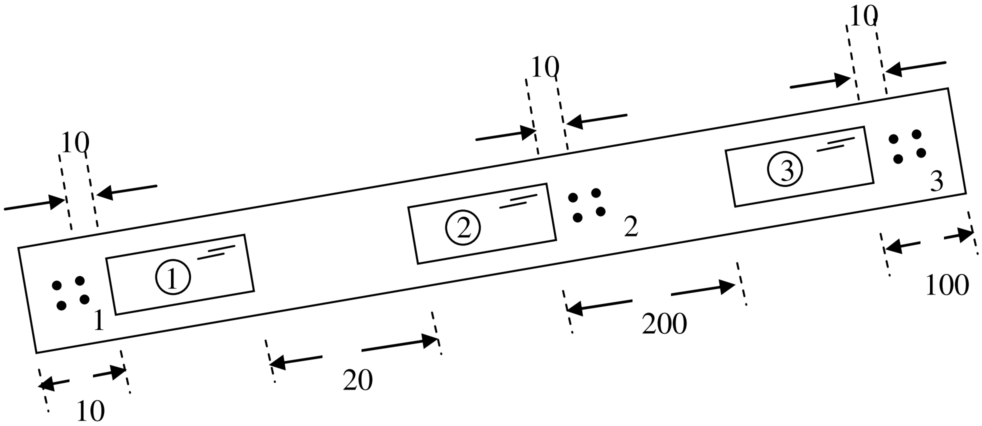


Figure 3.3 – Fabrication of test specimens

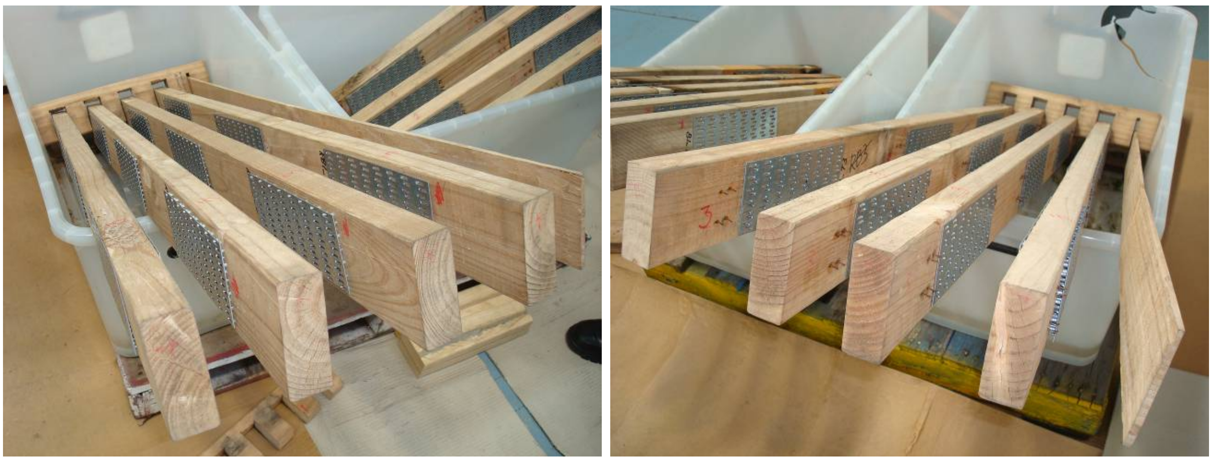


Figure 3.4 –Test specimens: left are of back-sawn Radiata; right are of quarter-sawn Radiata

Figure 3.5 – Spraying water with a pre-pressurised spray bottle

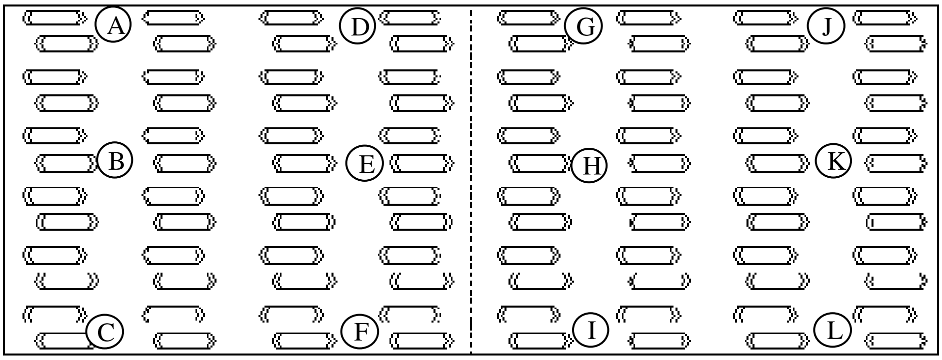


Figure 3.6 –12 positions marked on GQ75200 nailplates, where backout from timber to be measured

The joints of both test programs were wetted by spraying water every weekday (from Mon to Fri, except holidays), Figure 3.5. Backout at 12 positions on each nailplate as shown in Figure 3.6 was measured every month before wetting the joints, using a veneer calliper. Air temperature and timber moisture contents at both before and after wetting the joint were also recorded.

Results & Conclusions

MiTek reported the results of the first sealant test in terms of backout measurements on each nailplate with time, as typically shown in Figure 3.7. Note that only nailplate backout of the non-coated joints were measured and reported. Figure 3.8 shows the backout of non-coated joints in specimens A (plain finished surface). Figure 3.9 shows the backout of non-coated joints in specimens B (reed finished surface). No clear difference between the backout in non-coated joints on plain finished and reed finished surface was observed.

Backout of coated joints with 'Seal n Peel' products was not measured. From visual observations of the backout, it was found that the 'Seal n Peel' WB5000 has excellent performance in preventing the nailplate backout, giving almost no backout over the years with about 800 wetting cycles, as seen in Figure 3.10. The 'Seal n Peel' 660, however, gave poor performance, where breakage of the seal and hence nailplate backout occurred, as seen in Figure 3.11.

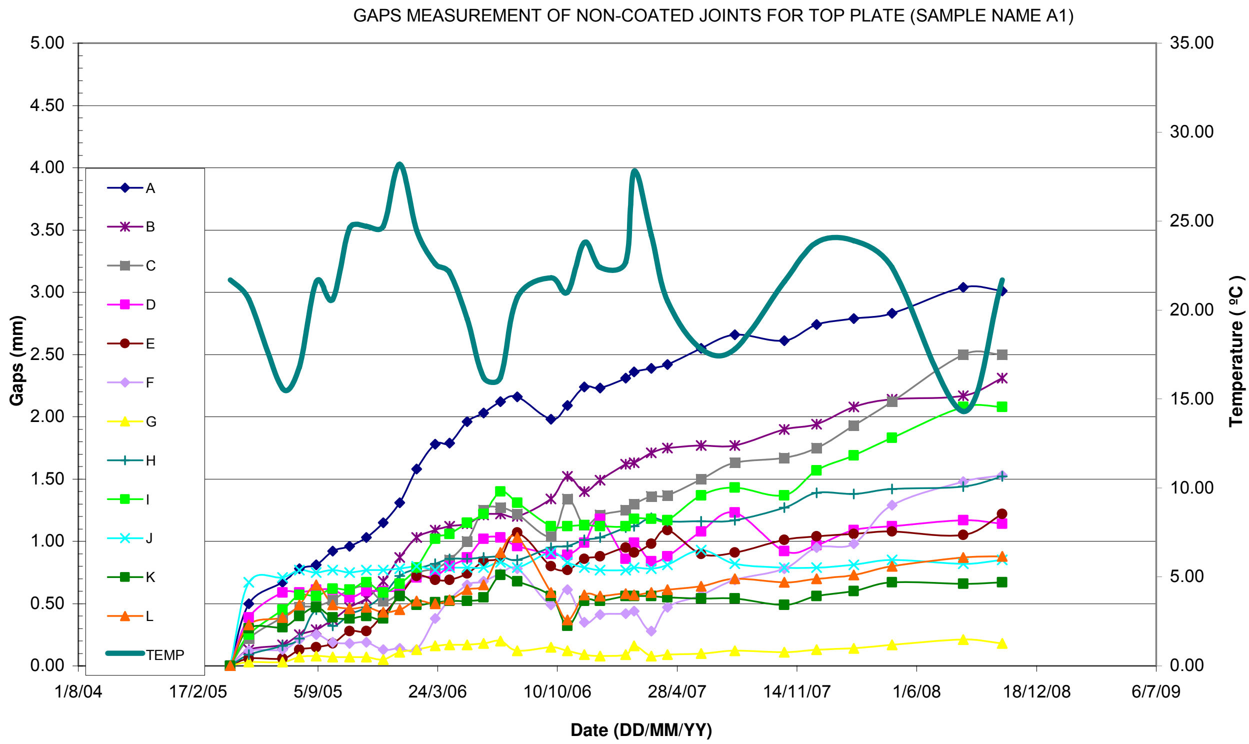


Figure 3.7 – Typical results of backout measurement on one nailplate

Figure 3.8 – Backout of non-coated joints in specimens A (plain finished)

Figure 3.9 – Backout of non-coated joints in specimens B (reed finished).

Figure 3.10 – Joints coated with 'Seal and Peel' WB5000. No backout observed.

Figure 3.11 – Backout in joints coated with 'Seal and Peel' 660

For the second test (Mechano-Sorptive) MiTek also reported the results of the test in terms of backout measurements on each nailplate with time, as typically shown in Figure 3.12. Figure 3.13 shows the backout on back-sawn Radiata pine specimens. Figure 3.14 shows the backout on quarter-sawn Radiata pine specimens. Figure 3.15 shows the backout on back-sawn Slash pine specimens. No clear difference between the backout in back-sawn and quarter-sawn Radiata pine specimens was observed.

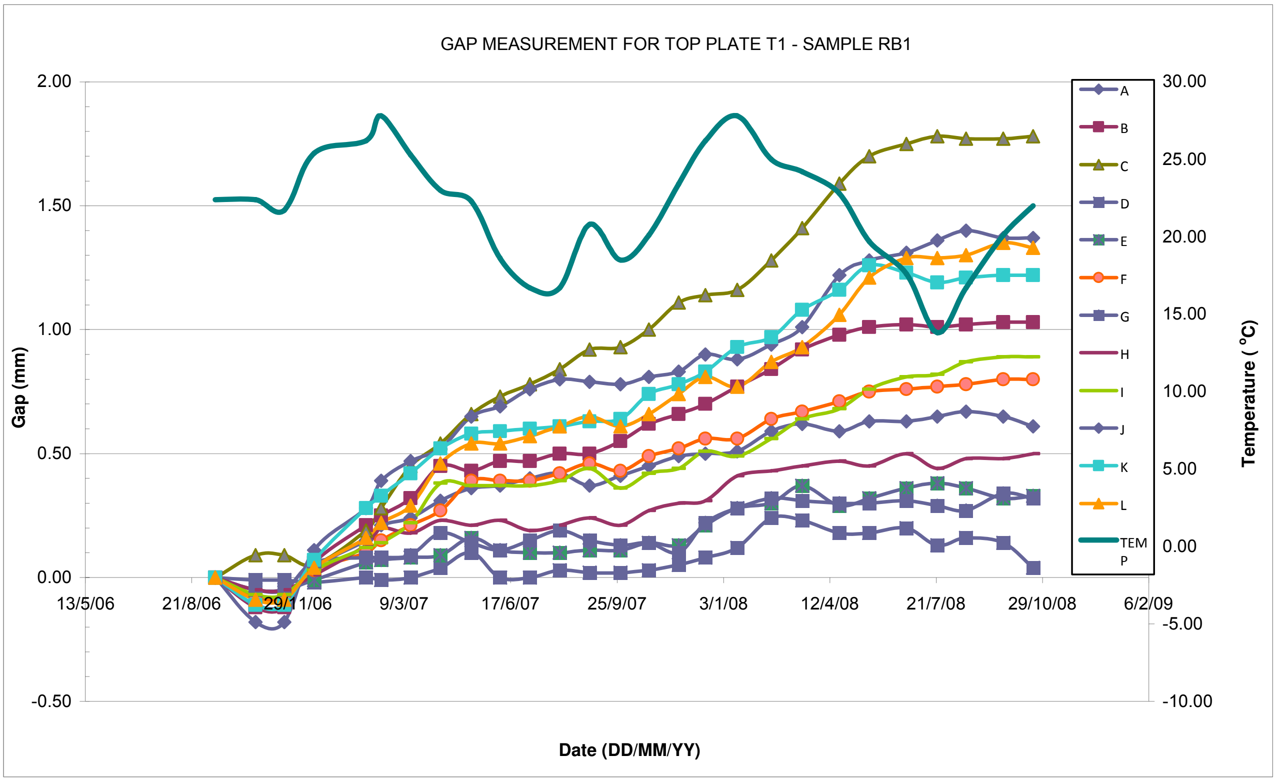


Figure 3.12 – Typical results of backout measurement on one nailplate

Figure 3.13 – Backout on back-sawn Radiata pine specimens

Figure 3.14 – Backout on quarter-sawn Radiata pine specimens

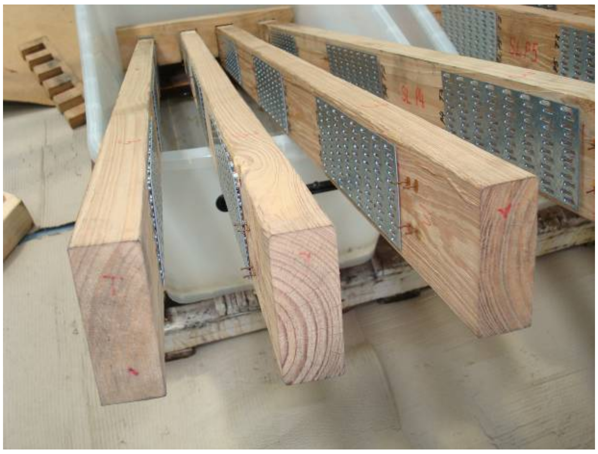


Figure 3.15 – Backout on back-sawn Slash pine specimens

For calibration of the CSIRO mechanical backout model, all the data of backout in non-coated Radiata joints in both MiTek test programs were used to estimate an average backout progressing with number of wetting pulses, as shown in Table 3.1. A wetting pulse corresponds to one wetting cycle by spraying water in the MiTek test. Therefore the data processing was made as follows,

- First step is to transfer the time into number of wetting pulse. Note that the water spraying was done every weekday, and there was no water spraying on holidays.
- Correct some odd backout values in the data that was clearly due to measurement errors, or due to bouncing effect of nailplate from timber at the beginning of the tests
- Evaluate the average backout from the measurements at the same number of pulses.

Table 3.1 - Average backout from MiTek test to be used for unloaded scenario

Number of pulses	Average backout
0	0.00
20	0.086
50	0.202
100	0.398
150	0.520
200	0.837
360	1.458
450	1.79
550	2.15
650	2.57
800	3.02

3.1.2. Spray Tests (CSIRO)

Objective

Spray tests were designed and conducted to investigate the mechanism of nailplate backout under moisture cycling, and to determine the effect of the applied joint loading on the rate of backout. Results from these tests were primarily used to:

- Provide data for the validation and calibration of the mechanical backout and wood swell-shrink models
- Determine the effect of different levels of joint loading on the rate of backout
- Physically measure the magnitude of a swell-shrink 'pulse' in the timber due to wetting and drying

Test Method

The tests were carried out in the Structures Laboratory at CSIRO Highett. In these tests, nailplate connection specimens were subjected to cycles of wetting and drying under a range of mechanical load levels. Loading was applied at 0%, 40%, 75%, 90% and 100% of the design load (7800N), as listed in Table 3.2. Specimens were thoroughly wetted every working day thoroughly with a hand-spray bottle (Figure 3.16), and dried naturally in the laboratory conditions (T = 22°C, RH = 45%). Wood and/or nailplate deformations over time were measured in fine detail under the cyclic wetting and drying. Deformation measurements had an accuracy of 0.01mm, and readings were continuously logged to a computer every 2 minutes.

The set up of the spray tests is shown in Figure 3.17. Tests were conducted two at a time (one on the left, and one on the right). Note that all the specimens tested had the teeth closest to the perpendicular edge removed to reduce variability of load-carrying capacities between specimens, Figure 3.18. Matched timber (Radiata Pine, 8% MC, along-grain direction) was also used for all test timbers.

Results and Conclusions

Five spray tests were carried out successfully, and the results of these are summarised in Table 3.3. Failures of the spray tests with 100% and 90% loads are shown in Figure 3.19, Figure 3.20, respectively. A sixth test was also conducted with 100% load and no wetting as a control, and no backout occurred in this test. A plot of the average backout versus time for the five different levels of applied loading is shown in Figure 3.21.

The results have demonstrated that the applied loading can have a significant and dominating effect on the rate of backout under repeated swell and shrink of the wood. This conclusion is quite logical, when considered in light of the conceptual mechanical model for backout developed in Section 7.5, as the application of a load effectively increases the ratio of re-penetration to withdrawal resistance (likely due to slight distortions of tooth and timber under load), which in turn increases the rate at which a nailplate under cyclic swell-shrink can be expelled through the 'ratcheting' mechanism described.

The fact that the nailplate connections failed after only a small number of wetting cycles supports the well-known fact that short-toothed nailplates such as those tested are not suitable at all for use in exposed environments. The wetting and drying regime simulated in these tests is an extreme exposure, and would only possibly be experienced by joints inside roof spaces due to roof leaking or wind driven rain in poorly constructed or maintained roofs.

It should be noted that these test specimens had only two rows of teeth on each side of the joint, and that this may have resulted in an accelerated failure for the specimens under load. However spray tests on full nailplates without loading exhibit mechano-sorptive backout at a similar rate to the non-loaded two-teeth-row specimens.

Mechanical Model Calibration

One of the objectives of the Spray Test program was to provide data for calibration of the mechanical backout model. This was achieved by taking the average wood swell-shrink time history measured in the test, and using it as an input to the mechanical model to calculate the predicted backout time history. The accumulation ratio parameter (R) used in the model was then adjusted to achieve a best fit with the experimentally measured backout.

These comparisons are shown in Figure 3.22 through Figure 3.25, where it can be seen that the model does a good job of predicting the backout time-history up to failure, given the time-history of the measured wood swell-shrink. Fitted model parameters used for the different tests are given in Table 3.2. Conveniently, a reasonable fit with test data is achieved by setting the accumulation ratio to the same value as the proportion of design load that is applied, except for the case of 0% loading, where backout still accumulates at a rate that is slightly greater than zero.

A second mechanical backout modelling approach has been developed in which the swell-shrink input is expressed as the number and amplitude of swell-shrink 'pulses' that a joint is subjected to in a lifetime. This approach is necessary for prediction of long-term backout, as long-term time-histories of wood swell-shrink are generally not measurable or practical to simulate. It was determined from the spray test wood swell-shrink measurements, that the amplitude of a swell-shrink pulse under a single cycle of wetting and drying is quite consistent and is generally around 0.2mm (i.e. +/- 0.1mm). Using this as the input for the model, backout predictions (for different loadings) can be plotted as a function of the number of wetting cycles, as shown in Figure 3.26. The spray test results as given in Table 3.3 can then be superimposed on top of the model predictions in Figure 3.26, to check the pulse-based mechanical model ability to predict a failure. Figure 3.26 shows that the pulse-based model under-predicts the backout for a given number of cycles in some cases. However, given that the trend is intuitively correct, and that there is a large variability in backout response and deformation at failure, the ability of the pulse-model to predict a 'failure' is adequate for the purposes of scenario comparisons.

Table 3.2 – Fitted Model Parameters

Test	Loading % design capacity	R* Accumulation Ratio	No. Cycles	Backout N cycles	T * Penetration Depth (mm)
SprayTest0% MiTek	0	0.06	200	0.84	8
SprayTest40%	40%	0.4	70	2.5	8
SprayTest75%	75%	0.75	30	2.7	8
SprayTest90%	90%	0.9	19	1.8	8
SprayTest100%	100%	1	23	4.0	8

* Penetration Depth and Accumulation Ratio are defined in Section 7.5

Table 3.3 – Summary and results for spray testing program

Test	Wetting	Result	Detailed Description
SprayTest0% CSIRO	23 cycles	0.5-0.8mm backout	No load is applied. Specimen is sprayed with water every working day. Approximately 0.5-0.8mm parallel backout was observed after 23 cycles of wetting
SprayTest0% MITEK	Up to 800 cycles	0.2-4.0mm backout	No load is applied. Treated and untreated specimens are sprayed with water every working day. On average, untreated specimens back out at a linear rate of 0.005mm per spray. Some of the treated specimens had significantly reduced backout rates.
SprayTest40%	70 cycles	Failed >2.5mm backout;	Initial load of 3000N is applied. Load reduced and stable at 2814N after several days. Specimen was then sprayed with water every working day. Significant backout of around 2-3mm occurred after 70 cycles of wetting.
SprayTest75%	30 cycles	Failed to rupture at 2.7mm	Initial load of 6000N is applied. Load reduced and stayed stable at 5658N after several days. Specimen was then sprayed with water every working day. Specimen failed to rupture after 30 cycles of wetting.
SprayTest90%	19 cycles	Failed to rupture at 1.8mm	Initial load of 7800N is applied. Load reduced and stayed stable at 7036N after several days. Specimen was then sprayed with water every working day. Specimen failed to rupture after 19 cycles of wetting.
SprayTest100%	23 cycles	Failed to rupture at 4.0mm	Initial load of 8300N is applied. Load reduced and stayed stable at 7800N after several days. Specimen was then sprayed with water every working day. Specimen failed to rupture after 23 cycles of wetting.
SprayTest90% (No Wetting)	none	No backout	Initial load of 7800N is applied. Load reduced and stayed stable at 7150N after several days. The specimen was kept dry. No backout is observed.

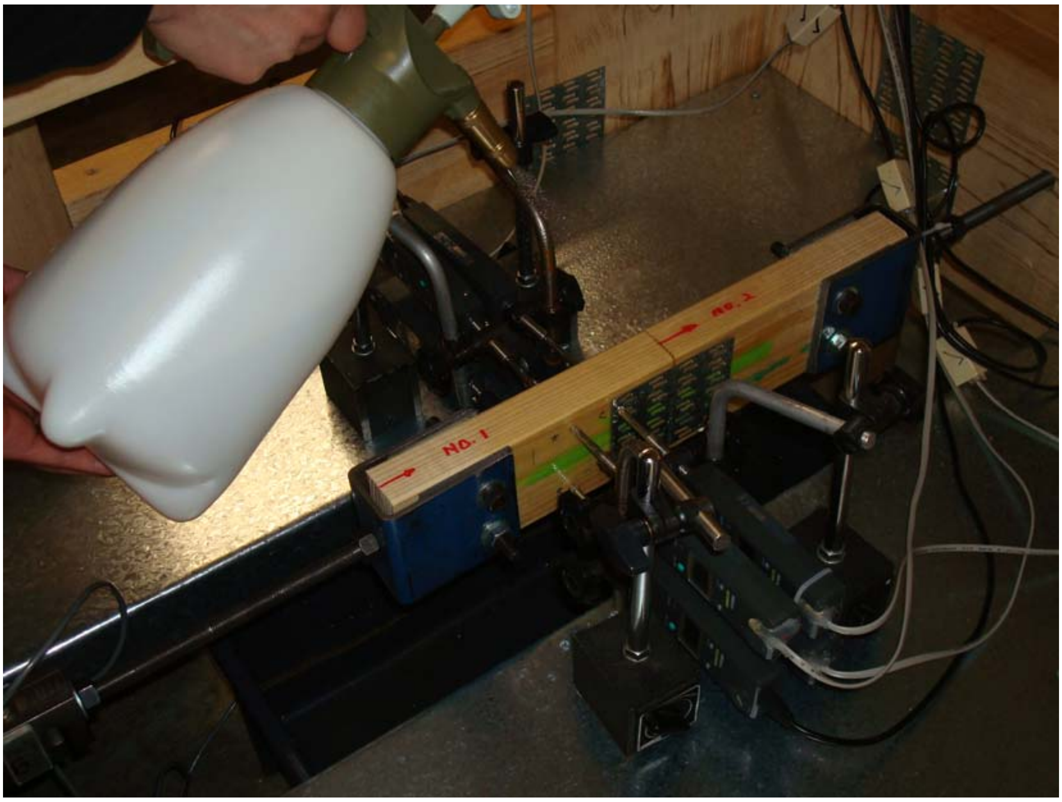


Figure 3.16 – Wetting of specimens using a pressurised spray bottle

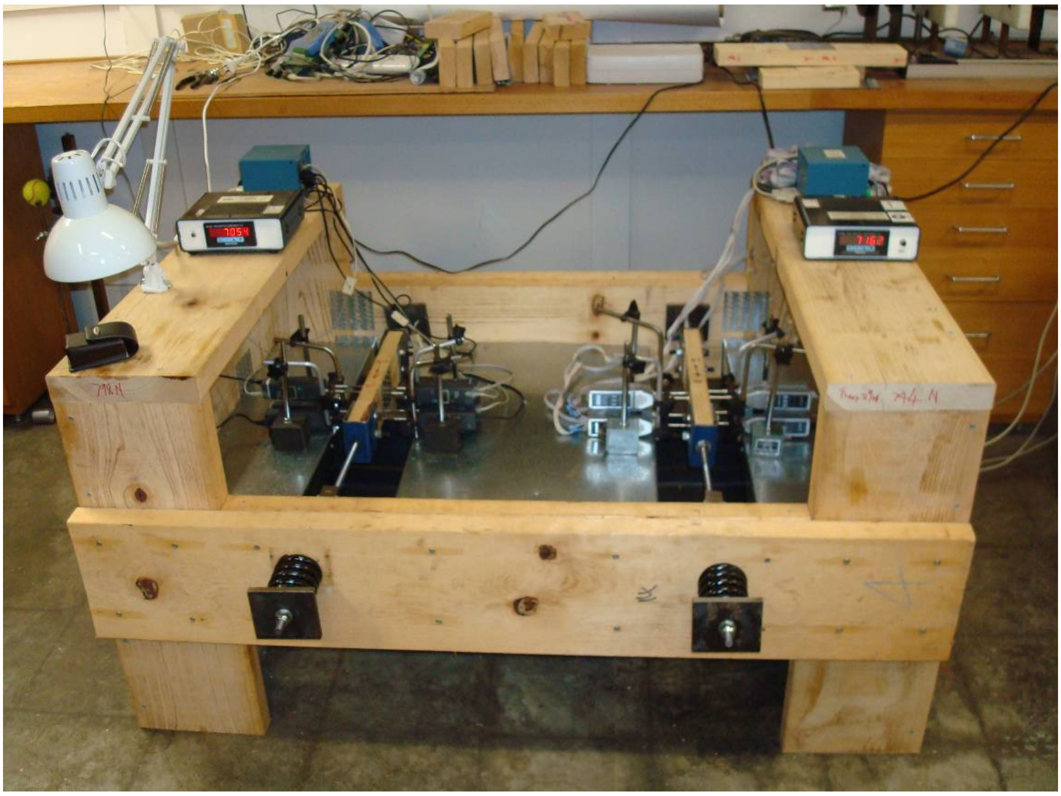


Figure 3.17 – Setup for two side-by side spray tests

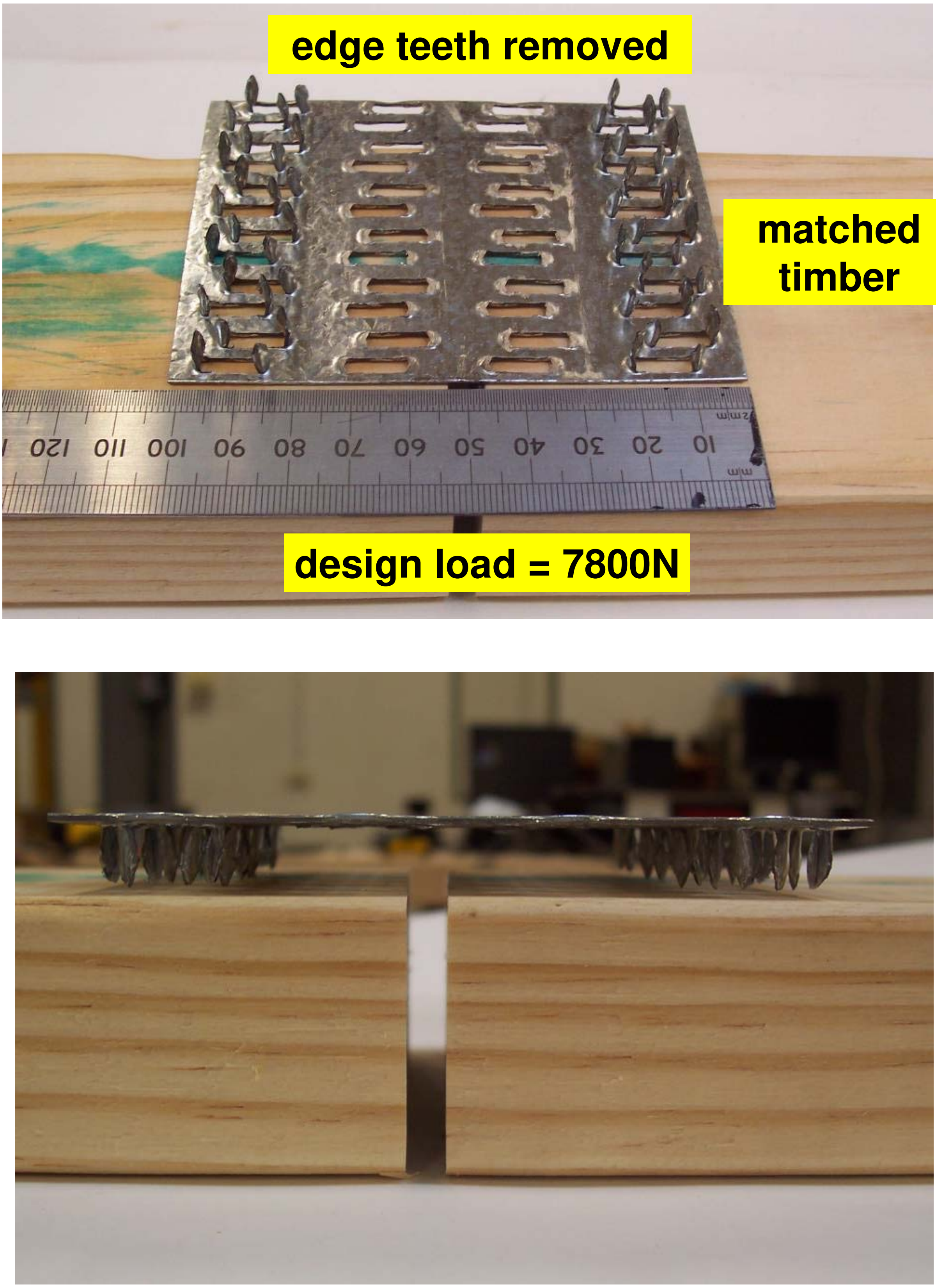


Figure 3.18 – Example test specimen before pressing, teeth near edge removed

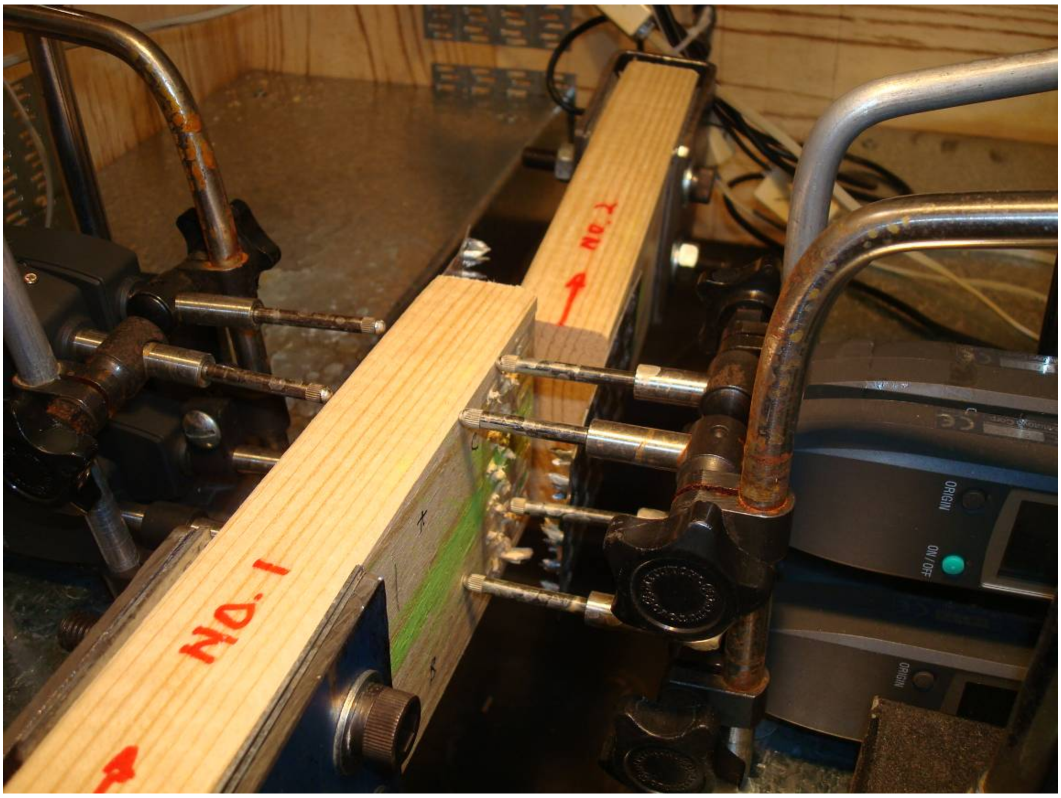


Figure 3.19 – Failure of Spray Test 100% after 23 cycles of wetting

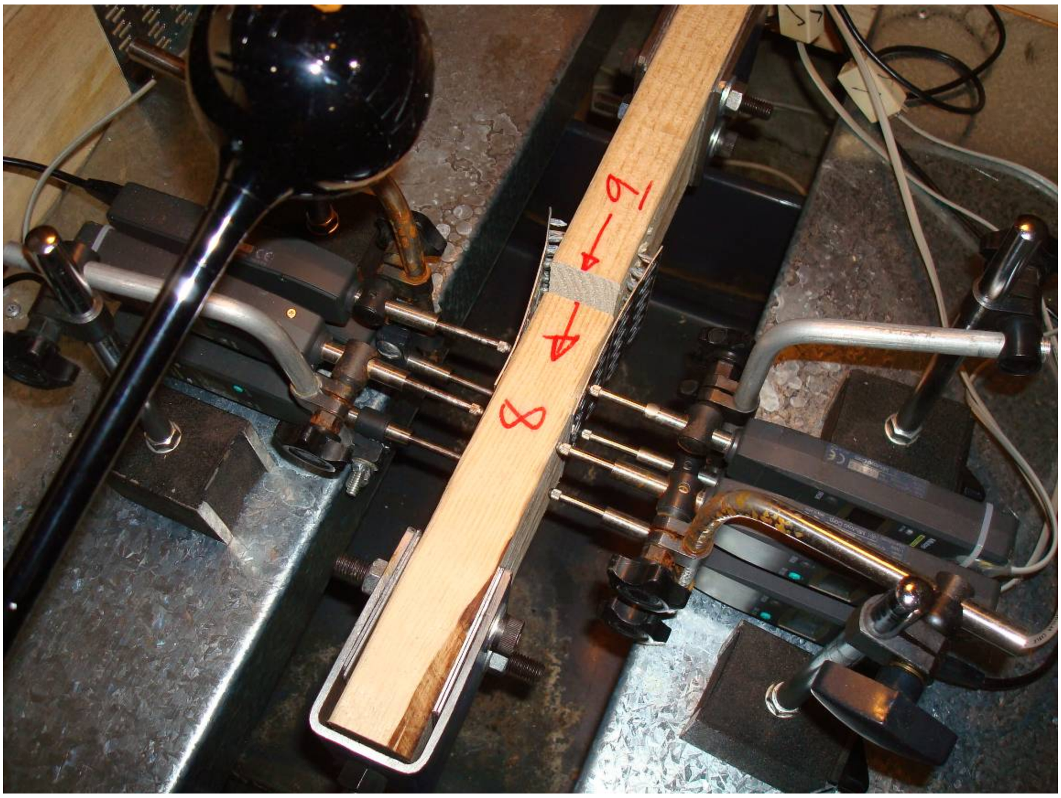


Figure 3.20 – Failure of SprayTest90% after 19 cycles of wetting

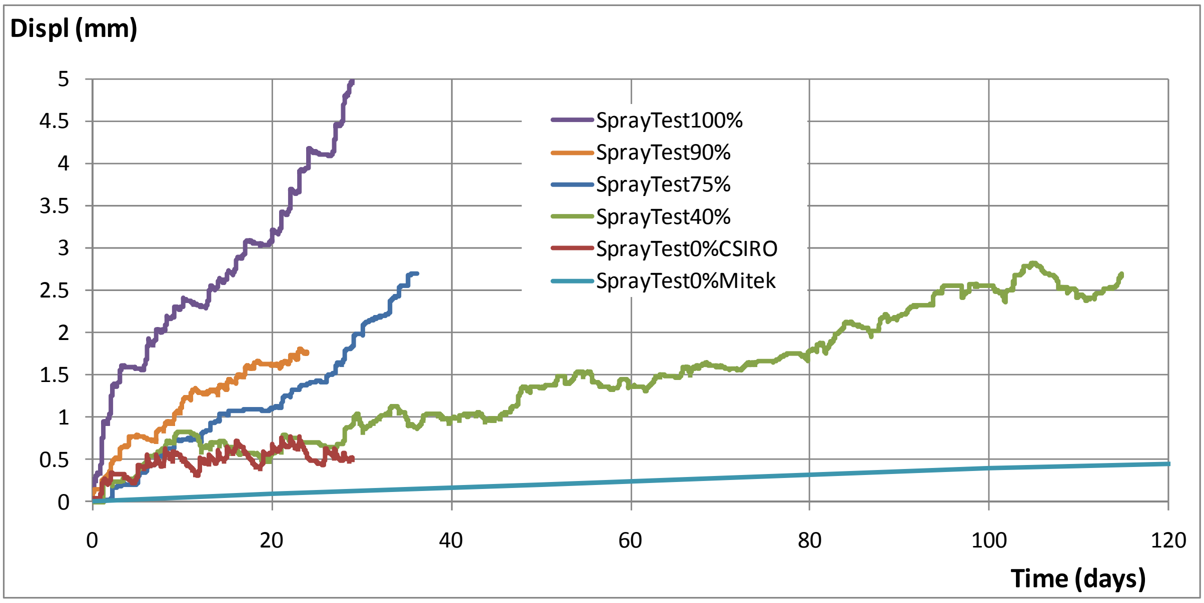


Figure 3.21 – Comparison of spray tests under different loading levels

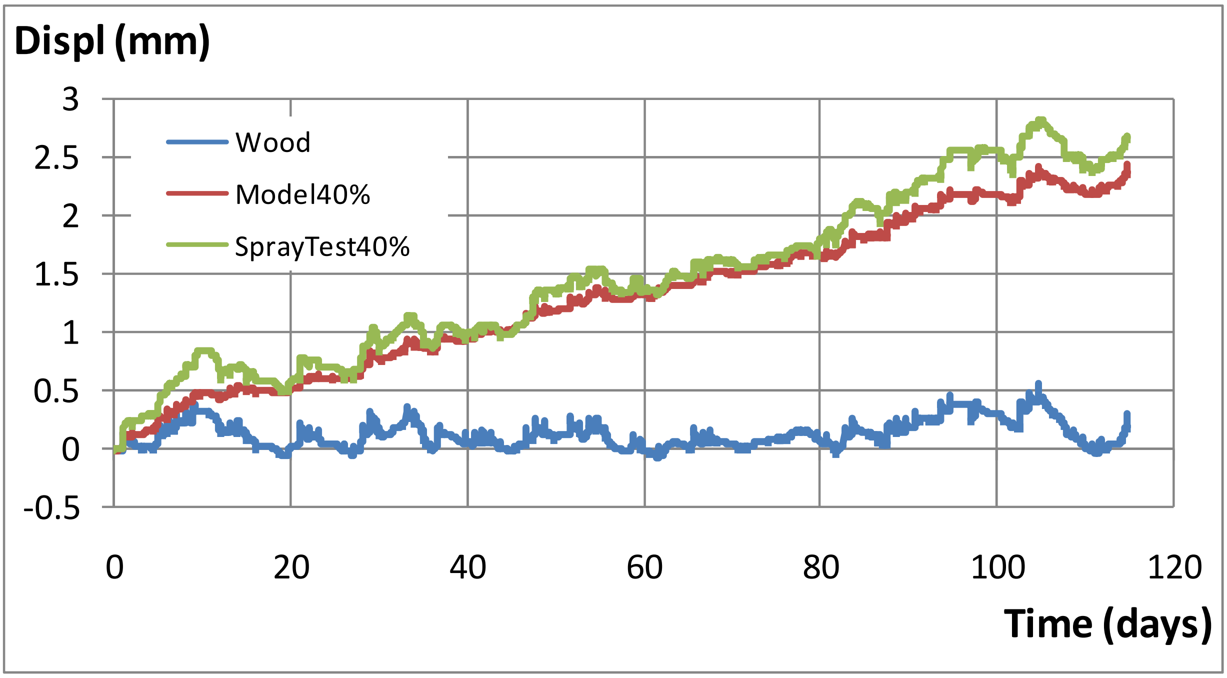


Figure 3.22 – Comparison of model prediction and spray test result for loading level of 40%.

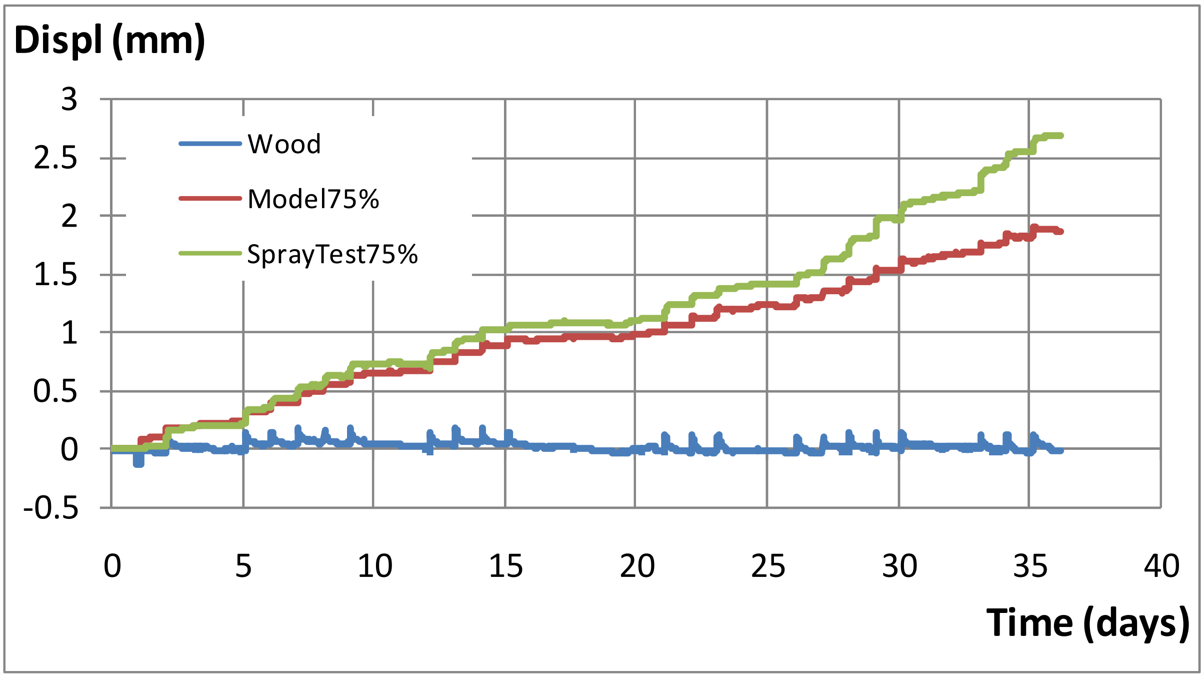


Figure 3.23 – Comparison of model prediction and spray test result for loading level of 75%.

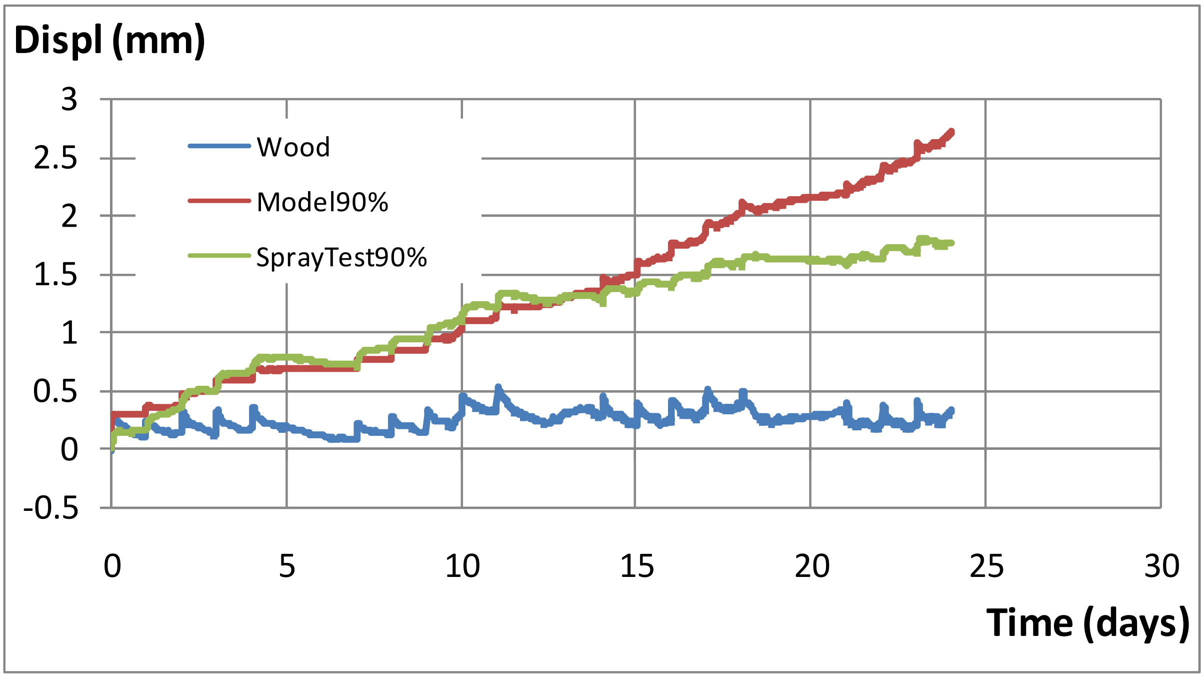


Figure 3.24 – Comparison of model prediction and spray test result for loading level of 90%.

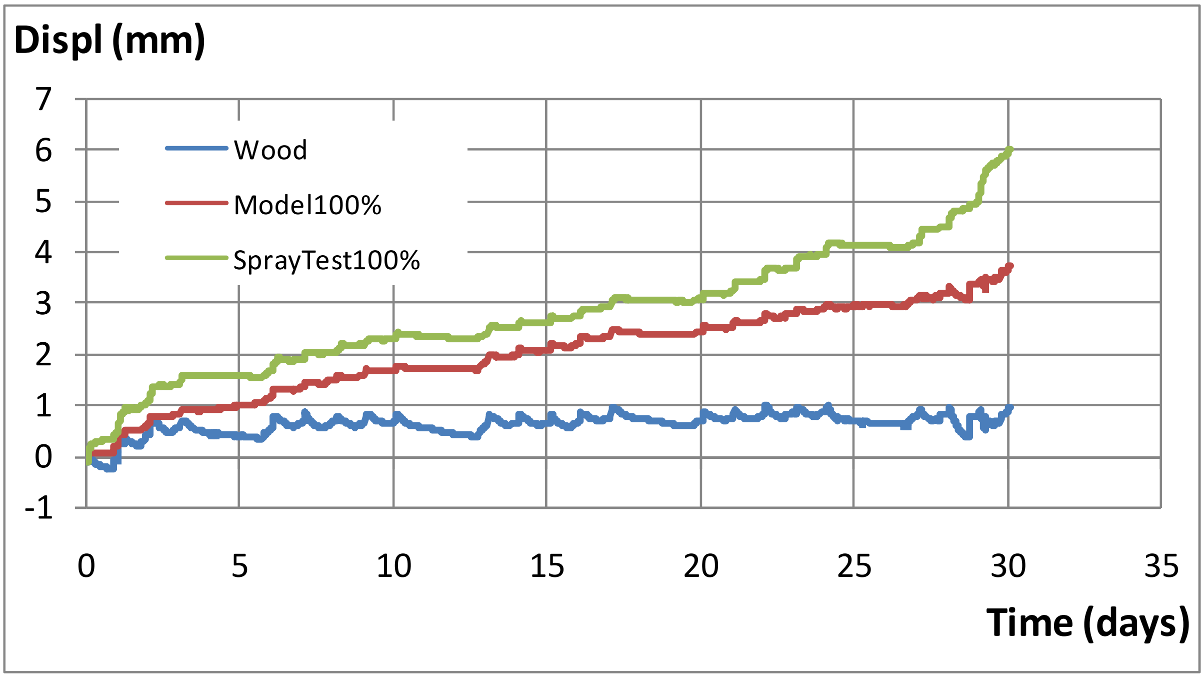


Figure 3.25 – Comparison of model prediction and spray test result for 100% loading

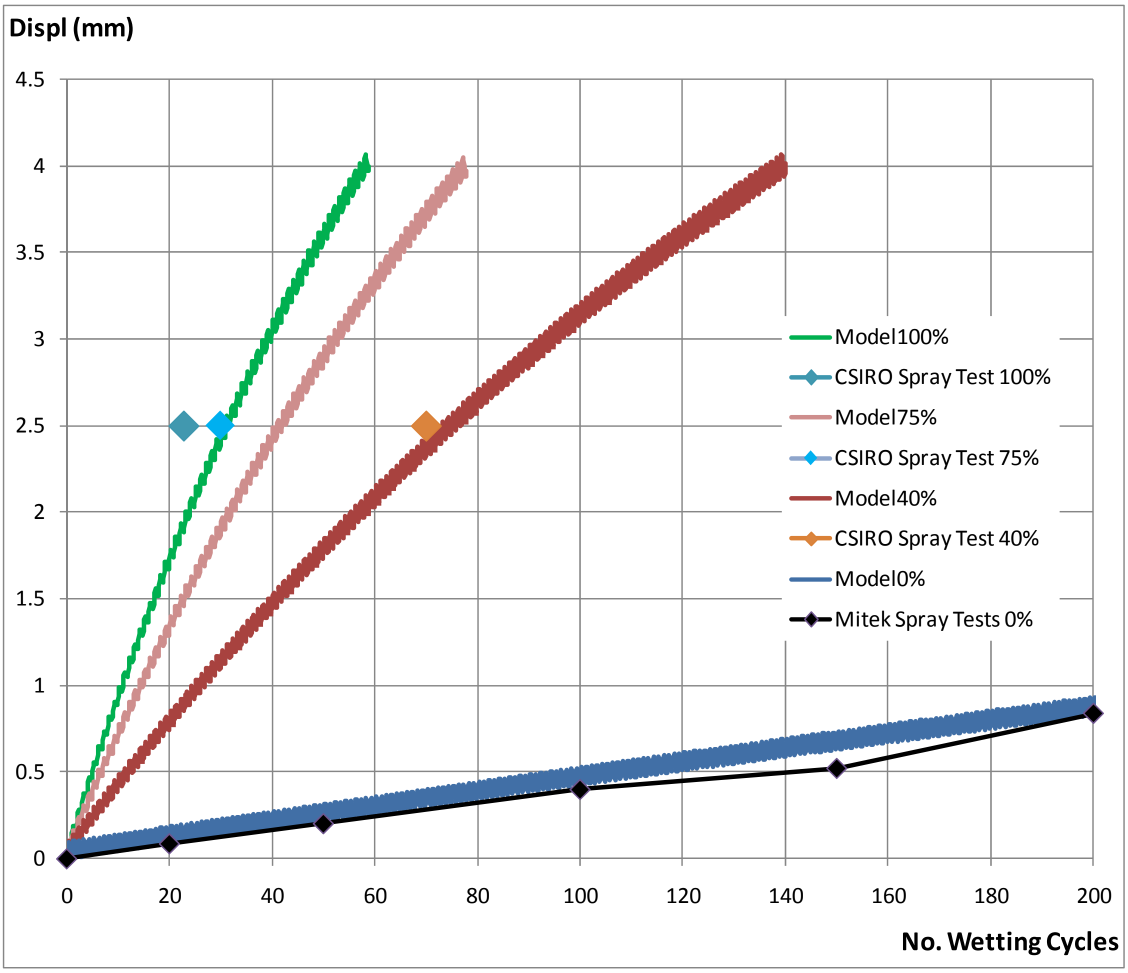


Figure 3.26 – Comparison of Pulse Model predictions versus spray test results

3.1.3. Natural Humidity Test: Short-Term

Objective

The objective of the short term natural humidity test was to determine the magnitude and time-history of wood swell-shrink under naturally varying humidity and temperature conditions in a roofspace-like environment. This information was required so that the wood swell-shrink models outlined in Section 7 could be verified using real temperature, humidity and swell-shrink data.

Test Method

A timber specimen was placed in a well ventilated hut at CSIRO Highett, and wood deformation, temperature and relative humidity were measured in fine detail. The hut provided a similar micro-climatic condition to an un-sarked roof, where the specimen was sheltered from sun, rain and wind, but surrounded with reasonably well ventilated air.

The timber used in the test was similar to specimens chosen for the spray-test experiments (90x35mm radiata pine). As shown in the test setup in Figure 3.27, swell-shrink deformations were measured on opposite sides of the specimen on one end only. Temperature, Relative Humidity and deformations were recorded continuously every ten minutes for more than a month during summer. The data collected is used to calibrate the algorithm to compute wood shrinkage with time from T and RH data.

Figure 3.27 – Natural Humidity Test set up

Results and Conclusions

An example of the swell shrink deformation, relative humidity and temperature data for a period of 16 days is shown in Figure 3.28. This graph shows how the measured deformation is quite well correlated with the long-term relative humidity trend. Figure 3.29 shows the measured swell-shrink deformation compared to the value calculated using the swell-shrink model described in Section 7. The model uses the measured temperature (T) and relative humidity (RH) data as an input and does a good job of simulating the measured deformation. Based on these results, we can be confident that the swell shrink model can predict wood deformation reasonably well, so long as the T and RH data is appropriate.

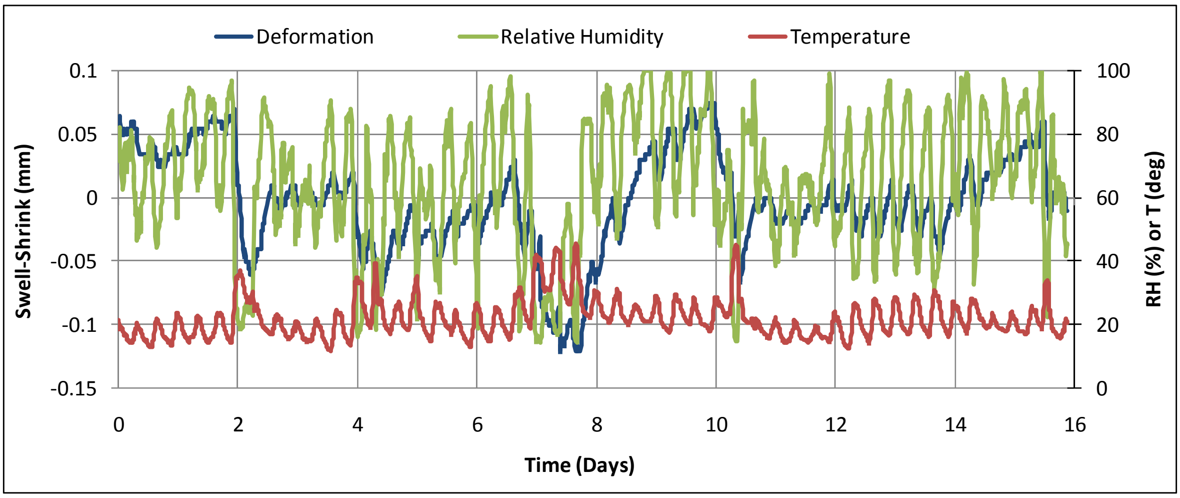


Figure 3.28 – Example of measured deformation, RH, and T in natural humidity swell-shrink tests

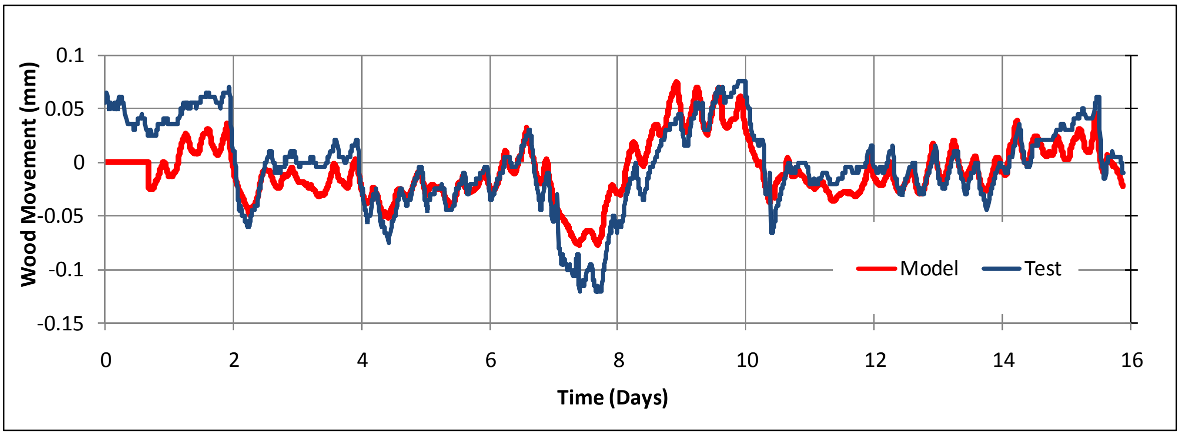


Figure 3.29 – Measured swell-shrink deformation compared to model calculated deformation based on measured T and RH data

3.1.4. Natural Humidity Tests – Long-Term

Objective

A series of creep tests on nailplate connections in softwood were conducted by Leicester & Lhuede (1992) to determine the effect of long term loading on joint capacity. Although these tests were not designed to measure nailplate backout, some rough ballpark estimates of backout under long-term natural humidity fluctuations can be extracted from the results, and used to roughly check the model predictions of mechano-sorptive backout under long-term humidity cycling.

Test Method

Short-term joint capacities for nailplated joints (1.2mm Gangnail nailplates with 10mm long teeth) were determined from tension tests. The specimens were then re-built from the same timber, loaded to 20% and 30% of their experimentally determined short-term capacities, and left under load in a shed in Melbourne for 9 years. Deformation measurements from dial gauges were manually recorded, and after 9 years sustained loading, the specimens were unloaded and then re-loaded to failure. Specimens were protected from the sun and rain, and were in a non-airtight environment with some ventilation gaps – hence the humidity conditions in the shed are somewhat similar to an un-sarked tiled roof. The test setup and results are shown in figure 3.30.

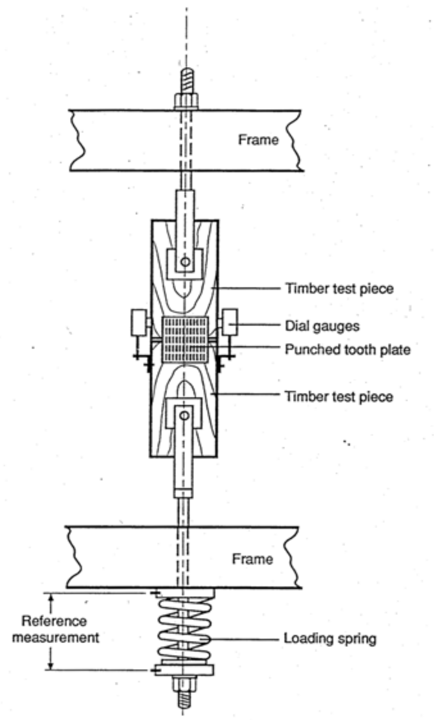


Figure 3.30 – Long-term test set up and results from Leicester & Lhuede (1992)

Results and Conclusions

For the 20% short term capacity tests (approx. 65% of design load), four specimens were tested after 9 years loading, and their residual strengths were 74%, 76%, 85% & 91% of short-term strength.

For the 30% short term capacity tests (approx. 100% of design load), four specimens were tested after 9 years loading and their residual strengths were 0%, 58%, 66% & 75% of short-term strength.

In order to use these results to make a ballpark estimate of the backout that occurred after 9 years under load (backout was observed on the specimens, but was not measured), we need to estimate how much of the strength loss in the specimens was due to nailplate backout, and how much was due to 'creep' of the joint. If we assume half the strength loss is due to nailplate backout and half to creep, and then use the results from previous backout versus strength studies reviewed in Nguyen & Paevere (2006), and summarised in Figure 2.3,, it can be estimated that the residual strength for the 65% of design load tests could be indicative of backout of around 0.25mm. For the 100% of design load tests (ignoring the 0% result, which failed after 9 years of long-term loading) the residual strength values could be indicative of backout of around 0.5mm. These estimated 9-year backout results are plotted against the predicted long-term backout under Melbourne humidity fluctuations in Figure 3.31. Although the backout estimates are somewhat arbitrary, as they assume an arbitrary amount of strength loss due to backout, they indicate that the models are at least capable of predicting backout to the correct order of magnitude.

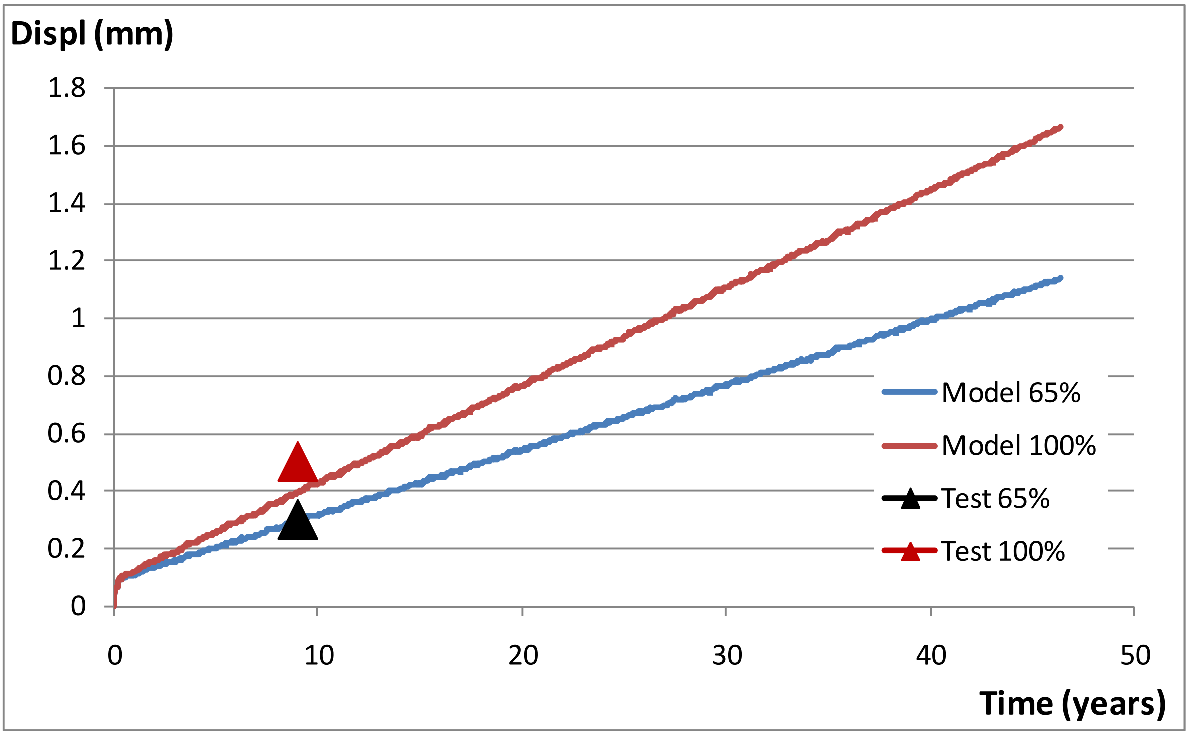


Figure 3.31 – Comparison of model predicted backout under Melbourne humidity conditions against estimated backout from long-term creep tests

3.1.5. Steaming Tests

Objective

The objective of the steaming tests was primarily to measure the magnitude of wood swell-shrink deformation that can be caused by 'steam' when introduced into a roofspace, as may occur when bathrooms or kitchens are vented into the roof void rather than to the outside.

Test Method

Timber specimens were subjected to cold steaming in an enclosed Perspex box for five minutes using a vapouriser. The test setup is shown in Figure 3.32. Humidity conditions were crudely maintained for 30 minutes around the specimen using the Perspex box. After 30 minutes, the ends of the box were removed and the environment around the specimen was restored to laboratory conditions (T = 22°C, RH = 45%). Wood deformation, temperature and relative humidity were measured in fine detail. A second experiment was also conducted in which hot steam was introduced into the roof-space of the sarked test-house (see Section 5.1 for description of test houses), and the humidity levels were measured at a few locations within the roof void.

Results and Conclusions

The cold steam tests indicate a wood swell-shrink magnitude of approximately 0.05mm to 0.09mm under direct cold steaming, which is approximately 25-50% of the pulse size observed for wetting and drying cycles. This is most likely an extreme example as steam is directly applied to wood in an enclosed chamber

The simple hot-steam tests in the roof space showed that steam introduced for short periods only affects moisture conditions in the immediate vicinity of the entrance point, but makes very little difference to the overall roof microclimate. This would suggest that it is only joints in the immediate vicinity of roofspace vents that could potentially be affected by steam from bathrooms and kitchens.

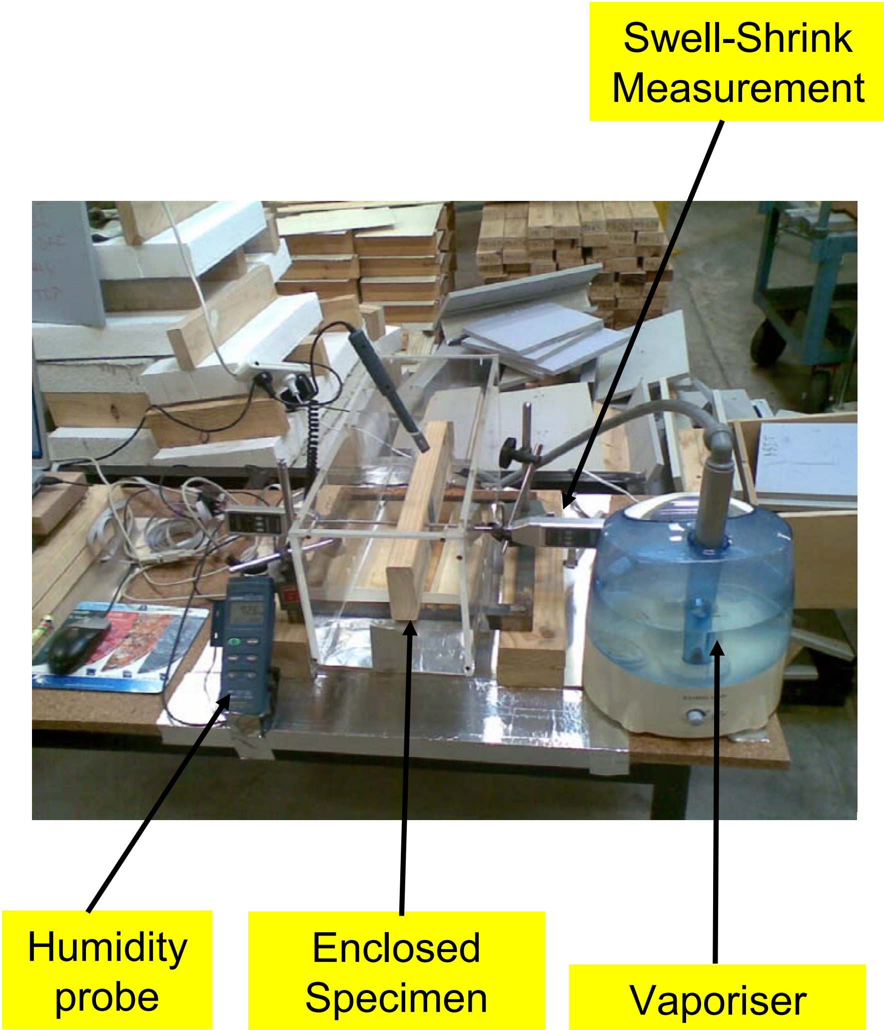


Figure 3.32 – Experimental setup for cold steam tests

3.2. Press-Pull Tests

3.2.1. Scope and Objectives

The objective of the press-pull experimental program was to investigate if the underlying mechanical properties of nailplate connections are in the range that would allow cumulative backout to occur under cyclic swell and shrink of the parent wood. The specific aim was to determine the ratio of the re-penetration resistance to the withdrawal resistance for different exposure conditions, withdrawal magnitude, and grain directions. According to the analysis presented in Paevere et al. (2009), if this ratio is less than 0.1, then cumulative backout can not occur, and if it is greater than 10, then backout can accumulate at the maximum rate.

3.2.2. Experiment Description

Experiment Program

The experimental program was limited to the standard MiTek 1.0 mm thick GQ nailplate which was used for all the experiments. The program was also limited to a single timber species – Pinus radiata, with a narrow density range. The density range of 493 kg/m3 ± 5% i.e. 518 kg/m3 to 470 kg/m3 were considered representative of the material commonly used in timber trusses.

The following broad parameters were to be investigated:

- Exposure time scale. Instantaneous, 1 month and 6 months
- Exposure conditions. moisture content (mc) for interior location, i.e. 12% mc, Wet, i.e. 20% - 25 % mc, Dry, i.e. 4% - 6% mc, Wet then dry, 20% - 25% then 4% - 6% mc, in-service and externally exposed.
- Amount of withdrawal. 0.8 mm, 1.6 mm and 3.0 mm from fully pressed.
- Grain orientation. Nailplate pressed into barkside and pithside face of backsawn material and into face of quartersawn timber, Figure 3.33.

The limits on the 12% nominal mc specimens were 10% to 14 %. Backsawn timber (for the barkside and pithside specimens) and quartersawn timber specimens were selected on the basis that the growth rings at the centre of the end section were within 15º of true backsawn and true quartersawn timber.

Table 3.4 outlines which parameters were varied in the experimental program.

The experiments were carried out at a loading head movement rate of 5 mm/min.

Five replicates of each test were performed. The barkside, pithside and quartersawn orientations of nailplate to timber were as shown in Figure 3.33.

Table 3.4 - Experimental program for the press-pull tests

Time	Exposure	Withdrawal	Grain type		
			Barkside	Pithside	Quarter sawn
Instant	12%	0.8	✓	✓	✓
		1.6	✓	✓	✓
		3	✓		
	Wet >20%	0.8	✓		
		1.6	✓		
		3	✓		
	Dry <6%	0.8	✓		
		1.6	✓		
		3	✓		
	Wet + Dry	0.8	✓	✓	✓
		1.6	✓	✓	✓
		3	✓		
1 month	In-service*	0.8			
		1.6			
		3			
	Exposed	0.8	✓		
		1.6	✓		
		3	✓		
6 months	In-service*	0.8	✓		
		1.6	✓		
		3	✓		
	Exposed	0.8	✓		
		1.6	✓		
		3	✓		

* specimens stored in roof space and brought to laboratory only for testing

Exposure Conditions

Six distinct exposure conditions were investigated as noted in the exposure column of Table 3.4. The nominal 12% mc specimens were conditioned in the laboratory. The dry specimens were dried in a conditioning room set at approximately 45ºC and 18% RH to achieve a target moisture content of 6% at 4 mm depth. The wet specimens were soaked in a bath to achieve a target moisture content of 22.5% at 4 mm depth. The wet + dry specimens were firstly soaked in the bath to 22.5% then dried in the conditioning room to 6%. The in-service specimens were located in the experimental house un-sarked roof space and the exposed specimens were fixed to north facing exposure racks. Both the experimental house and the exposure racks were located at the CSIRO Highett, Victoria site. The 1 month external exposure took place in July 2007. The 6 month exposures for both the external exposure and the in-service exposures took place from July to December 2007 inclusive. The facilities used for the above exposure conditions are shown in Figure 3.34.

Moisture Content of Test Specimens

The nominal 12% mc specimens were selected on the basis of resistance moisture meter readings. The moisture meter was calibrated for pinus Radiata. The range of moisture content for selection of test specimens was 10% to 14%. The moisture content of the wet and dry specimens was also determined by resistance moisture meter. The moisture meter probes were driven into the timber so that the mid height of the uninsulated tips of the probes were at about 4 mm depth – half the depth of the nailplate nails.

Details of Experimental Apparatus and Procedure

The MiTek 1.0 mm thick GQ nailplate was spot welded to a 5 mm thick mild steel nailplate as shown in Figure 3.35. This nailplate was attached to a steel loading block and mounted in the test machine as shown in Figure 3.36.

The nailplate was lowered until the nail tips made contact with the timber. Contact of the nail tips was assumed to be when a load of approximately 10 to 20 N (1 to 2 kg) was registered by the load cell. The displacement transducer in contact with the loading head was zeroed and displacement measured from that point.

The nailplate was then pressed into the timber until the load displacement curve trended up at a rate of approximately 20 kN/mm. Generally this occurred at a load of around 30 to 35 kN. At that load rate it was assumed that the nailplate had been fully pressed.

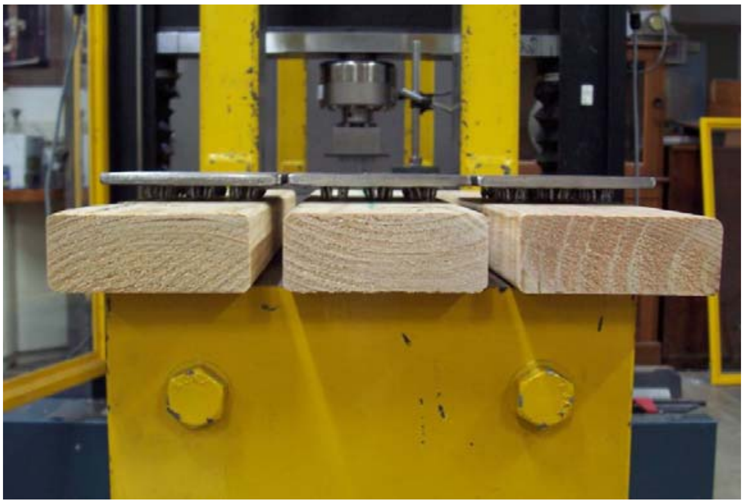


Figure 3.33 – Orientations of nailplate to timber – barkside (left), pithside (centre) and quartersawn (right)

(a)

(b)

(c)

(d)

Figure 3.34 – Exposure facilities (a) dry conditioning room, (b) soaking bath, (c) in-service, (d) exposed

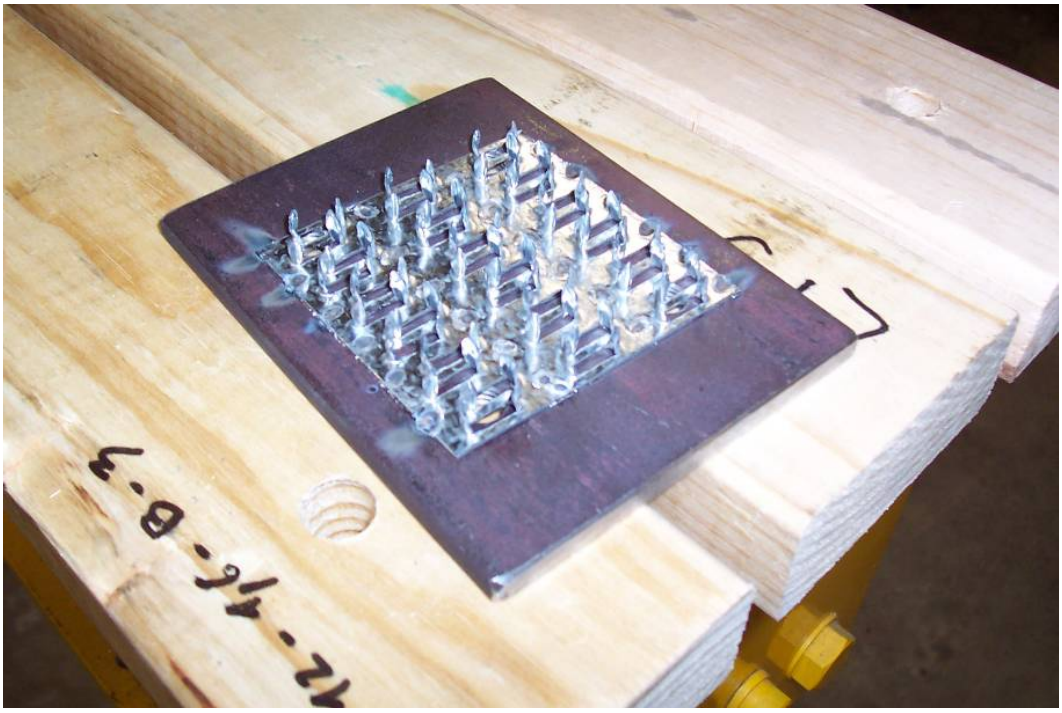


Figure 3.35 – MiTek 1.0 mm thick GQ nailplate spot welded to 5 mm thick nailplate.

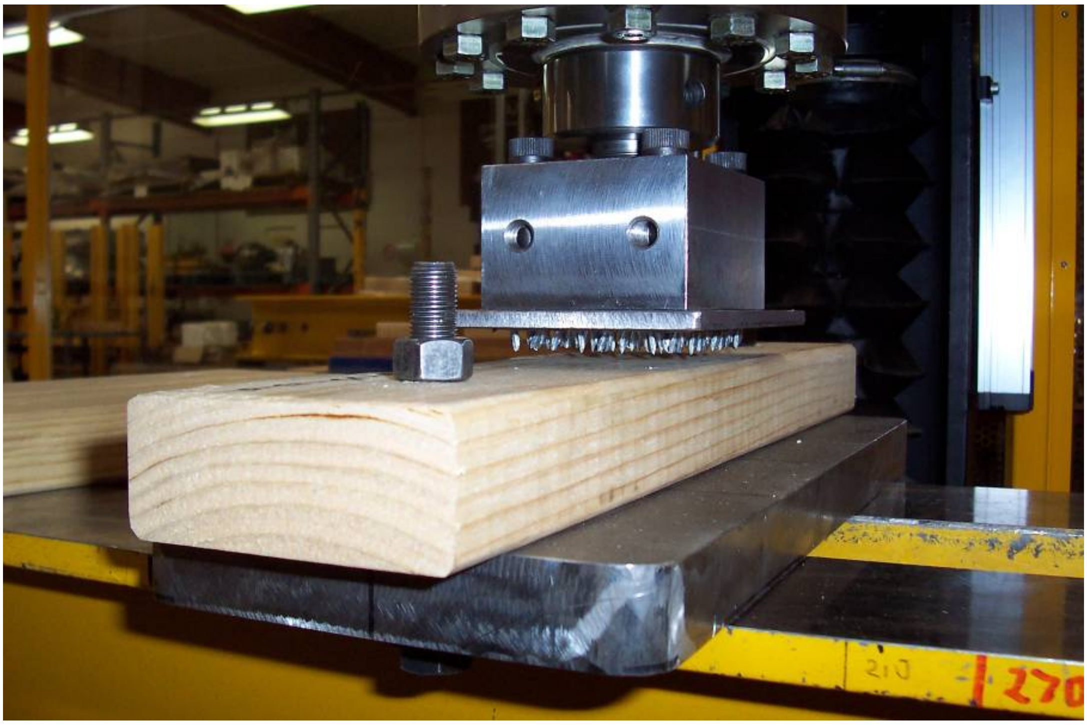


Figure 3.36 – Test arrangement for press pull tests.

All nailplates were pressed into the timber when the moisture content was nominally 12% (10% to 14%). Withdrawals of 0.8, 1.6 and 3.0 mm were then performed accordingly. Subsequent pressings and withdrawals were then performed depending on the exposure conditions as follows:

For 12% mc specimens, the nailplate was fully pressed again and withdrawn for a second time. On the second (last) withdrawal, the nailplate was fully withdrawn. The nailplate loading for the 12% mc specimens was represented notionally as shown in Figure 3.37.

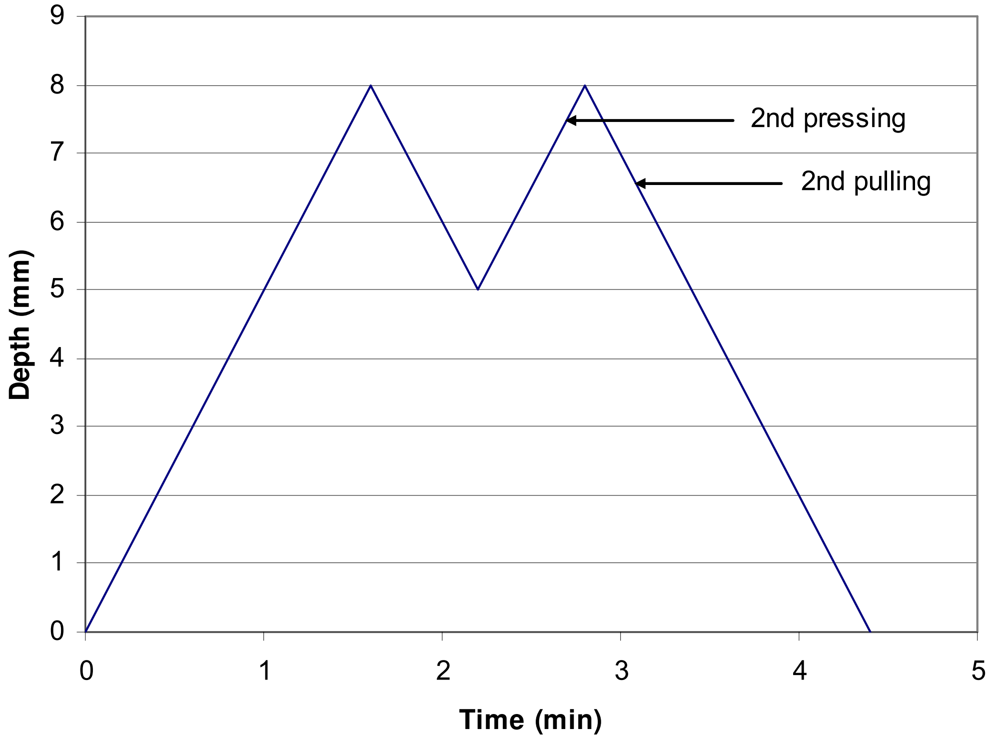


Figure 3.37 – Notional loading for 12% mc specimens, 3.0 mm withdrawal.

For the wet, dry, wet + dry, in-service and exposed tests, the specimen (with nailplate withdrawn the specified amount) was removed from the test rig and subjected to the specified exposure condition. Following the exposure, the specimen was placed back into the test rig and the nailplate fully pressed again and withdrawn for a second time. On the second (last) withdrawal, the nailplate was fully withdrawn.

The second pressing and withdrawal were the appropriate sections of the plots from which to take data for the following reasons: On the first pressing the nails of the nailplate cut a hole through solid timber and, as with the second pressing, the swell-shrink cycling in service occurs in a hole which has already been fully cut. As shown in Figure 3.38 the second withdrawal requires less force than the first.

3.2.3. Results and Conclusions

Figure 3.38 below shows a typical plot for the push pull experiment, in this case for the instantaneous, 12% mc, 0.8 mm withdrawal replicate 4 test. The determination of the second pressing force Pp2 and second withdrawal/pulling force Pw2 are indicated in Figure 3.38.

Due to the small movements occurring during the swell-shrink cycling of the nailplate/timber assembly in-service, attention was focused on the 0.8 and 1.6 mm withdrawal results. The results were broken down into end/point resistance and frictional resistance components on the basis of the following idealised model that focussed on the small movements near the base of the hole. On withdrawal, side friction on the nail provides the resistance to withdrawal. It is reasonable to assume therefore, that on pressing, the side friction is similar and the difference between the measured force and the side friction force is the end/point force. This approach is illustrated in Figure 3.39.

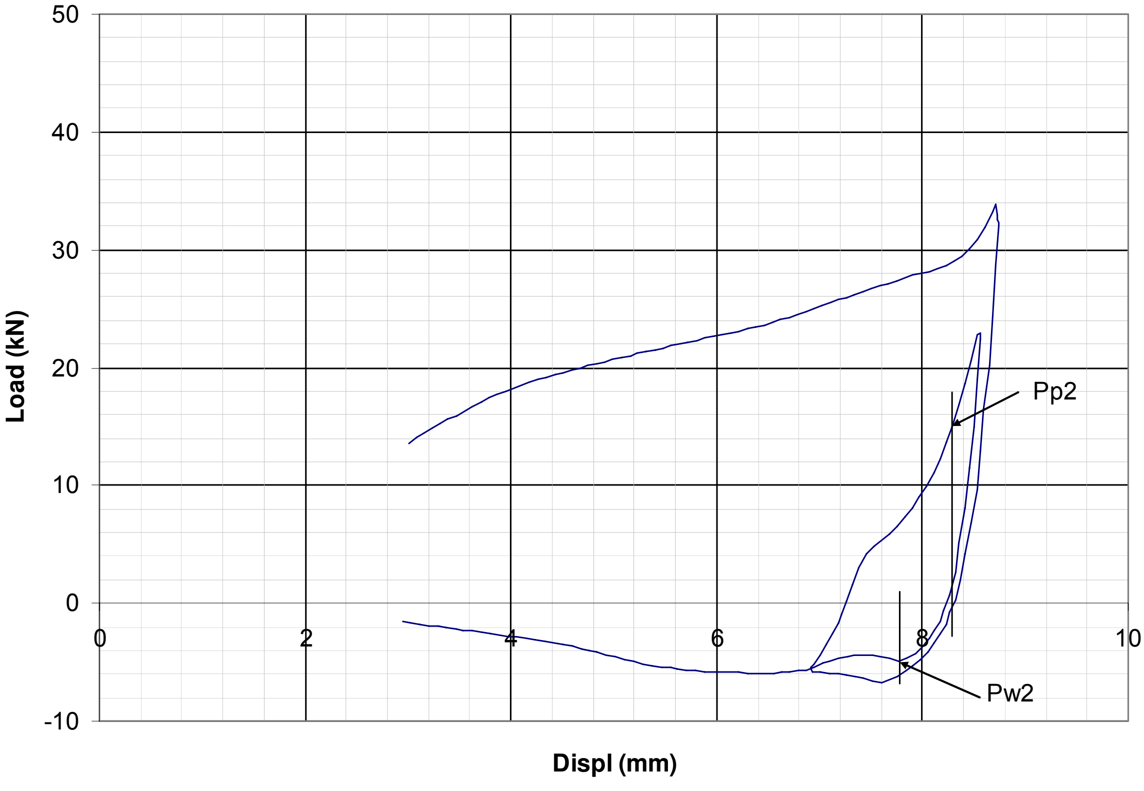


Figure 3.38 – Typical plot for push pull experiment

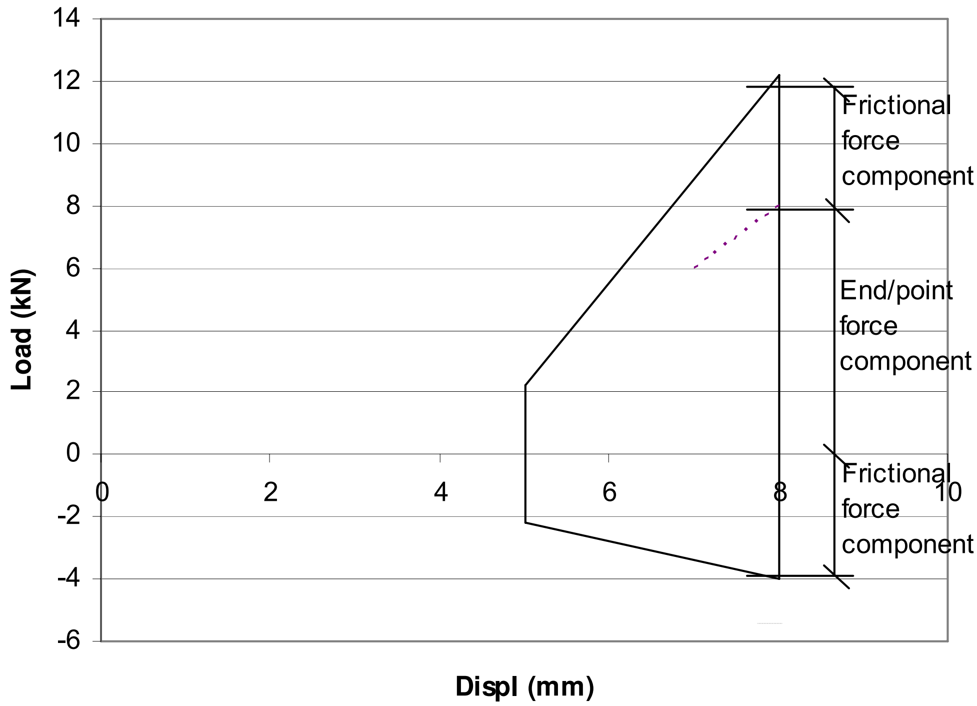


Figure 3.39 – Idealised model showing frictional component and end/point component of force.

A summary of the results for the barkside push/pull tests is shown in Table 3.5.

It appears that the end resistance is not as significantly affected by the various exposure conditions as the frictional resistance. The highest push/pull ratios were for the Wet-Dry and 6 month exposed tests.

In Table 3.6, Table 3.7, Table 3.8, average results for different grain orientations are shown for the two exposure conditions tested.

The conclusion of this program of tests were:

- Ratios of re-penetration to withdrawal resistance ranged from 3.13 to 9.72. This indicates that cumulative nailplate backout under cyclic wood swell-shrink is possible under a wide range of exposure conditions, (from dry to wet), grain directions, and withdrawal magnitudes.
- No strong or consistent trends were observed for various grain orientations in the results. The only notable effect seems to be that the penetration to withdrawal resistance ratio for the pith-side specimens is higher than for quarter-sawn or bark-side specimens.

Table 3.5 - Average forces and ratios for barkside push/pull tests.

Time	Exposure	Push/Pull ratio*		End resistance (kN)		Frictional resistance at full depth (kN)	
		0.8 mm	1.6 mm	0.8 mm	1.6 mm	0.8 mm	1.6 mm
Inst	12%	3.13	3.28	8.8	9.65	4.12	4.23
Inst	Wet	4.18	3.33	11.31	8.38	3.55	3.6
Inst	Dry	7.21	5.78	11.35	10.52	1.83	2.2
Inst	Wet-Dry	8.61	9.58	12.39	14.85	1.63	1.73
1 month	Exposed	3.71	6.46	9.5	13.1	3.5	2.4
6 months	Exposed	9.72	8.71	13.24	13.44	1.52	1.88
6 months	In-service	4.93	5.63	10.43	11.55	2.65	2.49

* Push = End resistance + Frictional resistance; and Pull = Frictional resistance only.

Table 3.6 - Average push/pull ratios for different grain orientations

Exposure	Barkside		Pithside		Quartersawn	
	0.8 mm	1.6 mm	0.8 mm	1.6 mm	0.8 mm	1.6 mm
12%	3.13	3.28	3.46	4.06	2.54	3.56
Wet-Dry	4.18	3.33	7.33	6.15	4.78	4.73

Table 3.7 - Average end resistance (kN) for different grain orientations

Exposure	Barkside		Pithside		Quartersawn	
	0.8 mm	1.6 mm	0.8 mm	1.6 mm	0.8 mm	1.6 mm
12%	8.80	9.65	9.16	8.65	8.35	8.65
Wet-Dry	12.39	14.85	14.21	13.70	12.10	16.63

Table 3.8 - Average frictional resistance at full depth (kN) for different grain orientations

Exposure	Barkside		Pithside		Quartersawn	
	0.8 mm	1.6 mm	0.8 mm	1.6 mm	0.8 mm	1.6 mm
12%	4.12	4.23	3.72	2.83	5.41	3.37
Wet-Dry	1.63	1.73	2.25	2.66	3.20	4.45

4. Load Capacity Test

4.1.1. Objective

The objective of the load capacity test was to estimate the short-term capacity for the joints used in the spray-tests conducted under load. This was required so that the spray tests could be loaded to a targeted proportion of the design load (i.e. 40%, 75%, 90%, 100% of design load) which is based on short-term capacity. The capacity was also required for the estimation of the backout versus load relationship for existing long-term joint test data (section 3.1.4) so that this could in-turn be used for calibration of the mechanical backout model.

4.1.2. Test Method

As shown in Figure 4.1, a test specimen was constructed using matched timber and modified nailplate with edge teeth removed as in the spray-tests. Loads were applied at a displacement rate of approximately 1mm/min through bolts as shown in the photograph in Figure 4.2. Extra nailplates were pressed at the loading points to avoid splitting during the test, and to force failure at the joint rather than the point of loading. The specimen was loaded at a constant displacement rate of approximately 1mm per minute until rupture.

4.1.3. Results and Conclusion

The test result indicated that the short term joint capacity of the connection as tested was 18kN, as shown in Figure 4.3. This is only an approximate value as the result is based on only one test. The design capacity for the joint is 7.8 kN, which works out at 43% of short term capacity. It is usual for the design capacity to sit at around one-third of the short term capacity, so this result may be a little at the lower end.

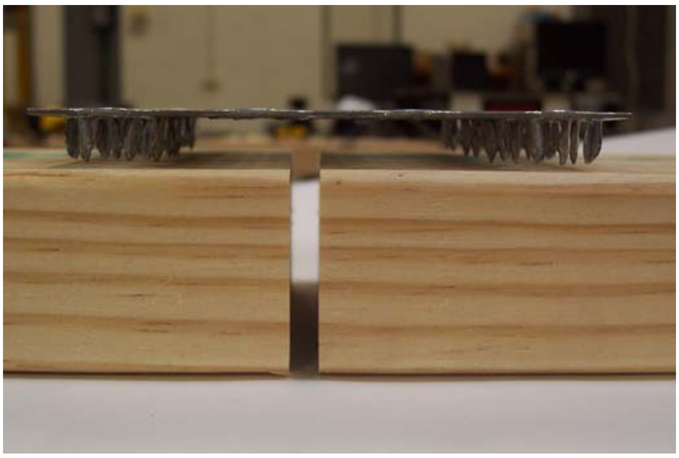


Figure 4.1 – Example test specimen before pressing, teeth near edge removed

Figure 4.2 – Setup for short term capacity test

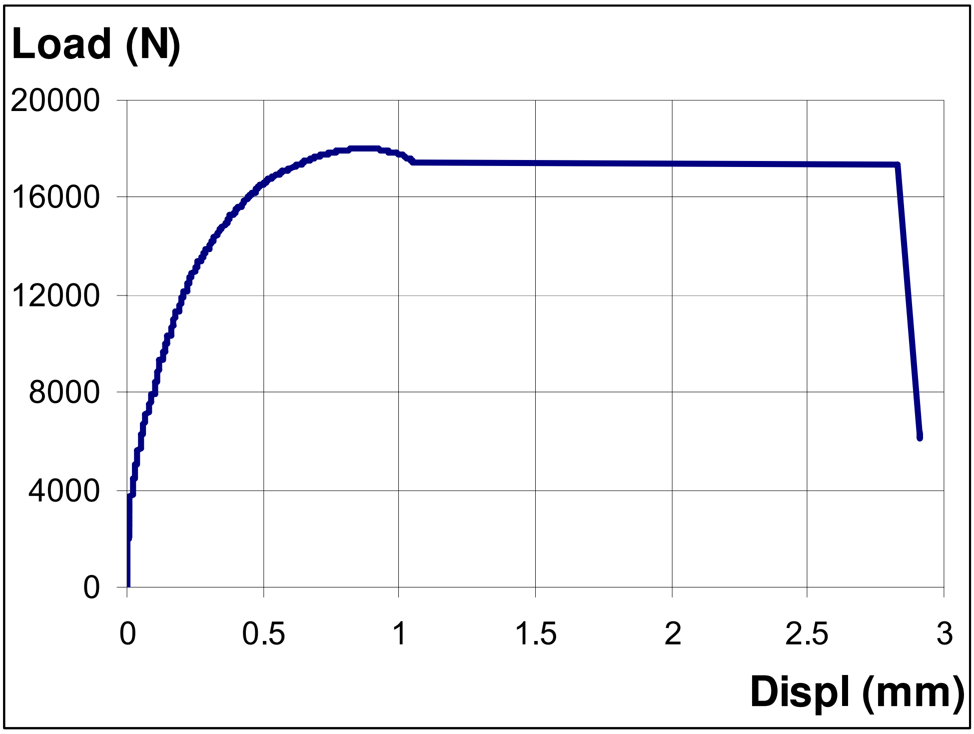


Figure 4.3 – Load versus deformation for short-term capacity test

5. Field Monitoring

5.1. Highett Test Houses

5.1.1. Objective

To study the effect of the conventional sarking on the roof space microclimates for tiled roofs.

5.1.2. Test Method

Two test houses have been built at CSIRO Highett site, as shown in Figure 5.1. The houses are identical in dimension, configuration and materials used, except one is sarked with a moisture barrier under the tiles, and one un-sarked, as shown in Figure 5.2. Monitoring systems, including 2 sets of Oregon Scientific wireless weather stations and additional independent sensors with data loggers, are installed at various locations in the 2 test houses, as depicted in Figure 5.3. Figure 5.4 shows the data logging systems on PC windows.

Figure 5.1 – Two test houses at CSIRO Highett site

Figure 5.2 – Un-sarked roof (left) vs. Sarked roof (right) in the test houses

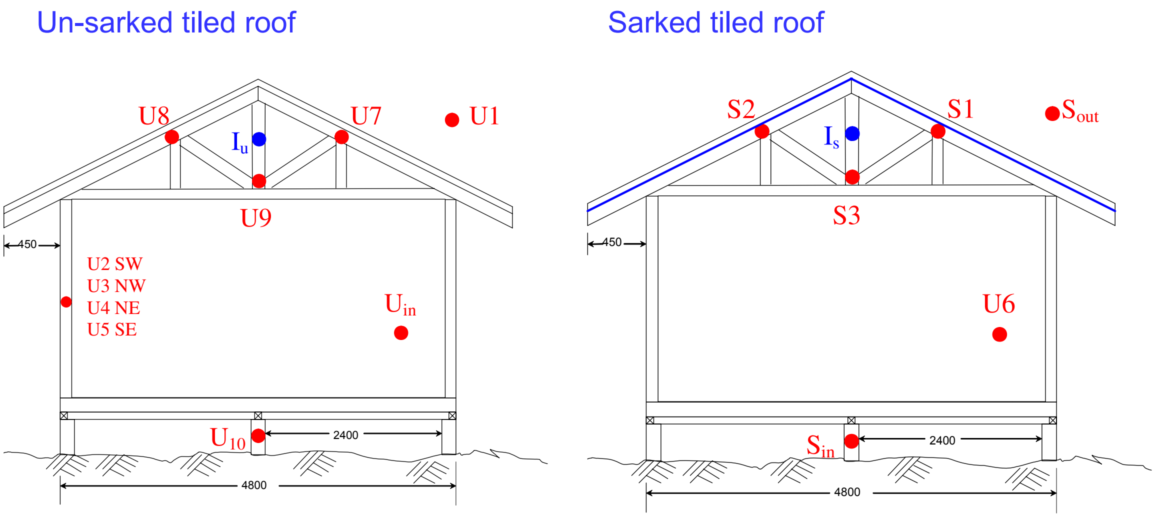


Figure 5.3 – Temperature and Humidity sensors in the two test houses. Red marks are for the sensors from the Oregon Scientific wireless weather stations. Blue marks are for independent data loggers CENTRE 324

Figure 5.4 - Data logging systems on PC

The monitoring was carried out from June 2007 to July 2008 to obtain more than one-year of recorded data. The measured climate parameters are

- Outdoor air temperature and relative humidity
- Rain fall and intensity, Air pressure
- Wind speed and direction
- Global solar radiation
- For each house
  - 4 thermo-hygro (TH) sensors in the roof space
  - 1 TH sensor indoor
  - 1 TH sensor in sub-floor
  - For the un-sarked house only: 4 TH sensor in 4 wall cavities.

5.1.3. Results & conclusions

Temperature in roof space of the test houses

Figure 5.5 shows the comparison of temperature in the roof space of the two test houses measured in January (summer) and July 2008 (winter). Quite similar temperatures observed in both roof spaces, particularly in summer. In winter, the sarked roof with reflective side downward kept the temperature within the roof space higher than that of the un-sarked roof at night time, when the outdoor temperature was very low.

Therefore in general, it can be concluded that the sarking layer has an effect on reducing the temperature variation in the roof space. The effect is very minimal in summer, and becomes more pronounced in winter, where the sarking layer keeps the night time temperature higher than that in the un-sarked roof.

Humidity in roof space of the test houses

Figure 5.5 also shows the comparison of relative humidity in the roof space of the two test houses measured in January (summer) and July (winter). A significantly lower humidity variation was observed in the sarked roof space, compared to the un-sarked roof-space.

Therefore, it can be concluded that the sarking layer has a very strong effect on reducing the humidity variation in the roof space.

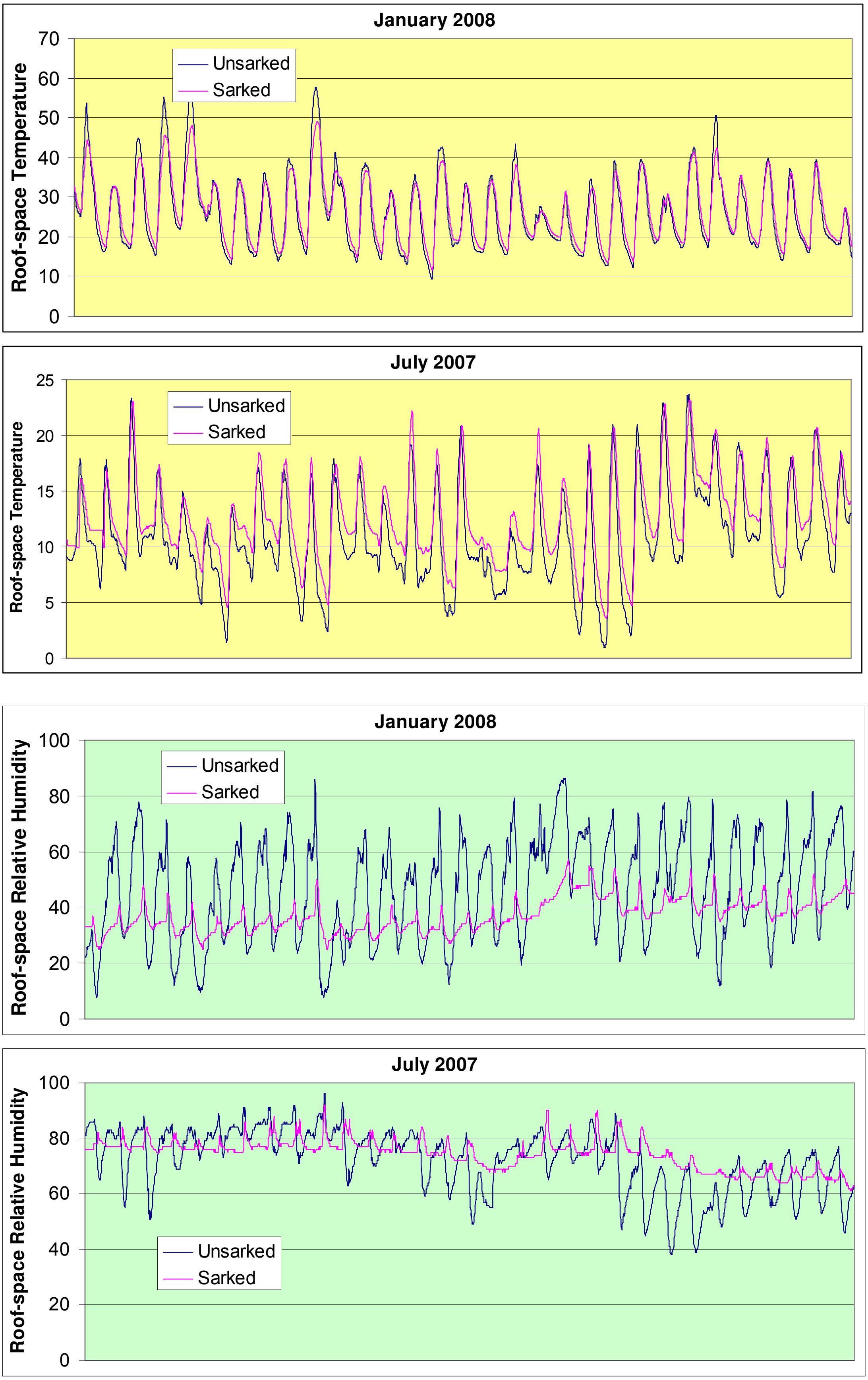


Figure 5.5 - Temperature & Humidity in the roof space of the two test houses measured in January (summer) and July (winter)

Surface moisture content of timber in roof space of the test houses

Figure 5.6 present the surface equilibrium moisture content (*semc*) of timber in the un-sarked and sarked roofs. The timber surface moisture contents were computed from the measured T and RH using the model presented in Section 7.3.1. It can be seen that the daily variation of surface moisture contents was lower by up to 70% in the sarked roofspace. A comparison of the distributions of daily variation of *semc* in the un-sarked and sarked roofs is presented in Figure 5., where the mean daily *semc* variation of the sarked roof is found to be only about one-third that in the un-sarked roof.

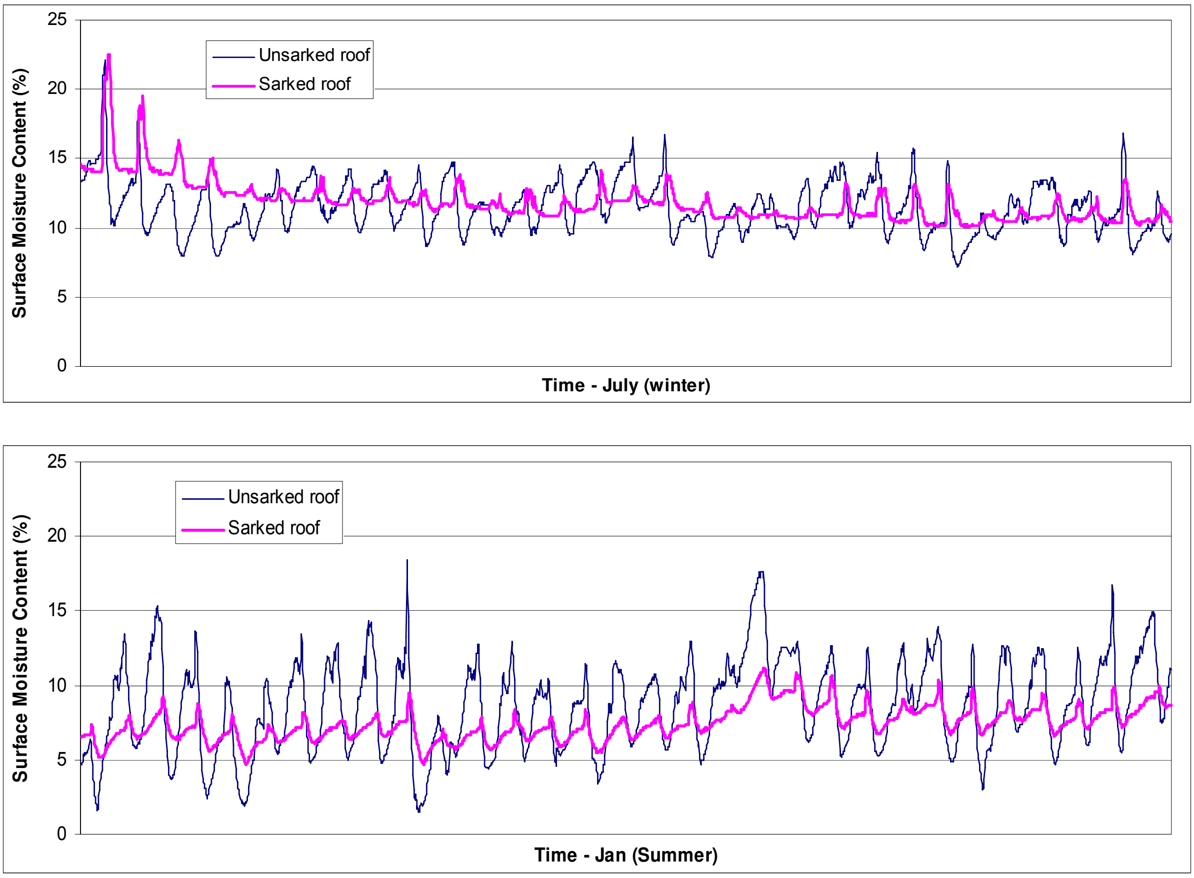


Figure 5.6 – Timber Surface Moisture Content in the roof spaces of the two test houses computed from measured T and RH in January (summer) and July (winter)

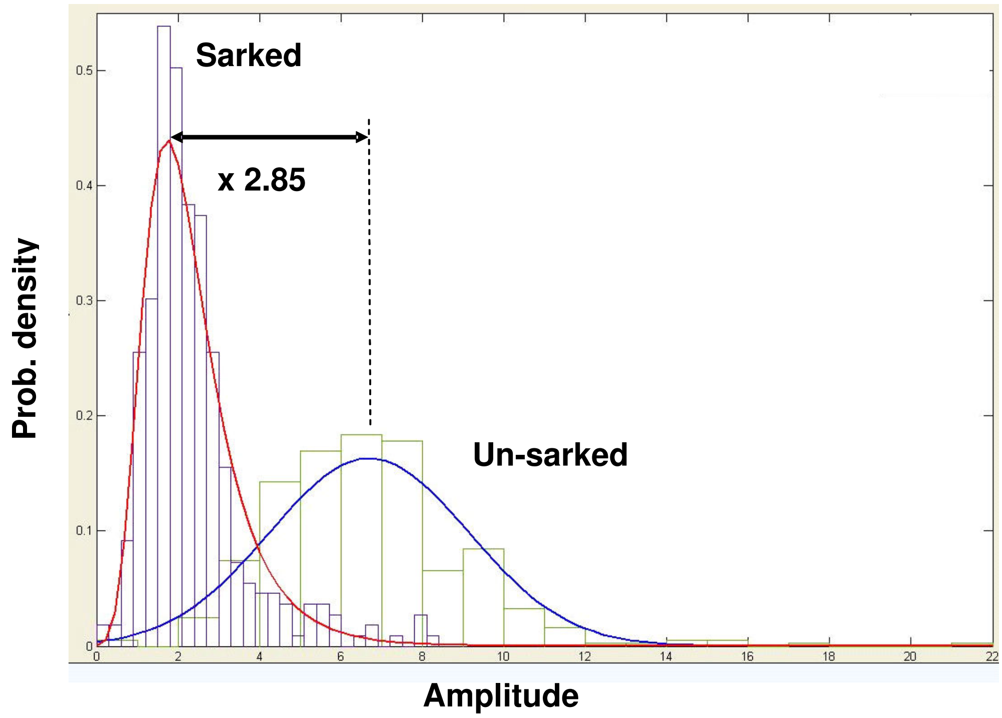


Figure 5.7 - PDF of semc – Highett Test houses

5.1.4. Model calibration

The results from comparatively monitoring the two test houses was used to established a model to estimate the *semc* in sarked roof from the *semc* in un-sarked roof, as presented in Section 7.3.3. Figure 5. shows a good similarity between the *semc* computed from measured T & RH in sarked roof and the model-prediction *semc*.

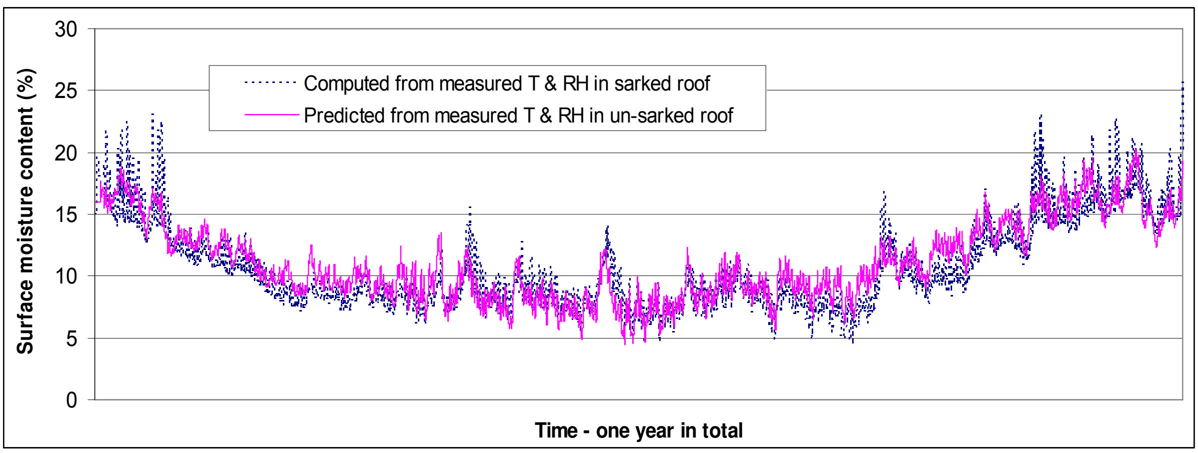


Figure 5.8 - A comparison of the measured surface moisture in sarked roof and the prediction

5.2. Field Houses

5.2.1. Objective

To collect data of roof space microclimates in real in-service houses for a reality check and calibration of the microclimate models.

5.2.2. Test method

Microclimates in roof-spaces and other internal locations of 3 in-service houses have been monitored, as described in the following sections. The locations of the 3 houses are relatively close to each other in South East Melbourne. The outdoor climate parameters, which are only measured at house No.1, are therefore assumed to be similar at house No.2 and No.3.

House No.1

The house No.1 is shown in Figure 5.9. This is a 32-year-old house in Keysborough, VIC, with un-sarked, low-pitched, light red concrete tiled roof.

Figure 5.9 - House No.1

The roof space of the house has been monitored for more than a year since 1 November 2006. Using an Oregon Scientific wireless weather station and some additional independent sensors with data logger, various climate parameters have been monitored every 20 minutes, including

- Outside air temperature and relative humidity

- Temperature and relative humidity of the air in the roof space
- Temperature and relative humidity at the truss top chord
- Temperature and relative humidity at the truss top chord under the roof side facing North
- Temperature and relative humidity at the truss top chord under the roof side facing South
- Temperature and relative humidity at the truss top chord under the roof side facing West, and right above a shower room with vents to the roof space
- Rain gauge
- Wind speed and direction
- Air pressure
- Global solar radiation
- Indoor temperature and relative humidity

The outdoor monitoring systems, the sensors within the roof space, and the data logging station at the house are shown in Figure 5.10, Figure 5.11, Figure 5.12 respectively.

Figure 5.10 - Monitoring system for outdoor climate parameters, including air temperature & humidity, wind direction & speed, rain intensity and solar radiation

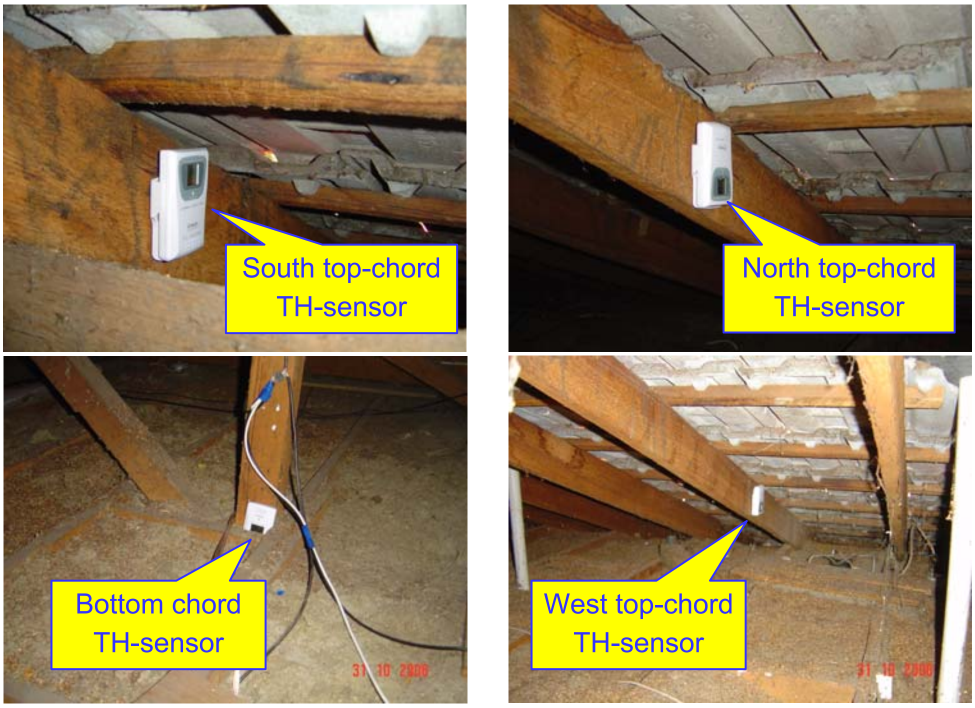


Figure 5.11 - Temperature and humidity sensors within the roof space of house No.1

Figure 5.12 - Data logging station at House No.1

House No.2

The house No.2 is shown in Figure 5.13. This is a 28-year-old house in Keysborough, VIC, with un-sarked, low-pitched, dark red concrete tiled roof.

Figure 5.13 - House No.2 and TH data logger CENTER 342

The roof space of the house was monitored for more than one year, beginning in September 2007. Using independent Temperature and Humidity data loggers CENTER 342 (see Figure 5.13), temperature and relative humidity in the roof space and indoor were monitored every 20 minutes.

House No.3

The house No.3 is shown in Figure 5.. This is a 2-year-old house in Springvale South, VIC, with un-sarked, low-pitched, black terracotta tiled roof.

Similar to the house No.2, the roof space of the house was monitored for more than one year commencing in September 2007. Temperature and relative humidity in the roof space and inside the house were monitored and recorded every 20 minutes using the CENTER 342 data logger (Fig.5.1.3).

Figure 5.14 - House No.3

5.2.3. Results & conclusions

Comparison of indoor microclimates measured at the 3 houses

It was found that the indoor microclimates can have an effect on the roof-space microclimate, particularly in winter. The indoor temperature and humidity were also monitored in the 3 in-service houses to study the effects.

The comparison of in-house microclimates, including temperature and relative humidity measured at the 3 houses are shown in Figure 5.15 and Figure 5.16, respectively. In general, it can be noted that

- The indoor microclimates are similar, when temperature is in the range of 18 to 26°C, and have a strong correlation with outdoor conditions.
- Roof microclimates depend to some degree on occupants' habits and thermostat settings/systems on hot days (T>28°C) and cold days (T<18°C)

These findings were used for the development of a model to estimate the in-house microclimate based on the outdoor conditions. The model was then used for modifying the models for roof-space microclimates.

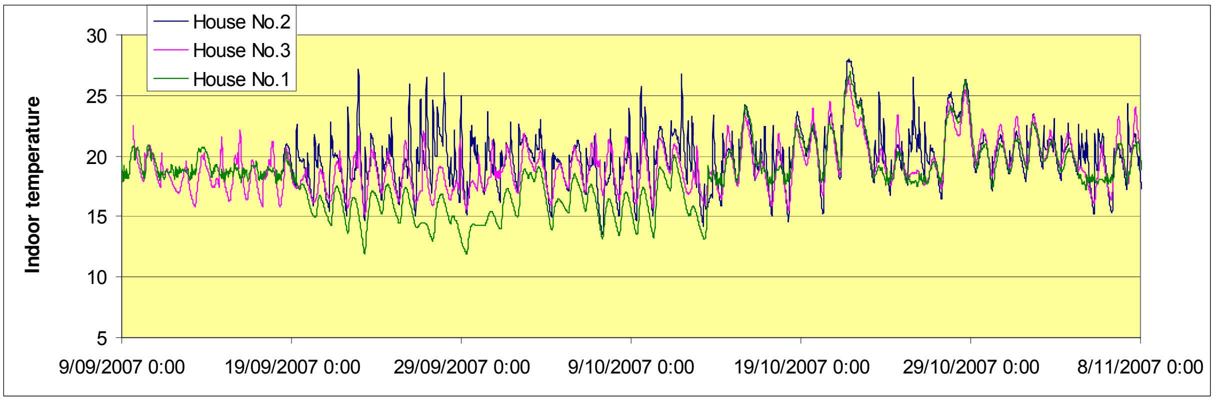


Figure 5.15 - Comparison of in-house temperature measured at the 3 houses

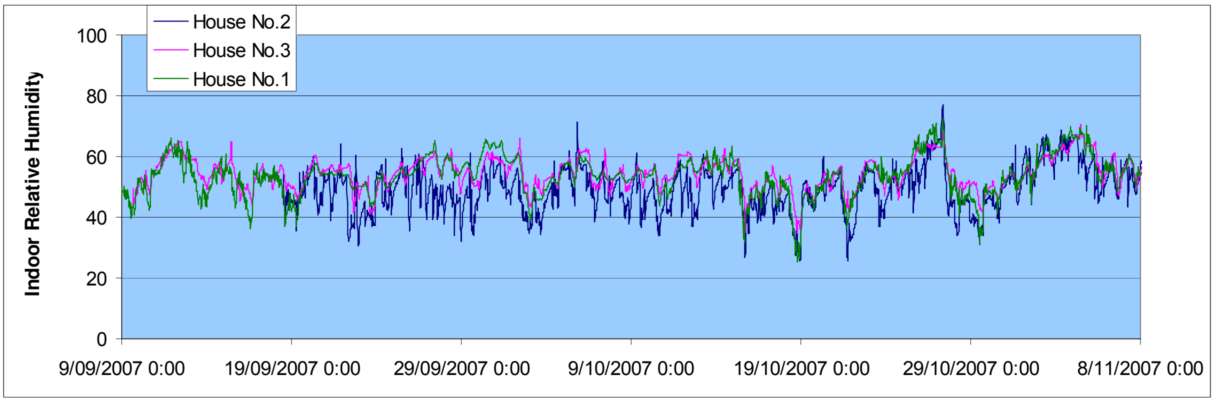


Figure 5.16 - Comparison of in-house humidity measured at the 3 houses

Comparison of microclimates within the roof spaces of the 3 houses

The comparison of roof-space microclimates, including temperature and relative humidity measured at the 3 houses are shown in Figure 5.17 and Figure 5.18, respectively. It can be concluded that:

- The microclimates in the 3 un-sarked roof spaces are quite similar, especially with regards to temperature
- House No.3 roofspace has the largest variation of temperature and humidity. This may be explained by the black terracotta tiles of the roof.
- The comparison suggests that for a given external climate, there is reasonable consistency between microclimates in un-sarked tiled roof spaces.

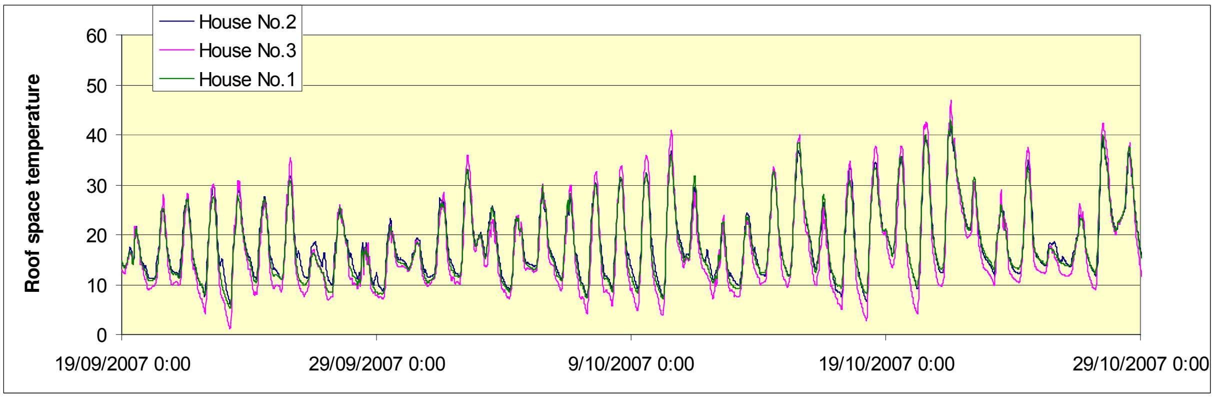


Figure 5.17 - Comparison of temperature within the roof spaces measured at the 3 houses

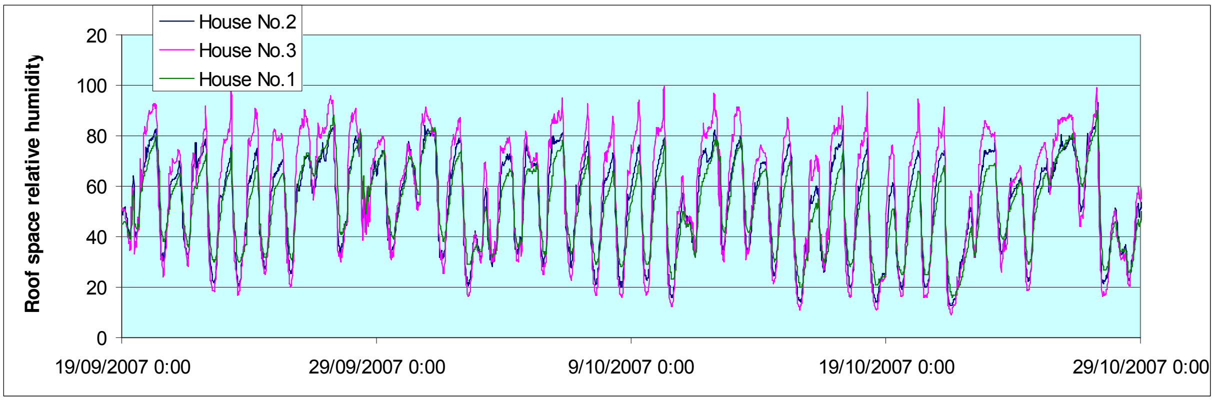


Figure 5.18 - Comparison of humidity within the roof spaces measured at the 3 houses

5.2.4. Model calibration

The monitoring data has also been used for calibrating the roof-space microclimate models presented in Section 7. The predicted temperatures agree very well with the measured ones, as typically compared in Figure 5.19 for summer (Jan) and winter (July) for roof space; and in Figure 5.20 for in-house temperature.

For the relative humidity in the roofspace, as shown in Figure 5.21, the agreement is found to be very good for summer (January). For winter (July), there are some discrepancies, mainly due to indoor moisture being neglected. Nevertheless, the model prediction here gives good results for predicting the number and the amplitude of humidity fluctuations, which are the main factor of interest for humidity related mechano-sorptive nailplate backout, and therefore is acceptable for the purpose of this study.

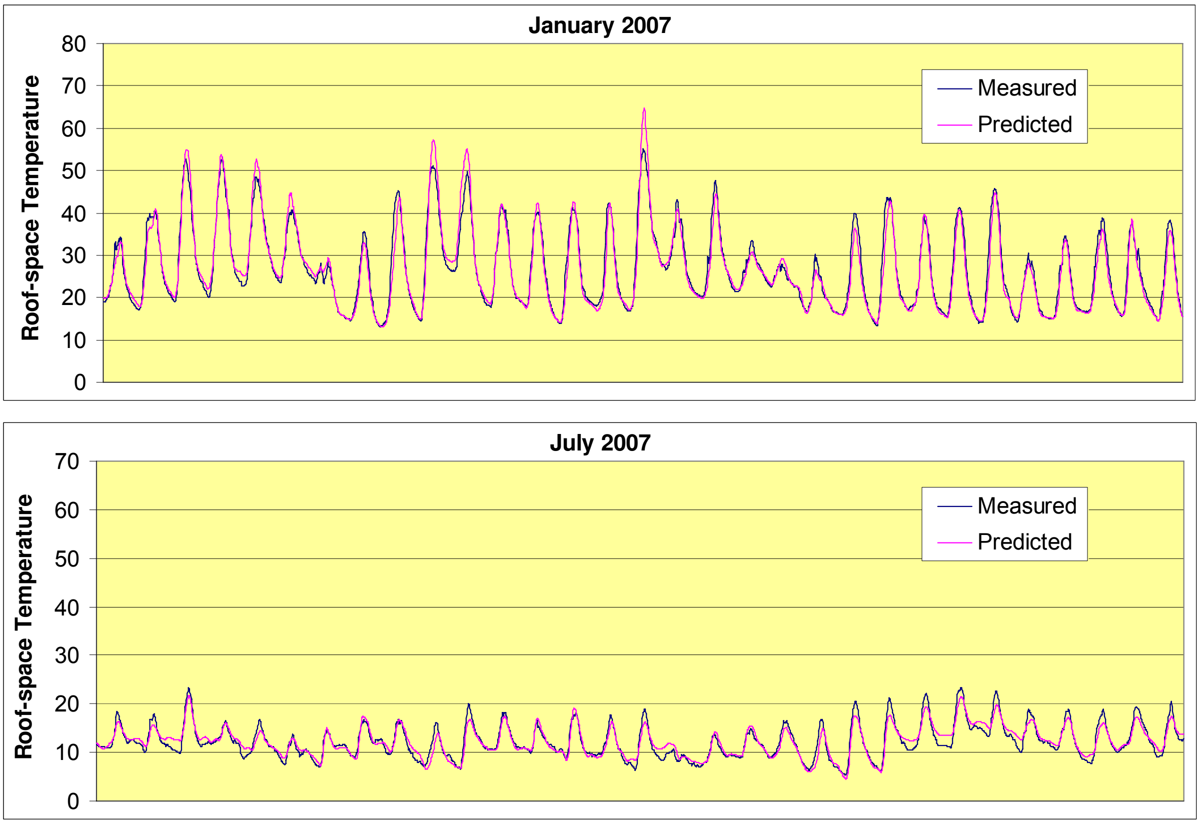


Figure 5.19 - Comparison of model-predicted and measured temperature in the roof space of the house No.1

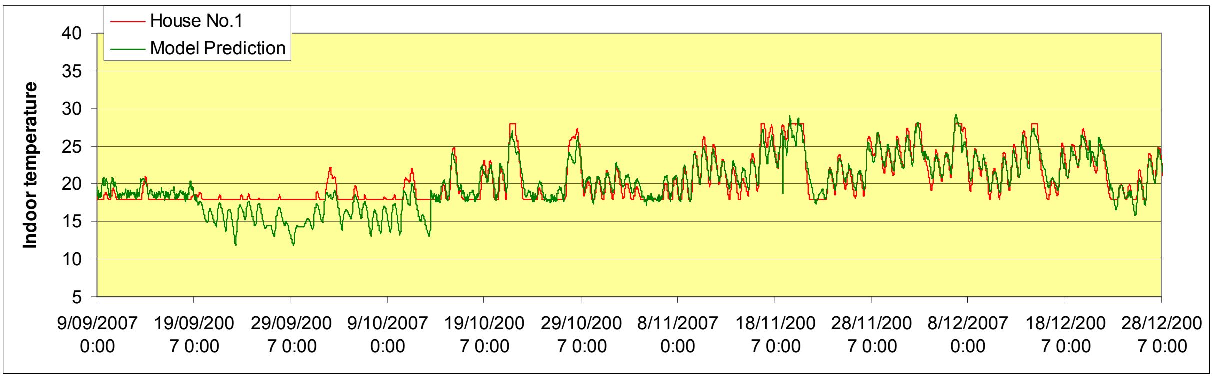


Figure 5.20 - Comparison of model-predicted and measured in-house temperature of the house No.1 (Un-occupied from 19/09/07 to 15/10/07)

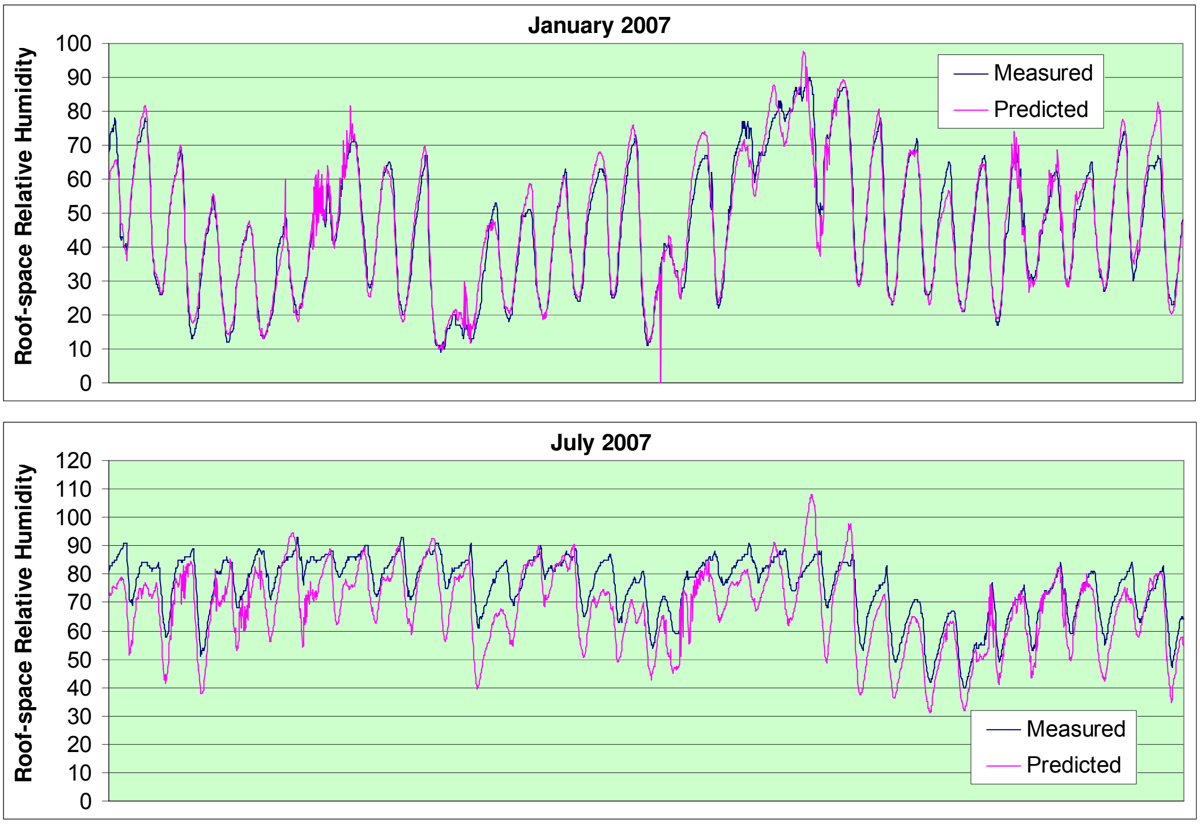


Figure 5.21 - Comparison of predicted and measured relative humidity in the roof space of the monitored house

6. Field Inspections

6.1. Random Inspections in Victoria

6.1.1. Objective

The objective of the 'random' field inspections was to get an estimation of the extent of occurrence (and type) of nailplate backout in a random selection of roof-spaces in Victoria.

6.1.2. Inspection methodology

A set of inspection checklists was developed to document backout in roof spaces. The checklists were given to an experienced building inspector (John Thornton & Associates), to fill in during pre-purchase inspections. Houses were effectively selected at random, as the inspections were based on the consultants database of previous inspections, and on new inspection jobs that eventuated during the study period, however a preference for softwood trusses and houses aged 5-30 years old was requested.

6.1.3. Results & conclusions

In total 41 roof spaces in Southern Victoria were inspected by John Thornton and Associates. The inspection checklists and photos are all presented in *Nguyen & Paevere* (2009). A summary table of inspection results at the 41 houses is given in Table 6.1. The characteristics of the inspected roofs are as follows:

- 41 roof spaces in Southern Victoria, ages from 3 to 35 years
- 16 concrete tiled roofs, 6 terracotta tiled roofs, 19 metal roofs
- Sarking only found in metal roofs, all tiled roofs are un-sarked
- Number of joints inspected per roof is about 70% of the total number of joints
- 33 roofs with Radiata trusses, 8 roofs with hardwood trusses.

From the completed checklists and inspection of the photos taken in the different roof spaces, the following observations were made:

- 16 roofs had no problem found
- 25 roofs had 'problem joints' (backout of more than 1.5mm at a point)
- 8 roofs with 1 problem joint each,
- 13 roofs with 2 problem joints each,
- 4 roofs with 3 problem joints each

Types of nailplate backout were also recorded based on the classification given in Figure 2.4. The number of the joints exhibiting backout for each type is:

- Alignment: 19
- Taper: 7
- Curling: 8
- Pear 7
- Thickness: 6
- Heaving: 2
- Bulge: 1
- Doming:1
- Parallel: 1
- Cupping: 0
- Some of problem joints have combined types

A typical photo of the 'alignment' type is shown in Figure 6.1. This was the most common type found from the inspections, and was sometimes due to warping of web members. The most spectacular case of nailplate backout (shown in Figure 6.2) was, where the nailplate had almost completely separated from the timber in a combination of taper, heaving and alignment types. Note that this case was found in the roof space of House No. 15, which was a very young house of 2 years old. More photos of backout and full details of the inspected house are given in Nguyen & Paevere (2009).

From these inspections it can be concluded that although some cases of nailplate backout were found during the inspections, mechano-sorptive backout does not appear to be a widespread and systematic problem in Victoria. It must be noted however that this conclusion is based on a very small sample size (less than 20 roofs with susceptible configuration of un-sarked tiles and softwood trusses) and from one geographic region only.

Figure 6.1 - A typical case of the ‘alignment’ type – the most common type found in the inspections

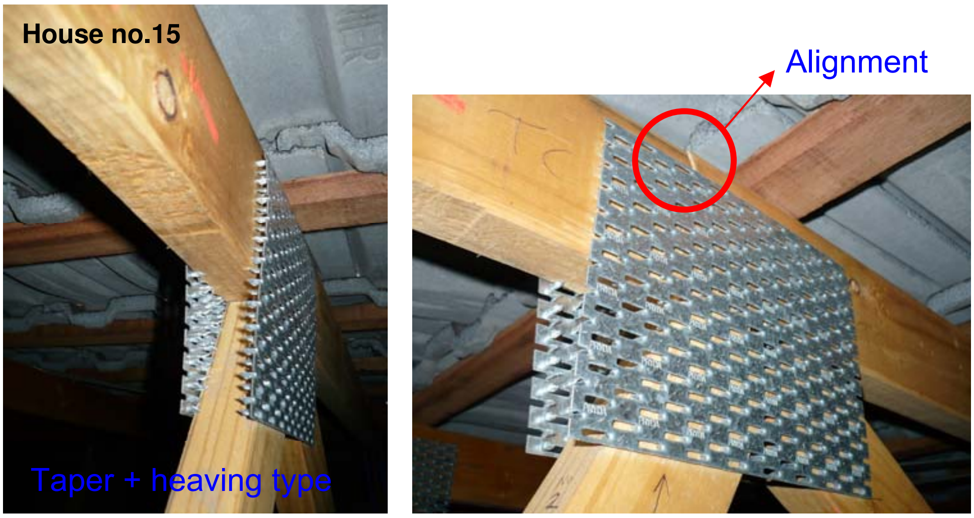


Figure 6.2 – The most spectacular case of the nailplate backout found in the inspections

Table 6.1 – Summary of random inspections

No.	Age (yrs)	Roof	Sark	% joints inspect	Wood	No. of problem joints	Problem joint 1			Problem joint 2			Problem joint 3			Note
							Loc.	Max Backout (mm)	Backout Type	Loc.	Max Backout (mm)	Backout Type	Loc.	Max Backout (mm)	Backout Type	
01	5	metal	yes	-	R	0										
02	35	terracotta		-	H	3	TC	2.0	pear	TC	3.0	construct	BC	2.0	pear	Non-standard NP
03	18	metal		-	R	1	BC	1.6	curling/ taper							
04	21	metal	yes	-	H	1	BC	1.5	thick/taper							
05	33	metal	yes	71	R	0										
06	20	terracotta		60	R	0										
07	5	terracotta		67	R	0										
08	19	metal	yes	71	R	0										
09	19	metal	yes	75	R	0										
10	25	metal	yes	100	R	1	TC	2.3	Align/thick							
11	5	concrete		70	R	0										
12	24	concrete		64	R	2	TC	1.8	Align	BC	1.6	curling				
13	22	metal	yes	62	H	0										
14	8	metal	yes	-	R	1	BC	1.6	Thick/taper							
15	3	concrete		55	R	2	TC?	4.0	curling	TC	7.0	Taper heaving				
16	10	concrete		64	R	2	TC	2.0	align	TC	2.3	align				
17	4	concrete		71	R	0										
18	11	metal	Yes	59	R	0										
19	32	concrete		-	H	1	?	5.0	curling/ taper							
20	10	terracotta		71	R	2	apex	1.6	align	TC	2.1	align				
21	6	metal	Yes	69	R	2	apex	1.6	pear	apex	1.3	pear				
22	19	concrete		68	R	2	TC	1.6	align	TC	1.6	align				

No.	Age (yrs)	Roof	Sark	% joints inspect	Wood	No. of problem joints	Problem joint 1			Problem joint 2			Problem joint 3			Note
							Loc.	Max Backout (mm)	Backout Type	Loc.	Max Backout (mm)	Backout Type	Loc.	Max Backout (mm)	Backout Type	
23	13	metal	yes	87	R	2	BC	1.6		TC	4.0	align				
24	11	metal	yes	68	R	1	BC	1.5	align							
25	22	concrete		62	H	1	apex	1.6	thick							
26	13	concrete		67	R	3	?	4.0	taper	BC	5.0	taper	TC	2.0	align	
27	16	metal	yes	52	R	0										
28	7	metal	yes	-	R	2	apex	1.5	bulge	BC	1.7	align				
29	25	concrete		68	R	2	apex	2.0	align/ heaving	TC	2.5	align				
30	30	concrete		67	H	1	apex	1.5	curling							
31	11	concrete		45	H	2	TC	3.0	pear/ doming	apex	1.5	pear				
32	5	metal	yes	86	R	0										
33	25	concrete		65	R	3	apex	1.8	curling	apex	3.0	align	TC	1.4	pear/ align	
34	7	concrete		-	R	2	TC	1.8	Align/pear	TC	1.6	align				
35	35	terracotta	no	69	H	3	BC	1.6	Para/thick/ align	apex	1.6	parallel	apex	2	Thickness/ curling	Non-standard NP
36	6	metal	yes	-	R	2	BC	1.6	pear	apex	1.6	pear				
37	21	terracotta	no	71	R	2	TC	2	align	BC	3	curling				Sarking at truss pitch
38	18	metal	yes	40	R	0										
39	3	metal	yes	60	R	0										
40	7	concrete	no		R	0										
41	1	concrete	no	71	R	0										

6.2. 'Problem Roof' Inspections

6.2.1. Objective and methodology

A selection of 'problem roofs', where performance problems had been reported by occupants or owners, have been inspected by nailplate manufacturers and other consultants. For some of these inspections the specially developed checklists were filled out, but the majority took place before these were developed and hence do not have a common data collection framework. Full details of the different inspections are given in *Nguyen & Paevere (2009)*. For the purposes of this study, these inspections are used as an additional data source to help indicate similarities between situations where backout may be more likely to occur.

6.2.2. Summary of results and conclusions

Detailed reports of causes of observed backout for the many different cases of backout are given in *Nguyen & Paevere (2009)*. Each documented case of backout needs to be considered in its own context, however some common features of many of the problem roofs were:

- Steelfast brand nailplates (these are no longer used), which are under-designed and carrying larger than appropriate loads
- Un-sarked concrete tiled roofs
- Evidence of water penetration was found into the roof space where backout due to mechano-sorptive creep effects were observed
- Majority of nailplate backouts were attributed to improper manufacture and improper storage and handling of trusses.

Hereafter are summaries of the inspections at the following places:

- Brisbane Area Retirement Homes, 27th-28th May 2003
- Glynde Retirement Homes, 18th January 2005
- North Haven & Crestview Retirement Homes, 20th Jan 2003
- Hampton Heath Retirement Homes, 15th October 2003
- Trinity College Roof Truss Inspection, June 2006

Brisbane Area Retirement Homes (QLD)

An inspection team of nailplate companies have inspected 8 units, which were considered the worst among 34 units with claimed problems of nailplate backouts detected by insurance assessors. The inspection was carried out on the 27th and 28th May 2003. These units have un-sarked concrete tiled roofs, approximately 8 to 18 years olds.

After detailed joint measurement and analysis, a couple of joints have been required to be repaired:

- A few apex nailplates on Units 104 and 118 Tranquillity Gardens: these apex nailplates were found to have backouts at time of manufacture (Unit 118), or due to mishandling at the construction stage (Unit 104).
- A heel joint on Unit 82 Southport: this nailplate was the only one found to have backout due to mechano-sorptive creep effects with direct wetting by leaking and /or wind-driven rain water. This was evidenced by many signs of water penetration into the joint area, including water marks on plasterboard ceiling, timber staining, and corrosion of the nailplates.

No evidence was found for any other joints suffering from mechano-sorptive creep effects. Most of the gaps in the joint could be attributed to pressing problem with slash pine. There were also evidences of poor on-site handling and storage, which have contributed to many backouts found in the inspected units.

Glynde Retirement Homes (SA)

MiTek nailplate company have inspected 2 units, Units 81 and 14, which were claimed to have progressive nailplate backouts by the insurance assessors. The inspection was carried out on the 18th January 2005. These units have un-sarked concrete tiled roofs, approximately 9 years olds.

It was found that most nailplate backouts in the units were due to mechano-sorptive creep effects with direct wetting by leaking and /or wind-driven rain water. In Unit 81 the roof tiles were very poorly fitted and do not have weather grooves on the overlapping edge. These construction faults have facilitated considerable wind-driven rain water penetration into the roof space and significantly wetted the timber within, causing progressive backout of nailplate from timber over time. The wind-driven rain water penetration was clearly evidenced with many indications found in the roof space, including considerable amount of leaf matter, patches of moist timber, water stains running along the top of some top chords with a small patch of timber decay. There were also quite a few areas where water stains were found due to leaky tiles and leaky ridge capping. Evidences of mishandling and storage of trusses before installation were also found, where mud and large nailplate backouts were found on one side of a truss, possibly having been left on wet ground for a long time. Unit 14's roof also had signs of water penetration with water marks on ceiling floor.

Although the degree of backouts at the time of the inspection did not required immediate repair, measures to prevent further backouts progressing with time have been requested. It was also strongly recommended that stopping water penetration is needed to prevent further rain water damage to the structure.

North Haven Village & Crestview Retirement Homes (SA)

An inspection team led by nailplate companies have inspected 3 units in North Haven Village and 1 unit in Crestview Retirement Homes to investigate the extent and possible reasons of nailplate backouts found by a trade person hired by ISA. The inspection was carried out on the 20th January 2003. These units have un-sarked concrete tiled roofs, approximately 7 years olds.

The nailplate backouts in the 3 units in North Haven Village were found mainly due to pressing problem in truss manufacturing process, i.e. nailplate not fully pressed/under-pressed or not properly pressed. One of the blackouts was found due to different thickness of timber members.

The nailplate backouts in the Crestview Retirement Homes unit were found all on the top chord joints and exhibited a small amount of heaving.

Hampton Heath Retirement Homes (VIC)

An inspection team led by MiTek nailplate company inspected 3 units at the Hampton Heath Retirement Homes. This was an attempt to find the reason why so many Steelfast joints showing signs of nailplate distress. The inspection was carried out on the 15th October 2003. These units had un-sarked concrete tiled roofs and were approximately 10 to 12 years olds.

Significant nailplate backouts were found on heel joints of large span trusses. The backouts were in the curling/peeling form, which indicated that the nailplates were overloaded. Further investigation and analysis revealed that the overloading occurred due to the following reasons:

- Smaller nailplate size than designed had been used for truss manufacturing
- Poorly pressed joints at the time of manufacture.
- Optimistic tooth design load by Steelfast. It was found that for the design joint the ratio of long-term load per tooth over allowable design load (LTL/ADL) would be 0.86 using the Steelfast published data. However, using MiTek data, which is more realistic for this type of joint, the computed ratio LTL/ADL was 1.59, indicating that the joint was 59% overloaded.

Trinity College – Gawler Campus

Roof Trusses of Theatre Buildings and 3 other Buildings, named Building 1, 2, and 3 at Gawler campus, Trinity College (SA) were inspected in Oct 2006, as a number of nailplate backouts were found in the roof spaces. All the buildings were approximately 10 years old at the time of inspections. All had metal sheet roofs, unsarked, except Building 3 which was sarked. Pryda Claw nailplates were used in

Theatre Building; Steelfast nailplates were used in Building 1; MiTek nailplates were used in Building 2 and 3.

It was reported that a number of joints with large nailplate backouts were found in all buildings. The backouts were found predominantly at the web and bottom chord joints in Building 1; and at the top chord splice and adjacent web/top chord joints in the other buildings. Reasons for the backouts were reported unclear. However, in particular, there was a nailplate completely backing out of a timber joint which was near a damaged evaporative cooling duct in the Theatre Building. This suggested that the complete backout may be due to shrink/swell of timber due to the damaged duct.

From limited descriptions and photos, it was thought that the backouts were most possibly due to overloading at the bottom chord to web joint in Building 1, and due to improper handling during constructions in the other buildings. The buildings have been inspected recently by a Pryda staff to ensure all problem joints were properly repaired and no further problem developed.

7. Models Summary

7.1. Overview

As outlined in the diagram in Figure 7.1, a series of inter-connected analysis techniques and numerical models have been developed to enable the prediction of nailplate backout, based on climatic conditions (rainfall, humidity, solar radiation, wind, temperature), and roof configuration (sarked, un-sarked, joint loading). This section provides an outline of the four inter-connected models, which deal with the prediction of:

- roof-space microclimate given external climate and roof configuration
- wood moisture content given roof-space microclimate
- wood shrink-swell given wood moisture content profile
- nailplate backout given the wood shrink-swell

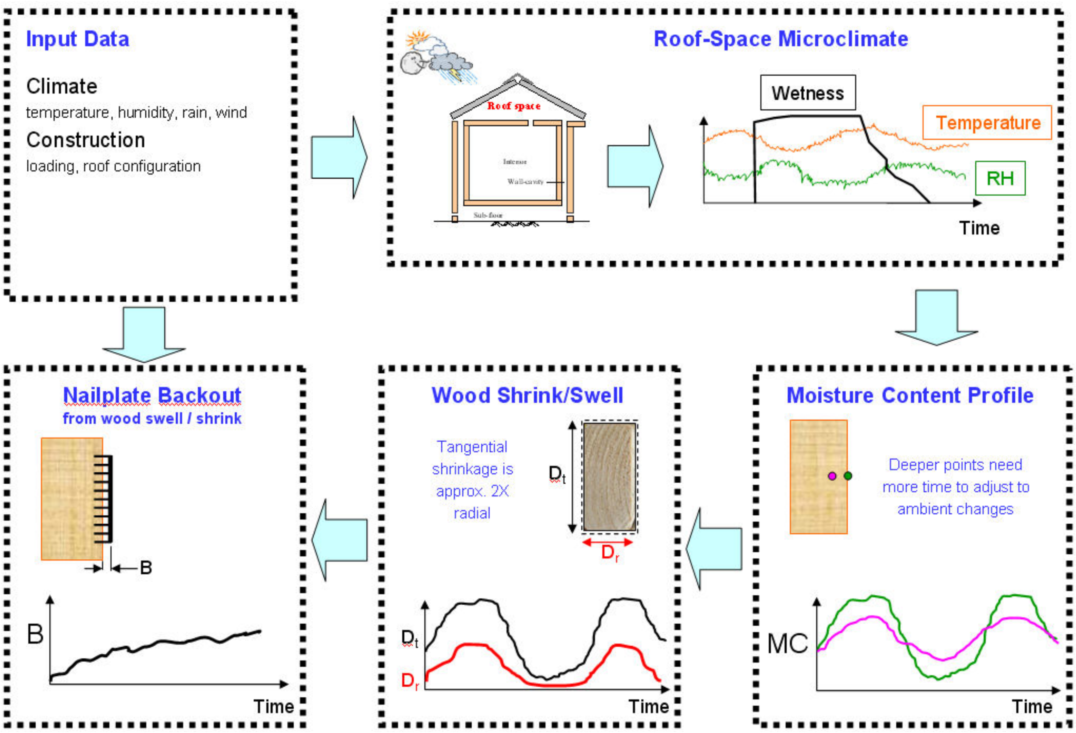


Figure 7.1 – Modelling Approach

7.2. Roof-Space Microclimate

This Section presents the models equations for roof-space microclimates. The development of the models is presented in *Nguyen et. al.* (2009).

7.2.1. Input data from BOM

- Outdoor Temperature, T_o (°C)
- Outdoor Relative Humidity, RH_{out} (%)
- Mean Wind Speed, V_{out} (m/s)
- Global Solar Radiation, I_n (W/m^2)

7.2.2. In-roof Temperature T_{inroof} (°C)

$$T_{inroof,t} = A_T \frac{\alpha}{h_o} I_{n,t-3hours} + B_T \left(4T_{out,t-3hours} + T_{indoor,t-3hours}\right) \tag{7.1}$$

where A_T = 3x10^{-5}, B_T = 0.2, α = 0.2 ~ 0.8, depending on tile's colour, taking 0.5 for most common tile colour in practice. The convective heat transfer coefficient at exterior roof surface h_0 can be computed by

$$h_0 = T_{out}^{-2.0} \tag{7.2}$$

The indoor temperature can be estimated from the outdoor temperature by

$$T_{indoor,t} = \begin{cases} 18 & \text{if } T_t < 18 \\ T_t & \text{if } 18 \le T_t \le 28 \\ 28 & \text{if } T_t > 28 \end{cases} \quad \text{where } T_t = \frac{\sum_{i=0}^{24}\left(T_{out,t-i}(24-i)\right)}{\sum_{i=0}^{24}(24-i)} \tag{7.3}$$

7.2.3. In-roof Relative Humidity RH_{inroof} (%)

$$RH_{inroof} = \frac{AH_{inroof}}{AH_{0,inroof}} 100\% \tag{7.4}$$

where

$$AH_{0,inroof} = \frac{2.167}{(T_{inroof} + 273)} \exp\left(53.4 - \frac{6516}{(T_{inroof} + 273)} - 4.1\ln(T_{inroof} + 273)\right) \tag{7.5}$$

$$AH_{inroof,t} = \frac{\sum_{t=\text{now}}^{\text{previous } n \text{ hrs}} \left(AH_{out,t} \frac{T_{out} + 273}{T_{inroof} + 273} V_{out,t} \right)}{\sum_{t=\text{now}}^{\text{previous } n \text{ hrs}} V_{out,t}} \tag{7.6}$$

$$AH_{out} = \frac{RH_{out}}{100} \frac{2.167}{(T_{out} + 273)} \exp\left(53.4 - \frac{6516}{T_{out} + 273} - 4.1\ln(T_{out} + 273)\right) \tag{7.7}$$

The duration of time t_Q from *now* to the past n hours used for the summations is estimated by iteratively solving the following equation,

$$t_Q = 24 - \frac{8 \sum_{t=now}^{-t_Q} V_{out,t}}{t_Q} \tag{7.8}$$

7.3. Wood Moisture Content

This Section presents the models equations for wood moisture content. The development of the models is presented in *Nguyen et. al.* (2009).

7.3.1. Timber Surface Moisture Content (semc)

$$semc = \frac{1800}{W}\left[\frac{KH}{1-KH} + \frac{K_1KH + 2K_1K_2K^2H^2}{1+K_1KH+K_1K_2K^2H^2}\right] \tag{7.9}$$

where H is relative humidity in decimal number, and W, K, K_1, K_2 are functions of temperature T in °C:

$$\begin{aligned} W &= 349 + 1.29T + 0.0135T^2 \\ K &= 0.805 + 0.000736T - 0.00000273T^2 \\ K_1 &= 6.27 - 0.00938T - 0.000303T^2 \\ K_2 &= 1.91 + 0.0407T - 0.000293T^2 \end{aligned} \tag{7.10}$$

7.3.2. Timber Moisture Content profile

The moisture loading *semc* on timber surface can be divided into successive step changes with time. The moisture m at a depth x at time t then can be estimated by

$$m(x,t) = m(x,t-1) + \sum_{i=-47}^{0}(semc_{(t-i)} - semc_{(t-i-1)})\left(erfc\left(x/2\sqrt{D_x(t-i)}\right) - erfc\left(x/2\sqrt{D_x(t-i-1)}\right)\right) \tag{7.11}$$

where *erfc* is the standard complimentary error function

$$erfc(u) = 1 - \frac{2}{\sqrt{\pi}} \int_0^u e^{-\xi^2} d\xi \tag{7.12}$$

7.3.3. *Computing Timber semc in Sarked Roof from Timber semc in Un-sarked Roof*

$$semc\Big|_{sarked} = m(x = 3mm, t)\Big|_{unsarked} \tag{7.13}$$

Then increase the yearly component of the moisture content by a factor of 1.8

7.4. Wood Shrink/Swell

This Section presents the models equations for wood swell/shrink. The development of the models is presented in *Nguyen et. al.* (2009).

The wood shrinkage can be estimated from timber moisture profile *m(x,t)* by

$$\Delta S(t) = S_p \int_0^{X_{ref}} \left(\frac{m(x,t) - m_{ref}}{30} \right) dx \tag{7.14}$$

where

- m_{ref} is the reference moisture (m_{ref} = 8% is recommended)
- X_{ref} is the reference depth (X_{ref} = 17.5mm if referred to the middle of 35x90 timber)

Note that any range of *x* where *m(x)* > 30% must be excluded in the integral.

7.5. Mechanical Backout Model

This section presents the models for prediction of nailplate backout for a given time-history of wood swell and shrink. Nailplate backout can occur when cyclic mechano-sorptive swelling and shrinking of wood results in a ratcheting mechanism in which withdrawal deformations accumulate. The full development background for the models is presented in *Paevere et. al.* (2009).

The underlying concept of the mechanical backout model is that as wood swells and shrinks, there will be some point along the friction interface between a fastener and the timber it is embedded in, where the resultant forces are zero, and where there will be no movement of the wood relative to the tooth under swell-shrink movement. This point is referred to as the ***matching point position (MPP)***. The movement of this matching point over time is identical to the movement of the fastener relative to the timber. The MPP at any time is dependant on the ratio of the penetration to withdrawal resistance of the fastener (Rcf), and the direction of the wood movement (i.e. swell or shrink). When the ratio is within certain bounds, the fastener will cumulatively back out of the parent timber, when it is below a certain level, backout cannot occur.

A simplified model has been developed to simulate the backout phenomenon under wood swell-shrink. The value of Rcf required in this model is dependant on a number of factors including the level of loading on the tooth in shear (as this will in turn effect the withdrawal and re-penetration resistances), and the 'stickiness' of the side friction, which may be dependant on whether the wood swell and shrink is caused by wetting, humidity change, or temperature change. Hence, for a simplified model it is therefore appropriate to use a higher order parameter R, which we can define as the ***accumulation ratio (R)*** which ranges from 0 to 1.0. When R=0, no backout occurs (and MPP is at mid point of friction surface), and when R=1.0, backout accumulates at the maximum rate (and MPP is at base of friction surface). Notation used for the simplified model is given in Figure 7.2.

The simplified analytical model can be summarised as follows:

On time-variable swelling and shrinkage of wood, the withdrawal of the tooth (W) tracks according to the movement of the MPP.

- MPP under swelling is:
  - MPP = 0.5 x Sc (7.15)
- MPP under shrinkage is:
  - MPP = (0.5 + R/2) x Sc (7.16)

    where R is the accumulation ratio ($0 \leq R \leq 1$)

Note that R is the initial value of the accumulation ratio, and for the purposes of the simplified model it is assumed to be constant over time. Sc is the length of the friction surface, which depends on the tooth length (L) and the backout (W).

In the simplified model, a linear timber deformation profile to depth T is assumed. In order to determine T under wetting, and under humidity cycling, an analysis was undertaken using the models in section 7.3 and 7.4 to determine how the moisture content profile varies over time under changed surface moisture conditions. As shown in Figure 7.3 and 7.4, the penetration depth, T, of the swell–shrink caused by moisture change, can be linearly approximated as 100 times the value of the surface deformation as follows:

- For cycles of wetting and drying due to roof leak or wind-driven rain, events are assumed to be independent, and T is assumed to be constant at 8mm.
- For humidity cycling, T changes dynamically over time, and the moisture profile from a given humidity change is dependant on previous humidity cycles. If many cycles are assumed, then for the purposes of the mechanical backout model, a single ‘average’ penetration depth can be assumed. The value of T used for humidity cycling is therefore calculated as 100 times the average surface movement under a given (long) swell-shrink time history.

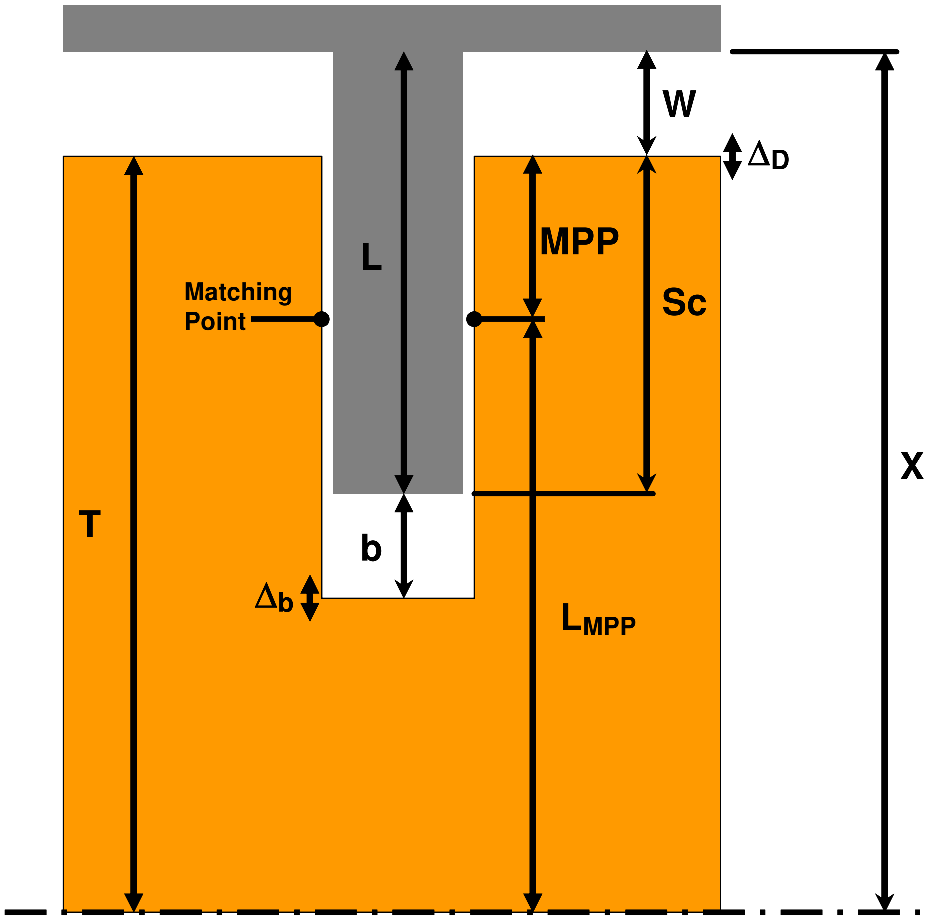


Figure 7.2 – Notation for simplified analytical model

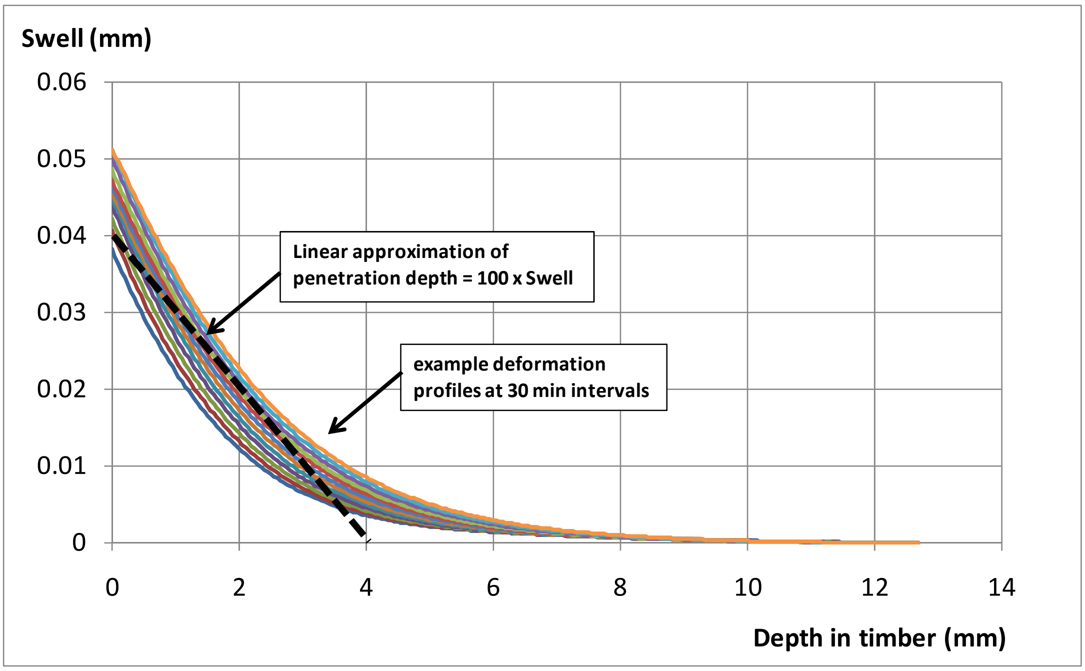


Figure 7.3 – Approximation of timber moisture profile due to humidity variation

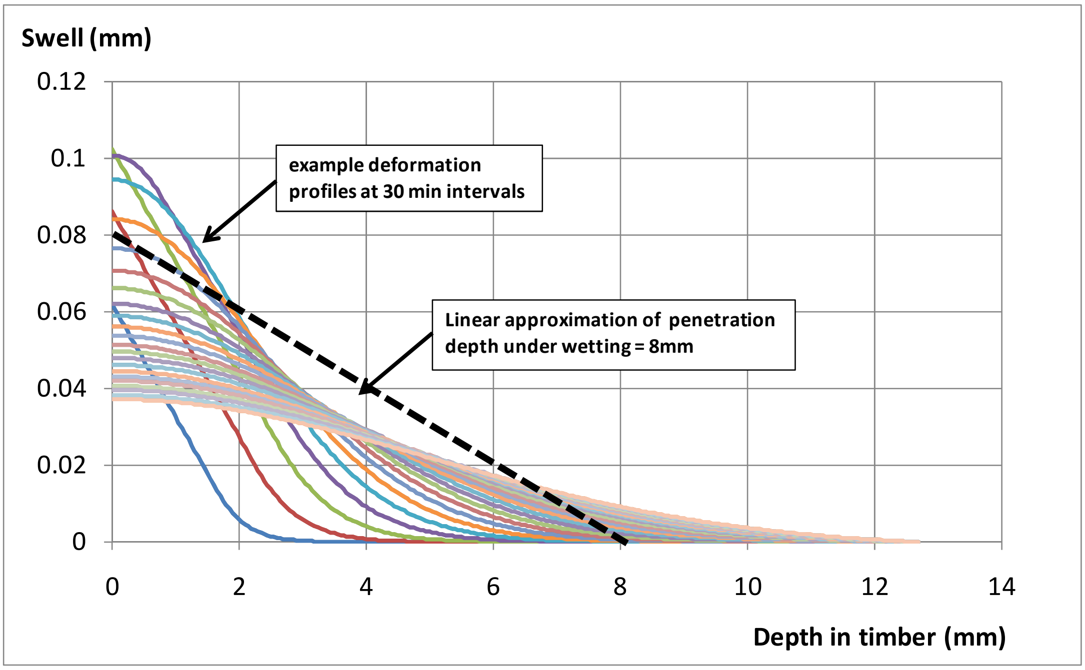


Figure 7.4 – Approximation of timber moisture profile due to wetting

8. Scenario Analysis

8.1. Objective

The objective of the scenario analysis is to make an estimate of the nailplate backout which is likely to occur under the following scenarios.

- 4 Cities: Adelaide, Melbourne, Sydney, Brisbane
- Joint loads: 0% 40%, 75% & 100% of design capacity
- Moisture regimes: humidity, wind-driven rain, roof leak
- Roof Construction: sarked and un-sarked

Four Bureau of Meteorology (BOM) stations were used for weather data that are used the scenario analysis. These are

- Adelaide (Kent Town), Station No. 023090
- Brisbane, Station No. 040913
- Sydney Airport, Station No. 066037
- Melbourne Regional Office, Station No. 086071

Global radiation data have been taken from the following BOM Global Radiation stations. Note that there is very limited number of Global Radiation stations. Therefore data from nearby stations have been used for Brisbane and Sydney.

- Melbourne
- Adelaide
- Rockhampton - used for Brisbane
- Wagga Wagga - used for Sydney

8.2. Humidity Cycling

8.2.1. Methodology

To estimate the amount of backout which could occur for a joint in a roofspace under 50 years of humidity fluctuations, the following procedure was used:

- Weather data for Adelaide, Melbourne, Sydney and Brisbane were used to develop 4-year time histories of temperature and relative humidity

- The roof microclimate model was then used to convert this weather data into typical 4-year time histories of roof-space temperature, humidity and timber *semc* for a sarked and an un-sarked roof for the four cities.
- The wood moisture model was used to calculate typical 4-year time histories of wood swell shrink for the four cities for sarked and un-sarked roofs.
- The wood swell-shrink time-histories were compiled serially into a 50-year equivalent, and then run through the mechanical model, assuming loading of 0%, 40%, 75% and 100% of joint capacity, and an effective penetration depth of 100 times the average surface movement (this ranges from 1.74mm to 2.56mm for the different cities)

8.2.2. Results and Conclusions

The results of the scenario analyses for estimated backout under 50 years of fluctuating humidity in a sarked and un-sarked roof space in the four different cities are presented in Table 8.1. The two main conclusions that can be drawn from these estimates are as follows.

- Highly loaded joints in un-sarked tiled roofs (as highlighted in yellow in Table 8.1) can potentially be susceptible to structurally significant levels of backout (>1mm), with Brisbane being significantly worse than the other cities. The estimated values are considered a worst-case upper bound, as it is highly unlikely that any joint in a roofspace has a sustained load of more than 70% of its design capacity over a 50-year period, as loads will inevitably be re-distributed over time due to the high structural redundancy and inherent flexibility of most truss systems.
- Backout due to humidity fluctuation is likely to be 50 to 70% less in sarked roofs than in un-sarked roofs.

It should be noted that the model and approach used for predicting backout under humidity fluctuations has a high level of uncertainty in the estimation of specific backout values due to the limited data available for calibration and uncertainty in the input parameters. However, the relative backout between different roof configurations is likely to be more accurate as these factors in the analysis are based on more robust calibration data from field and laboratory experiments.

Table 8.1 – Scenario Analysis: Humidity cycling for 50 Years

City	Tiled Roof Config.	T (mm)	Load (% Design)	R	Backout (mm)
Melb	Un-sarked	2.56	0%	0.01	0.39
Melb	Un-sarked	2.56	40%	0.02	0.67
Melb	Un-sarked	2.56	75%	0.04	1.22
Melb	Un-sarked	2.56	100%	0.06	1.79
Melb	Sarked	1.74	0%	0.01	0.14
Melb	Sarked	1.74	40%	0.02	0.22
Melb	Sarked	1.74	75%	0.04	0.37
Melb	Sarked	1.74	100%	0.06	0.52
Syd	Un-sarked	1.87	0%	0.01	0.34
Syd	Un-sarked	1.87	40%	0.02	0.59
Syd	Un-sarked	1.87	75%	0.04	1.09
Syd	Un-sarked	1.87	100%	0.06	1.6
Syd	Sarked	1.49	0%	0.01	0.14
Syd	Sarked	1.49	40%	0.02	0.22
Syd	Sarked	1.49	75%	0.04	0.37
Syd	Sarked	1.49	100%	0.06	0.52
Bris	Un-sarked	2.57	0%	0.01	0.544
Bris	Un-sarked	2.57	40%	0.02	0.97
Bris	Un-sarked	2.57	75%	0.04	1.83
Bris	Un-sarked	2.57	100%	0.06	2.7
Bris	Sarked	1.97	0%	0.01	0.2
Bris	Sarked	1.97	40%	0.02	0.31
Bris	Sarked	1.97	75%	0.04	0.54
Bris	Sarked	1.97	100%	0.06	0.77
Adel	Un-sarked	2.04	0%	0.01	0.36
Adel	Un-sarked	2.04	30%	0.02	0.62
Adel	Un-sarked	2.04	75%	0.04	1.14
Adel	Un-sarked	2.04	100%	0.06	1.66
Adel	Sarked	2.05	0%	0.01	0.19
Adel	Sarked	2.05	30%	0.02	0.29
Adel	Sarked	2.05	75%	0.04	0.51
Adel	Sarked	2.05	100%	0.06	0.73

8.3. Roof Leak

8.3.1. Methodology

To estimate the amount of backout which could occur for a joint subjected to leaking from rain, in the case of cracked or broken tiles without sarking, the following procedure was used:

- Rain data for Adelaide, Melbourne, Sydney and Brisbane were used to develop graphs for rainfall threshold versus number of 'rain days'. This graph is shown in Figure 8.1, and can be used to estimate the number of 'leak events' in one year, for a given threshold of rainfall.
- Figure 8.1 was used to determine the number of annual leak events in the four cities for rain thresholds of 2mm, 10mm and 20mm.
- The mechanical backout model was used to predict the number of wetting cycles to failure (i.e. the number of wetting cycles required to result in a backout of 2mm) under loading of 0%, 40%, 75% and 100% of joint capacity. Each cycle of wetting and drying was represented by a wood swell shrink of +/- 0.1mm, and cycles were assumed to be independent of each other.
- Time to failure in years for each city and each load level was calculated based on the number of wetting cycles required for failure, and the number of events for each rain threshold value.

8.3.2. Results and conclusions

The results of the scenario analyses for estimated backout for joints subjected to leaking from rain in four different cities are presented in Table 8.2. The main conclusions that can be drawn from these estimates are that:

- Joints subjected to repeated wetting are highly susceptible to backout
- Highly loaded joints are more susceptible to significant backout under cycles wetting than are joints with small loads
- Highly loaded joints (>70% capacity) can tolerate approximately 30-40 cycles of wetting before failure; Moderately loaded joints (30-70%) can tolerate approximately 40-80 cycles; and joints with small loads (<30% capacity) can tolerate 80-520 cycles of wetting before failure

It should be noted that other issues resulting from leaks such as stains, odour, rust and rot could potentially become apparent before backout is an issue for joints with low loading. However for highly loaded joints, structurally significant backout is potentially a problem if moisture is allowed to penetrate the roofspace to the point where the roof trusses are becoming repeatedly wet.

Table 8.2 – Scenario Analysis: Roof Leaking

City	Daily Rain (mm)	Events per year	Events per 50 yr	T (mm)	Load (% Design)	R	Cycles to Failure	Time to Failure (Years)
Melb	20	2.7	135	8	0%	0.06	520	192.6
Melb	20	2.7	135	8	40%	0.4	80	29.6
Melb	20	2.7	135	8	70%	0.7	40	14.8
Melb	20	2.7	135	8	100%	1	30	11.1
Syd	20	14.4	720	8	0%	0.06	520	36.1
Syd	20	14.4	720	8	40%	0.4	80	5.6
Syd	20	14.4	720	8	70%	0.7	40	2.8
Syd	20	14.4	720	8	100%	1	30	2.1
Bris	20	16.8	840	8	0%	0.06	520	31.0
Bris	20	16.8	840	8	40%	0.4	80	4.8
Bris	20	16.8	840	8	70%	0.7	40	2.4
Bris	20	16.8	840	8	100%	1	30	1.8
Adel	20	3.2	160	8	0%	0.06	520	162.5
Adel	20	3.2	160	8	40%	0.4	80	25.0
Adel	20	3.2	160	8	70%	0.7	40	12.5
Adel	20	3.2	160	8	100%	1	30	9.4
Melb	10	10.4	520	8	0%	0.06	520	50.0
Melb	10	10.4	520	8	40%	0.4	80	7.7
Melb	10	10.4	520	8	70%	0.7	40	3.8
Melb	10	10.4	520	8	100%	1	30	2.9
Syd	10	38	1900	8	0%	0.06	520	13.7
Syd	10	38	1900	8	40%	0.4	80	2.1
Syd	10	38	1900	8	70%	0.7	40	1.1
Syd	10	38	1900	8	100%	1	30	0.8
Bris	10	35.8	1790	8	0%	0.06	520	14.5
Bris	10	35.8	1790	8	40%	0.4	80	2.2
Bris	10	35.8	1790	8	70%	0.7	40	1.1
Bris	10	35.8	1790	8	100%	1	30	0.8
Adel	10	17.4	870	8	0%	0.06	520	29.9
Adel	10	17.4	870	8	40%	0.4	80	4.6
Adel	10	17.4	870	8	70%	0.7	40	2.3
Adel	10	17.4	870	8	100%	1	30	1.7
Melb	2	80.5	4025	8	0%	0.06	520	6.5
Melb	2	80.5	4025	8	40%	0.4	80	1.0
Melb	2	80.5	4025	8	70%	0.7	40	0.5
Melb	2	80.5	4025	8	100%	1	30	0.4
Syd	2	106.1	5305	8	0%	0.06	520	4.9
Syd	2	106.1	5305	8	40%	0.4	80	0.8
Syd	2	106.1	5305	8	70%	0.7	40	0.4
Syd	2	106.1	5305	8	100%	1	30	0.3
Bris	2	79.9	3995	8	0%	0.06	520	6.5
Bris	2	79.9	3995	8	40%	0.4	80	1.0
Bris	2	79.9	3995	8	70%	0.7	40	0.5
Bris	2	79.9	3995	8	100%	1	30	0.4
Adel	2	93	4650	8	0%	0.06	520	5.6
Adel	2	93	4650	8	40%	0.4	80	0.9
Adel	2	93	4650	8	70%	0.7	40	0.4
Adel	2	93	4650	8	100%	1	30	0.3

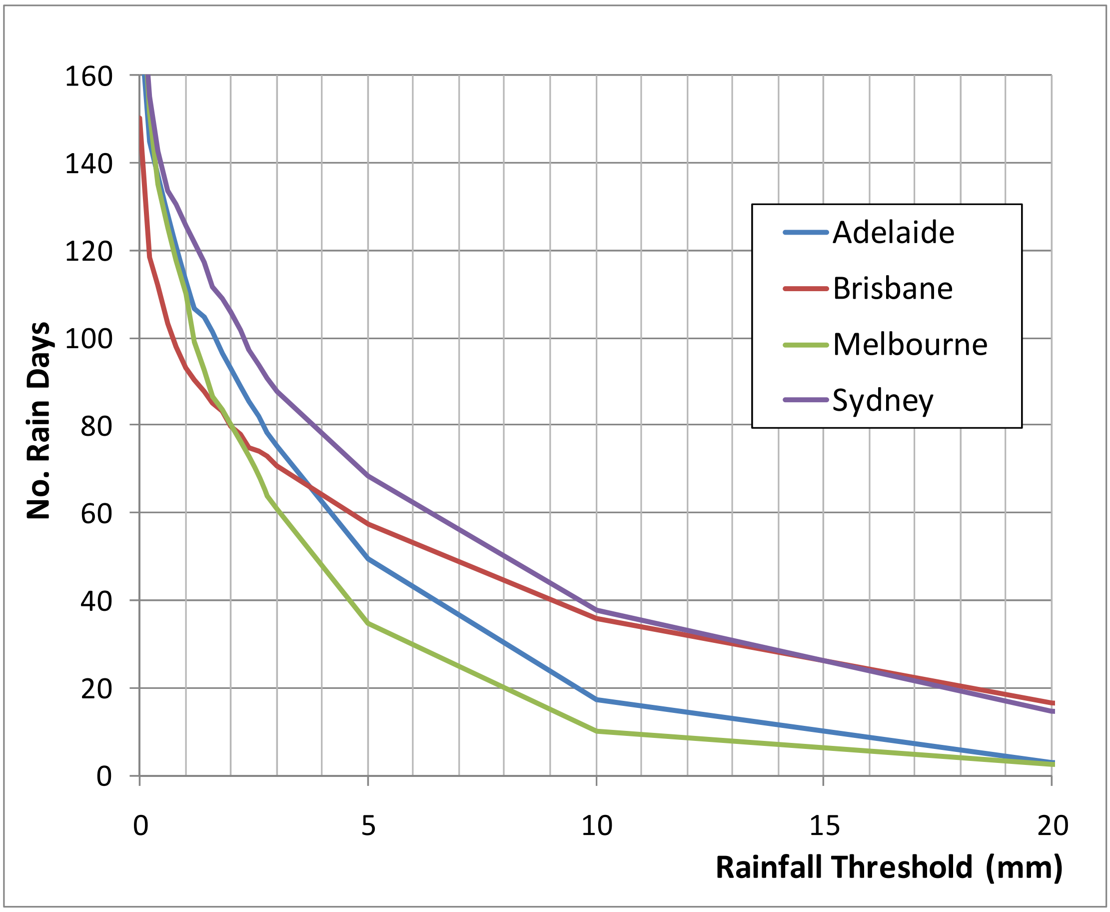


Figure 8.1 – No. of raindays vs rainfall threshold

8.4. Wind-Driven Rain

8.4.1. Methodology

An analysis was undertaken to estimate the required resistance to wind-driven rain (in terms of windspeed) that a roof system would need in order to avoid structurally significant backout over it's design life. Wind driven-rain, if prevalent, could potentially be a significant issue in the context of backout, because often only a small amount of water will penetrate, and although this may be enough to cause significant wood swell-shrink, other indicators of moisture penetration such as staining and odours may not be apparent. To estimate the required resistance to wind-driven rain, the following procedure was used:

- Wind and rain data for Adelaide, Melbourne, Sydney and Brisbane were used to develop tables of rainfall threshold versus gust wind speed for the four cities. Rainfall threshold was defined as the amount of rain that falls in any 30 minute period and the gust windspeed is based on the ten minute maximum. Tables 8.3 to 8.6 show the number of annual rain events for a given rainfall threshold and gust windspeed (i.e. number of times the two conditions occur simultaneously per year during the same thirty minute period). The graph in Figure 8.2 shows this data for a 2mm rainfall threshold.

- The mechanical backout model was used to predict the number of wetting cycles required to cause failure (i.e. the number of wetting cycles required to result in a backout of 2mm) under loading of 0%, 40%, 75% and 100% of joint capacity. Each cycle of wetting and drying was represented by a wood swell shrink of +/- 0.1mm, and cycles were assumed to be independent of each other.
- Tables 8.3 to 8.6 were used to look up the windspeed threshold (for 2mm threshold of rain) that would just cause the number of annual wetting cycles required for failure over a 50 year life.

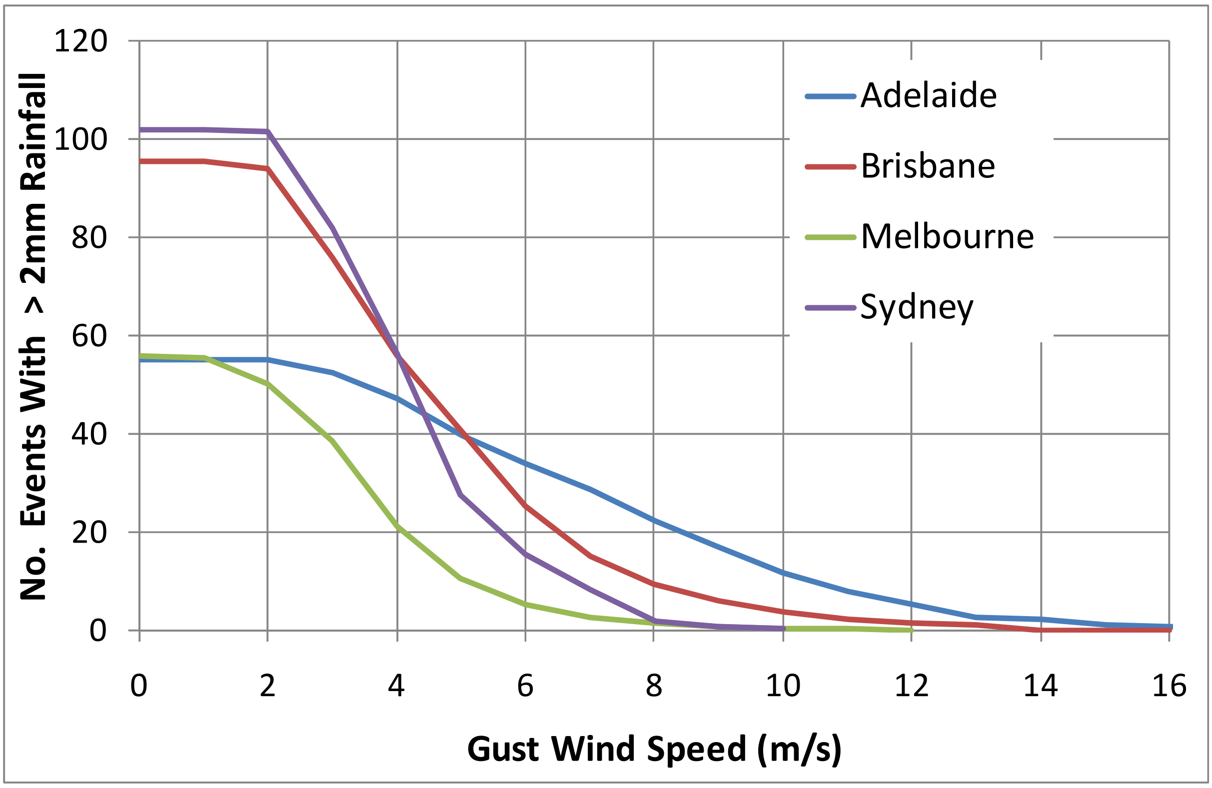


Figure 8.2 – No. of wind driven rain events vs gust wind speed

8.4.2. Results and conclusions

The results of the wind-driven rain analysis are given in Table 8.7. The main conclusions that can be drawn from the analyses are that:

- For light rainfall wind-driven rain (<1mm rain in 30 min.), Adelaide has the highest number of potential occurrences per year (for >6 m/s gust), over a 50 year lifetime and Melbourne has the lowest. This would indicate that we would be more likely to see backout from wind-driven rain in Adelaide than the other cities examined.

- As the rainfall threshold increases above 1mm, the number of wind-driven rain events that occur simultaneously with high winds (>6 m/s) reduces rapidly, and it is therefore unlikely that wind-driven rain under heavy rainfall will be a cause of backout problems in any location over a 50 year lifetime.
- To prevent structurally significant backout over a 50 year design life, roofs should be able to resist water penetration from light rainfall (<1mm rain in 30 min.) being driven by windspeeds of at least
  - 10 m/s for Melbourne and Sydney
  - 14 m/s for Brisbane
  - 18 m/s for Adelaide

Table 8.3 – Wind Driven Rain - Adelaide

Adelaide

Gust Wind Speed (m/s)	Rainfall Threshold (mm)														
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13-**	**17-**
0	727	164	55	25	15	9.9	6.4	4	3.2	2.9	2.1	1.3	1.1	0.5	0.3
1	725	164	55	25	15	9.9	6.4	4	3.2	2.9	2.1	1.3	1.1	0.5	0.3
2	717	163	55	25	15	9.9	6.4	4	3.2	2.9	2.1	1.3	1.1	0.5	0.3
3	637	151	52	24	14	9.4	6.1	3.7	2.9	2.7	2.1	1.3	1.1	0.5	0.3
4	540	130	47	21	12	8	5.6	3.2	2.7	2.7	2.1	1.3	1.1	0.5	0.3
5	456	113	40	18	11	7.2	4.8	2.9	2.4	2.4	1.9	1.1	0.8	0.3	0
6	362	94	34	15	9.1	5.9	4	2.4	1.9	1.9	1.6	0.8	0.5	0.3	0
7	290	76	29	12	7.2	5.1	3.2	1.9	1.3	1.3	1.1	0.5	0.3	0	0
8	214	59	22	9.1	5.9	4	2.4	1.3	0.8	0.8	0.5	0.3	0.3	0	0
9	152	44	17	6.1	3.5	2.1	1.3	1.1	0.5	0.5	0.3	0.3	0.3	0	0
10	99	30	11	4	1.9	1.3	0.8	0.5	0.3	0.3	0	0	0	0	0
11	64	20	8	2.7	0.8	0.5	0.3	0.3	0.3	0.3	0	0	0	0	0
12	40	13	5.1	1.6	0.3	0.3	0	0	0	0	0	0	0	0	0
13	23	9.4	2.7	0.3	0	0	0	0	0	0	0	0	0	0	0
14	14	5.6	2.1	0.3	0	0	0	0	0	0	0	0	0	0	0
15	7.2	2.9	1.1	0.3	0	0	0	0	0	0	0	0	0	0	0
16	4.3	2.1	0.8	0.3	0	0	0	0	0	0	0	0	0	0	0
17	2.7	1.3	0.3	0.3	0	0	0	0	0	0	0	0	0	0	0
18	1.1	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0.8	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 8.4 – Wind Driven Rain - Melbourne

Melbourne

	Rainfall Threshold (mm)																		
Gust Wind Speed (m/s)	0	1	2	3	4	5	6	7	8	9	10	11	12	13-	18-	20-	24-	30-	39-
0	793	162	56	21	14	10	7.5	5.3	4	3.7	2.9	2.1	2.1	1.6	1.3	1.1	0.8	0.5	0.3
1	782	161	55	21	14	10	7.5	5.3	4	3.7	2.9	2.1	2.1	1.6	1.3	1.1	0.8	0.5	0.3
2	705	145	50	19	13	9.1	6.1	4.3	2.9	2.9	2.7	2.1	2.1	1.6	1.3	1.1	0.8	0.5	0.3
3	511	110	38	15	9.6	7	4.5	2.9	2.4	2.4	2.1	1.6	1.6	1.1	1.1	1.1	0.8	0.5	0.3
4	300	61	21	7.8	4.8	3.5	2.4	2.1	1.9	1.9	1.6	1.3	1.3	0.8	0.8	0.8	0.5	0.3	0
5	158	30	10	3.5	1.9	1.3	0.8	0.5	0.5	0.5	0.3	0.3	0.3	0	0	0	0	0	0
6	74	15	5.1	2.7	1.1	0.5	0.3	0.3	0.3	0.3	0	0	0	0	0	0	0	0	0
7	37	8.8	2.7	1.9	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	19	5.6	1.3	0.5	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	8.6	2.1	0.8	0.5	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	3.2	0.8	0.5	0.5	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0.5	0.3	0.3	0.3	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 8.5 – Wind Driven Rain - Brisbane

Brisbane

	Rainfall Threshold (mm)																										
Gust Wind Speed (m/s)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20-	23-	29	30	31-	36-	41
0	706	224	95	55	36	23	17	12	11	9.9	8.6	7.2	6.7	5.3	5.1	4.3	4	3.2	3.2	2.9	2.1	1.9	1.6	1.1	0.8	0.5	0.3
1	703	224	95	55	36	23	17	12	11	9.9	8.6	7.2	6.7	5.3	5.1	4.3	4	3.2	3.2	2.9	2.1	1.9	1.6	1.1	0.8	0.5	0.3
2	677	220	94	54	36	23	17	12	11	9.9	8.6	7.2	6.7	5.3	5.1	4.3	4	3.2	3.2	2.9	2.1	1.9	1.6	1.1	0.8	0.5	0.3
3	518	173	76	44	30	19	14	10	9.6	8.8	7.5	6.4	6.1	4.8	4.5	4.3	4	3.2	3.2	2.9	2.1	1.9	1.6	1.1	0.8	0.5	0.3
4	335	117	56	32	23	15	11	8	7.2	6.7	5.3	5.1	4.8	4.3	4	3.7	3.7	2.9	2.9	2.7	2.1	1.9	1.6	1.1	0.8	0.5	0.3
5	200	76	41	24	18	11	8.6	6.1	5.6	5.6	4.8	4.5	4.3	3.7	3.7	3.7	3.7	2.9	2.9	2.7	2.1	1.9	1.6	1.1	0.8	0.5	0.3
6	121	48	25	15	12	7.8	5.9	4.3	4	4	3.7	3.7	3.5	2.9	2.9	2.9	2.9	2.4	2.4	2.4	2.1	1.9	1.6	1.1	0.8	0.5	0.3
7	73	28	15	9.4	7.5	5.1	4.3	3.5	3.2	3.2	3.2	3.2	2.9	2.7	2.7	2.7	2.7	2.1	2.1	2.1	1.9	1.6	1.3	0.8	0.5	0.3	0.3
8	45	16	9.4	5.9	4.3	3.5	2.9	2.4	2.4	2.4	2.4	2.4	2.1	1.9	1.9	1.9	1.9	1.6	1.6	1.6	1.3	1.3	1.1	0.5	0.3	0.3	0.3
9	25	9.6	5.9	3.5	2.4	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.6	1.6	1.6	1.6	1.3	1.3	1.3	1.1	1.1	0.8	0.5	0.3	0.3	0.3
10	11	5.6	3.7	1.9	1.6	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.5	0.5	0.3	0.3	0.3	0.3	0.3
11	7	4	2.4	1.3	1.3	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.5	0.5	0.3	0.3	0.3	0.3	0.3
12	3.5	2.4	1.6	0.8	0.8	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3
13	2.1	1.3	1.1	0.5	0.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0	0	0	0	0	0	0
14	0.5	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0.5	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 8.6 – Wind Driven Rain - Sydney

Sydney

	Rainfall Threshold (mm)																			
Gust Speed (m/s)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17-	19-	22
0	801	244	102	54	33	22	15	10	7.2	5.9	5.6	4.5	3.5	3.2	2.9	2.4	2.1	1.3	0.8	0.5
1	801	244	102	54	33	22	15	10	7.2	5.9	5.6	4.5	3.5	3.2	2.9	2.4	2.1	1.3	0.8	0.5
2	789	242	101	54	33	22	15	10	7.2	5.9	5.6	4.5	3.5	3.2	2.9	2.4	2.1	1.3	0.8	0.5
3	558	187	82	45	28	19	13	8.3	5.9	5.3	5.1	4	3.2	2.9	2.7	2.4	2.1	1.3	0.8	0.5
4	386	134	56	32	19	14	9.4	7.2	5.3	4.8	4.5	3.7	2.9	2.7	2.4	2.4	2.1	1.3	0.8	0.5
5	208	70	28	18	10	7.5	4.8	3.5	2.7	2.7	2.4	2.1	1.6	1.6	1.3	1.3	1.3	0.8	0.5	0.3
6	109	38	16	9.6	6.7	4.5	2.9	2.4	1.6	1.6	1.6	1.3	1.1	1.1	1.1	1.1	1.1	0.8	0.5	0.3
7	50	18	8	5.1	2.9	2.4	1.3	1.3	0.8	0.8	0.8	0.8	0.5	0.5	0.5	0.5	0.5	0.5	0.3	0.3
8	21	5.6	1.9	1.6	0.8	0.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
9	7.5	1.3	0.5	0.3	0.3	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	2.9	0.3	0.3	0.3	0.3	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 8.7 – Wind-Driven Rain: Required resistance for 50yr lifetime

City	Events per yr	Events per 50 yr	T (mm)	Load (%Design)	R	Required Windspeed Resistance (m/s)
Melb	10.4	520	8	0%	0.06	6.8
Melb	1.6	80	8	40%	0.4	9.6
Melb	0.8	40	8	70%	0.7	10
Melb	0.6	30	8	100%	1	10.6
Syd	10.4	520	8	0%	0.06	7.6
Syd	1.6	80	8	40%	0.4	8.8
Syd	0.8	40	8	70%	0.7	9.5
Syd	0.6	30	8	100%	1	9.8
Bris	10.4	520	8	0%	0.06	8.8
Bris	1.6	80	8	40%	0.4	12.8
Bris	0.8	40	8	70%	0.7	13.5
Bris	0.6	30	8	100%	1	13.8
Adel	10.4	520	8	0%	0.06	12.7
Adel	1.6	80	8	40%	0.4	16.6
Adel	0.8	40	8	70%	0.7	17.6
Adel	0.6	30	8	100%	1	17.8

9. Key Conclusions

Based on the findings from the coordinated program of laboratory experiments, field inspections, roofspace monitoring and numerical modelling, the following conclusions can be made:

- Nailplate backout can occur when cyclic mechano-sorptive swelling and shrinking of wood results in a ratcheting mechanism in which withdrawal deformations accumulate. This ratcheting mechanism occurs when frictional resistance to withdrawal between the side of the fastener and timber is significantly less than the re-penetration resistance. Laboratory experiments confirmed that the re-penetration to withdrawal ratio for 8mm tooth nailplates in softwood is within the range required for cumulative nailplate backout to occur. This ratio increases dramatically when the fastener is loaded in shear, and hence highly loaded joints are more susceptible to mechano-sorptive backout than joints with small loads.
- Many of the reported examples of mechano-sorptive backout in 'problem roofs' have occurred in un-sarked concrete tiled roofs and/or in roof spaces with evidence of water penetration. However there are also many examples of the separation of nailplates from parent timber that can be most likely attributed to manufacturing and handling errors, warping of timber, and overloading (e.g. Steelfast brand nailplates were in many cases under-designed and therefore carrying larger loads than appropriate). Some cases of nailplate separation have no apparent explanation.
- Based on data collected during 41 'random' roof inspections, it can be concluded that moisture-related backout does not appear to be a widespread and systematic problem in trussed roofs. It must be noted however that this conclusion is based on a very small sample size (less than 20 roofs with the susceptible configuration of un-sarked tiles supported by softwood trusses) and from one geographic region only (Victoria).
- A suite of numerical models were developed for the prediction of mechano-sorptive nailplate backout. It was shown through a program of laboratory experiments that the models are capable of predicting nailplate backout behaviour under a wide range of moisture cycling regimes and loading conditions, however the uncertainty in the inputs to the models is high, and hence confidence in the values of the backout estimates are low.
- Laboratory experiments in which joints were subjected to cycles of wetting and drying showed that:
    - Highly loaded joints (>70% of design load) can potentially fail to rupture under a small number of cycles of wetting and drying (<50 cycles).

These tests used nailplates with only two rows of teeth per side which may have accelerated failure compared to a full nailplate connection

    - Application of a sealant can potentially slow or stop nailplate backout from occurring under cycles of wetting and drying.

- Analysis of the measured roof microclimates in two test houses showed that installation of a moisture barrier in a tiled roof will result in a drastic reduction in the amplitude of the daily humidity fluctuation, and a very significant reduction (up to 70%) in the daily variation of wood surface equilibrium moisture content when compared to an un-sarked roof. This means that humidity-driven mechano-sorptive backout is much less likely to occur to a problematic level in sarked roof spaces.
- Analysis of roof microclimate data collected from three real houses showed that the measured microclimates in the 3 roof-spaces were quite similar, suggesting that for a given external climate, the variation is small between microclimates in different un-sarked tiled roofs. It also showed that climatic conditions inside the house can have an impact on the roofspace microclimates, particularly in winter.
- Scenario analyses in which numerical models were used to estimate backout under a range of different conditions showed that:
    - *Humidity cycling:* Very highly loaded joints in un-sarked tiled roofs could potentially be susceptible to structurally significant levels of backout (>1mm) driven by long-term (50 yrs) daily humidity fluctuations, however the estimated backout values have low confidence, as they depend on model inputs which have large uncertainties. It was estimated that humidity driven backout could be reduced by as much as 70% in sarked roof spaces compared to un-sarked.
    - *Leaking:* Joints subjected to repeated wetting from roof leak are highly susceptible to backout and failure. Highly loaded joints (>70% design capacity) are more susceptible to significant backout under cycles of wetting than are joints with small loads. Sarked roofs are far less susceptible to water penetration and subsequent backout from leaking.
    - *Wind-Driven Rain:* Backout due to wetting from wind-driven rain is only likely under light-rainfall events (<1mm rainfall n 30 min.). These events are more frequent in Adelaide than in Melbourne Sydney or Brisbane. The required windspeed resistance to prevent structurally significant backout under wind-driven rain, over a 50 year design life is in the range 8-16 km/h for the four cities examined. Sarked roofs are not susceptible to wind-driven rain.

10. Recommendations

1. Sarking or equivalent measures to prevent external moisture penetration should be adopted for all roof construction in Australia.

Potential moisture-related backout problems that have been explored in this research could be largely eliminated in future by the installation of a moisture barrier in roofs for all Australian houses. Sarking of tiled roofs is already compulsory in Queensland, and the Building Code of Australia already specifies that a building is to be constructed to provide resistance to moisture from the outside. Although a small program of roof inspections has indicated that moisture-related backout is not widespread, this needs to be contrasted against the findings from the scenario modelling, which indicate that long-term humidity fluctuation, wind-driven rain, and roof leaking are all a potential threat to the long-term performance of nailplated roof truss systems. Universal adoption of sarking would serve to minimize humidity fluctuations and water penetration into the roofspace, which will also result in other benefits such as a more durable construction overall, and enhanced thermally efficiency. It should also be noted that there should be no water penetration into the roof space from mechanical equipment. Although no specific evidence of problems resulting from introduced steam from kitchen and bathroom fans, given the sensitivity of truss joints to moisture, it may be prudent for enhanced long term performance to vent steam to the outside where possible rather than directly into the roof space.

2. Examine the feasibility of reducing assumed tooth capacities for permanently loaded joints to below 100% of current values.

Given that highly loaded joints under permanent loads appear to be more susceptible to backout and premature failure than joints with lesser loadings, it may be prudent for plate manufacturers to examine the option of reducing specified tooth capacities for joints under permanent loads, by a factor which would not have a significant impact on overall truss cost. It is possible that this could lead to enhanced safety, and superior long term performance for very little cost penalty.

3. Explore sealant treatment on critical joints

It has been shown that wetting/drying cycles can cause rapid structural degradation of highly loaded nailplated joints, but that application of a sealant material can reduce susceptibility to moisture-related backout. It is therefore recommended that the application of sealant treatments during manufacturing, be considered for critical joints, such as heel joints and bottom chord splices in girder trusses. Although this will require further research, if an effective and low cost sealant treatment can be incorporated into the manufacturing processes, then this could potentially reduce the risk of failures of critical joints due to moisture penetration through poor construction or maintenance practices.

4. Explore tooth profile redesign in future metal-plate products

It is recommended that nailplate manufacturers examine the option of tooth profile re-design for increased withdrawal capacity when developing future products. This will reduce the potential for mechano-sorptive backout which will potentially enhance long-term performance of metal nailplate products. In addition it can potentially reduce nailplate separation problems that occur during handling and installation, and potentially open up new applications for nailplated connectors in more exposed environments.

It should be noted that limiting moisture penetration into the building envelope (recommendation 1) should be considered as a higher priority in the prevention hierarchy than other recommendations. It should also be stressed that of-course quality control of manufacturing and installation is essential so that nailplates are fully embedded during manufacture, and are not be handled in a manner that will create lateral joint displacements

11. References

Leicester, R.H. and Lhuede, E.P. (1992), Mechano-sorptive effects on toothed-plate connectors. Proc. IUFRO S5.02 Timber Engineering Meeting, Bordeaux, France, 17-21 August, 22 pages.

Nguyen, M.N., and Paevere, P.J. (2006), Literature Review and Document Scan*, PROJECT REPORT,* CSIRO Sustainable Ecosystems, Highett, Victoria, 2006.

Nguyen, M.N., and Paevere, P.J. (2009), Field Inspections*, FINAL PROJECT REPORT,* CSIRO Sustainable Ecosystems, Highett, Victoria, March 2009.

Nguyen, M.N.**,** Leicester, R.H., and Paevere, P.J. (2009), Models and Techniques – Part 1: Climate-Roof-space Wood Interaction Models*, FINAL PROJECT REPORT,* CSIRO Sustainable Ecosystems, Highett, Victoria, Feb 2009.

Paevere, P.J., Nguyen, M.N.**,** and Syme, M.J. (2009), Models and Techniques – Part 2: Response Models*, FINAL PROJECT REPORT,* CSIRO Sustainable Ecosystems, Highett, Victoria, Feb 2009.

Paevere, P., Leicester, R.H., Goldfinch, J.1., & Foliente, G.C. (2004) 'Performance of plated trusses', WCTE2004 8th World Conference on Timber Engineering, Lahti, Finland, June 14-17, 2004, pp. 499-504.