Screw- and nail-gluing techniques for wood composite structures

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ABSTRACT: Composite systems enhance the structural capacity and reliability of wood solutions for structures. With today engineered wood products and structural adhesives, high performing structures can be constructed. Hybrid assembly techniques that combine mechanical fasteners and an adhesive (screw- and nail-gluing techniques) allow manufacturing large dimension composite structures with reasonable infrastructure. They also give full composite properties to the interlayers. Furthermore, these hybrid connections can experience ductility. This paper presents a research on small-scale glued assemblies which were manufactured using screw- and nail-gluing techniques. It discusses qualitative and quantitative analyses that confirmed the full-composite properties and ductility of the interlayers. The analyses also show that superposing the behaviour of both connectors is reasonable to predict the strength and slip modulus of hybrid connections.

1 INTRODUCTION

Composite systems enhance the capacity and reliability of wood solutions for structures. In composite constructions, the effects of the natural growth characteristics of wood, which can be described as "defects" in term of structural performance, is soothed. Assembly techniques combining mechanical fasteners with adhesive allow constructing composite structures with large dimensions. Meanwhile, the investment for manufacturing infrastructures remains moderate. Furthermore, the composite assemblies can be assembled in the workshop or on-site.

Stressed-skin panels (SSP) consist of multiple layers (panels & joists) assembled compositely together using hybrid technology such as screw- or nail-gluing techniques. The composite action in the interlayers represents a significant aspect of SSP systems. Related to a comprehensive research on SSP systems (27 full-scale specimens) launched at the University of Technology, Sydney, in 2002, investigation on small-scale glued assemblies was carried out in order to finalise the interlayer characteristics of SSP specimens. This research aimed to (1) assess the performance of the adhesive currently used by Australian builders, (2) assess the suitability and performance of a one-component polyurethane adhesive with Radiata pine, (3) understand, and (4) characterise the serviceability and failure mechanism of screw- and nail-glued assemblies.

2 REVIEW OF THE LITERATURE

In screw- and nail-gluing techniques, the adhesive plays a major role. In the 1960's, innovations in elastomeric adhesives made these techniques more practical (Rose 1970). Corder & Jordan (1975) observed that wood-joist floors manufactured with nail-gluing technique experienced a large increase of stiffness compared to nailing alone. Further, the shear transfer between the joists and the sheathing is improved (Liu et al. 1995). Such observations confirm the significant role of the adhesive, which type should be governed by the anticipated load of service (nature, direction, level, duration, etc.) and climatic exposure (temperature, humidity, etc.). It also implies that structural adhesives should be used. Such glues are generally stronger than the wood substrates and maintain strength and rigidity under long-term load (Vick 1999).

For the manufacturing of glued interfaces, adhesive layer as uniform and thin (0.076–0.152mm) as possible is sought. This can be achieved by adapting the viscosity and spread of the glue to the conditions of the wood substrates and climatic conditions of the environment (Vick 1999), and to the pressuring technique. Further, the pressure and viscosity should be adequate in order to remove entrapped air and avoid starved interface. On the other hand, excessive pressure may cause damages to the adherents. The aspect of the pressure is critical to screw- and nail-gluing because both fasteners have the inconvenience of generating irregular and significantly less pressure (0.0–0.2MPa) on the glue line than hydraulic and pneumatic infrastructures (Kairi et al. 1999). The assemblies should also remain undisturbed or be handled with care until complete curing of the adhesive.

In recent years, the adhesive industry has developed products that require lower pressure and need shorter setting time. This new generation of adhesives is particularly adapted for screw- and nail-gluing techniques whereby adequate number of mechanical fasteners is required. Kairi et al. (1999) used screw-gluing technique to investigate the suitability of one-component polyurethane adhesives to low pressure. They observed that these products responded well to these conditions (0.03–0.1MPa pressure) i.e. shear strength of the specimens built under low pressure matched those of the specimens assembled under normal pressure (0.6 to 0.8MPa), and concluded that screw-gluing technique produce assemblies of similar strength to uniformly pressed specimens. However, they warned that lower pressure (0.01MPa and less) results in connections with insufficient strength. Kairi et al. also observed that the performance of polyurethane adhesives is equal to resorcinol-phenol glue.

Screw- and nail-gluing offer economical alternatives to expensive pressing infrastructures and enable to construct customized and large(r) composite structures. Both processes also allow moving the assemblies off the manufacturing rack before the complete curing of the glue as long as the mechanical fasteners provide enough strength and stiffness (Kairi et al. 1999). Under adequate supervision, these processes can also be applied on-site. Comparing both techniques, nailing produce lower pressure in the glue line than screwing but is more economical (material and labour costs).

Simulating and predicting the strength and slip modulus of screw- or nail-glued assemblies are highly complex because each connector has non-linear behaviour and works with areas of the wood members, which show heterogeneous properties. Expressed in another way, the nails are influenced by the wood properties around them locally while the glue interacts with the wood properties of or very near to the glue line. To account for this complexity, Pellicane (1992a; 1992b) proposed a model based on the concept of superposition for both the assembly strength and stiffness. This superposition model enabled accurate estimates of the structural properties of the connections within the range of service load. For loading beyond this range, the superposition model remained accurate for the strength, ultimate resistance included, but lacked such accuracy for the load slip modulus i.e. connection stiffness were consistently underestimated.

Elastomeric and one-component polyurethane adhesives have different manufacturing requirements. The first ones experience poly-condensation and require relatively high pressure and long pressing time. Speeding up the curing of elastomeric glues is achieved by implementing hot pressing processes. The binding reaction of one-component polyurethane glues is a polyaddition that has no need of high pressure and might have, depending on the formulation, short pressing time in room temperature. However, one-component polyurethanes require that the glue line thickness is less than 0.3mm in order to achieve maximum strength (Collano Ebnöther AG).

3 SIGNIFICANCE, AIMS AND LIMITATION

In SSP assemblies, nail- or screw-gluing is generally used to attach the superimposed sheathing to the joists. The properties of the interlayer have effects on the composite characteristics of the structure i.e. the strength and stiffness of the floor systems. Assemblies with elastomeric glues and wooden substrates have been studied comprehensively for structural and non-structural uses. On the other hand, little research has addressed one-component polyurethane adhesive in load bearing situations. Further, performance data for both adhesives with Australian softwood are rare.

The current investigation aimed to identify the performance of elastomeric and one-component polyurethane adhesives with Australian softwood (Radiata pine). It focused on the assessment of the adequacy (adherence) and performance (strength and slip modulus) of both adhesives with Radiata pine and low pressure conditions such as produced by nail- and screw gluing techniques.

The laboratory experiment focused on the quasi-static responses of the specimens. They were manufactured with seasoned and conditioned wood substrates, and were continuously stored in controlled climate (20°C and 50% AMC). Thus, the effects of extreme climatic changes were not considered. Studying the long term behaviour was also out of the scope of this research.

4 LABORATORY INVESTIGATION

4.1 *Research plan*

The research plan addressed the material mix of the full-scale SSP specimens investigated in the first author's PhD research. A synthetic rubber adhesive (RBA), Maxbond® (Fuller HB Company Australia Pty. Ltd. 2003), and a one-component polyurethane glue (PUR), Purbond VN1033 (Collano Ebnöther AG), were chosen. RBA corresponds to a construction adhesive widely used by builders in Australia. It requires long setting time, may be gap filling but may not meet structural requirements. RBA connections generally show significant deformability. It may also age poorly i.e. become brittle or deteriorate. PUR accounted for recent progress by the adhesive industry. It facilitates short processing time and high strength. It is generally considered to produce stiff connections (Kliger 1993). But Kairi et al. (1999) observed that it may have more ductility than conventional structural glues. The adherent mix comprised solid wood (*F11 Radiata Pine*) and engineered wood products *(F11 plywood and oriented strand board)*.

For symmetry reason, three-member specimens were chosen i.e. a solid wood central part to which two lengths of engineered wood product were attached (Figure 1).

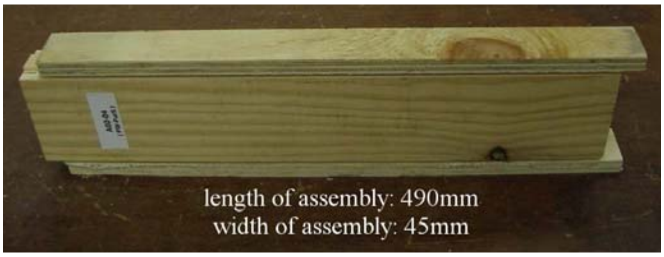

Figure 1: three-member specimen

The specimens were manufactured with nail- and screw-gluing techniques. But comparison test series where clamps assisted during adhesive curing were also manufactured. Table 1 presents the test series and the interlayer characteristics of the specimens.

Table 1: test series and specimen characteristics

Sequence	Interlayer characteristics	Sequence	Interlayer characteristics
A01	P[*]W[†]-Pur[‡]X[§]	A07	PW-Max[‡‡]X
A02	PW-PurS[**]	A08	PW-MaxS
A03	PW-PurN[††]	A09	PW-MaxN
A04	OW-PurX	A10	OW-MaxX
A05	OW-PurS	A11	OW-MaxS
A06	OW-PurN	A12	OW-MaxN

[*]plywood, [†]solid wood, [‡]one-component polyurethane, [§]no connector, [**]screw, [††]nail, [‡‡]rubber based adhesive.

4.2 *Test setting*

Destructive push-out tests were conducted in order to assess the strength and load-slip properties of the assemblies. The shear stress in the interlayers is generated by the load transfer between the interior and exterior members of the specimens (Figure 2).

The testing facilities were located in the Materials Testing Laboratory at the University of Technology, Sydney. The tests were carried out on a 50-ton Shimadzu machine. Test data such as the load and vertical displacement was captured at a frequency of 5Hz using a load cell and a Linear Variable Differential Transducer (LVDT) respectively. The data was conditioned by a signal converter and transmitted to a computer.

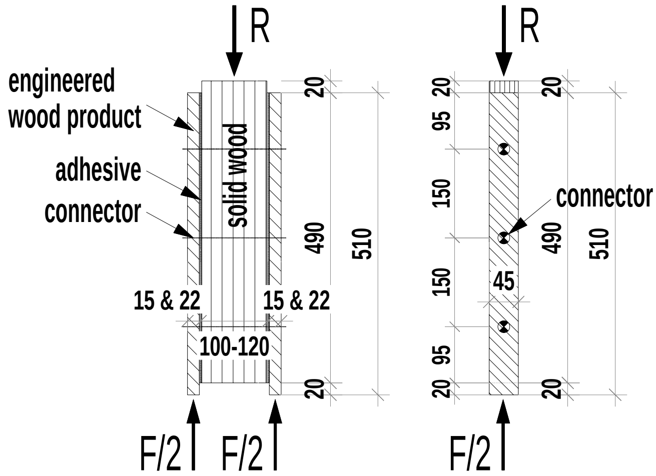

Figure 2: test principle (all dimensions in mm)

5 RESULTS AND ANALYSIS

The analysis methodology addressed the qualitative and quantitative responses of the specimens. Good qualitative response were defined by the amount of adherent failure. Predominant wood failure is an indication of good quality and well-made assembly (River 2003; Vick 1999). The requirements of the quantitative response were derived from AS/NZS 4364:1996 (Australian/New Zealand Standard™ 1996).

5.1 *Qualitative analysis of the results*

The qualitative analysis of glued wood-to-wood assemblies corresponds to a visual inspection of the connection areas of tested specimens. This analysis aims to identify and quantify the contributors to the assembly failure. Considering the adhesive, cohesion and adhesion failures were grouped together. Wood member failures were categorised into shear, rolling shear and delaminating failures.

With RBA specimens, the assembly failures were predominantly governed by the adhesive (about 99%). On the other hand, PUR specimens experienced about 61% of adherent failures. For the remainder of PUR specimens, the moduli of rupture were governed by the adhesive. With PUR specimen, failures inside the engineered wood product members — rolling shear and plywood delaminating — were also observed. In Table 2 the relative frequency of the moduli of rupture for RBA and PUR specimens is summarised.

Figure 3 depicts the relative frequency of the moduli of rupture identified for PUR test series. The graph shows the valid tests only.

Table 2: frequency and relative distribution of the failure modes

MOR code	RBA series		PUR series	
	*F	†R	F	R
no connection, NC	1	—	0	—
test not valid, TNV	1	—	1	—
shear of adherent, SS	0	0.000	1	0.002
internal rolling shear, piS	0	0.000	63	0.176
plywood delaminating, PD	0	0.000	100	0.279
PD & SS	0	0.000	1	0.002
adhesion/cohesion, AG	353	0.986	139	0.388
AG & piS	5	0.014	48	0.134
AG & PD	0	0.000	6	0.017
AG & SS	0	0.000	1	0.002
total of specimens	360	—	360	—
total of valid tests	358	1.000	359	1.000

*absolute frequency, †relative distribution.

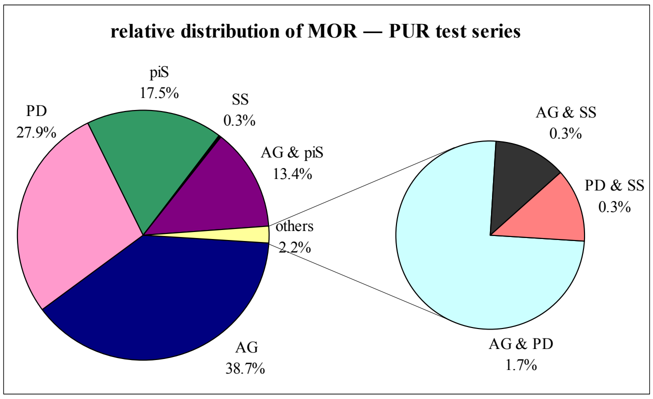

Figure 3: relative distribution of MOR (valid tests) for PUR test series

The qualitative analysis of RBA specimens, in which about 99% of the test failures were governed by the adhesive, indicates that RBA failed to meet the qualitative requirements for structural adhesive. With a rate of about 61% of failures governed by the adherents, PUR performed reasonably well with respect to the qualitative prerequisites.

5.2 *Quantitative analysis of the results*

5.2.1 *Ultimate strength*

The requirement for the quantitative response of specimen with hardwood adherent is described in AS/NZS 4364:1996 (Australian/New Zealand Standard™ 1996). However, no directives are given for assemblies with softwood. Generally in connections, the strength relies upon the nature of the connectors and the material of the adherents (Wilkinson 1974). But in structural glued assemblies, failures in the adherents should predominate and the ultimate strength of such joints must be equal or greater than the ultimate shear strength of the wood members. This also agrees with the methodology of the qualitative assessment. The ultimate resistance of the specimens was consequently derived from the characteristic shear strength of F11 Radiata Pine i.e. $f_{s,k}$ = 3.1MPa (Australian Standard™ 1997). The specimens were built with “ordinary” wood lengths i.e. no particular selection was carried out. Therefore, a 25% coefficient of variation is reasonable. Considering this assumption, a shear strength requirement of 4.4MPa was derived.

Typical statistical analysis was carried out on the specimen performance i.e. considering the average ultimate shear strength and the standard deviation and coefficient of variation (Table 3). The analysis showed that PUR performed well. Each PUR test series met the minimum strength requirement. RBA test series failed to meet the 4.4MPa mark; the highest resistance being 3.68MPa achieved by series A08. Variation coefficients less than 25% are acceptable for specimens with softwood adherents. Four PUR test series displayed higher variations. In correlation to the qualitative analysis — specimen failure predominantly governed by the adherent — the assembly strength relied on wood material significantly. Therefore, PUR variations could indicate that the material of the adherents had higher variability. This presumption might be validated by the results of RBA series, in which most specimens experienced bond failure and lower coefficients of variation were observed.

Table 3: ultimate strength – statistical data of the test series

Test series		*AVR	†SDEV	‡COV
	Sequence	[MPa]	[MPa]	[---]
PUR test series	A01	7.81	1.95	0.25
	A02	6.50	2.62	0.39
	A03	6.41	2.48	0.39
	A04	7.53	1.21	0.16
	A05	6.72	2.24	0.33
	A06	4.96	1.71	0.35
RBA test series	A07	2.16	0.76	0.35
	A08	3.68	1.08	0.29
	A09	3.26	0.78	0.24
	A10	2.30	0.75	0.33
	A11	3.51	0.71	0.20
	A12	2.86	0.69	0.24
AVR ≥ 4.4MPA (shaded)				

*average strength, †standard deviation, ‡coefficient of variation.

The analysis of the ultimate strength demonstrated that PUR complies with the strength requirement imposed on structural adhesives. On the other hand, RBA, even though it performed better than indicated by Fuller HB Company Australia Pty. Ltd. (2003), failed meeting the 4.4MPa mark. The coefficients of variation are generally (too) high but they could be related to the quality of the adherent material.

5.3 *Comparing the performance of the adhesives*

The qualitative and quantitative analyses could indicate that the performances of RBA and PUR are not similar. However, because PUR experienced higher variations than RBA, the difference between both adhesive may not be certain. For the assessment of the difference significance, the null hypothesis, *H0*, states that PUR performs higher strength than RBA. In order to test H0, statistical analyses on the difference between the averages of an RBA and PUR test series were conducted i.e. pairs of test series with similar adherent materials and assembly technique were compared.

The statistical analyses demonstrated that PUR connections are significantly stronger than RBA assemblies. The null hypothesis, *H0*, was statistically true with each pair of test series. Table 4 summarises the results of the statistical comparison.

Table 4: ultimate strength – statistical comparison of paired test series

Statistical data of the test series							Statements	
PUR series				RBA series				
	*SS [MPa]	SDEV [MPa]	versus		SS [MPa]	SDEV [MPa]	†TO	‡SD
A01	7.81	1.95	⇔	A07	2.16	0.76	no	yes
A02	6.50	2.62	⇔	A08	3.68	1.08	no	yes
A03	6.41	2.48	⇔	A09	3.26	0.78	no	yes
A04	7.53	1.21	⇔	A10	2.30	0.75	no	yes
A05	6.72	2.24	⇔	A11	3.51	0.71	no	yes
A06	4.96	1.71	⇔	A12	2.86	0.69	no	yes

*average shear strength, †tolerance overlap (Figure 4), ‡statistical difference.

Figure 4, which depicts the average strength of the test series, indicates clearly that the PUR test series performed higher strength than RBA test series.

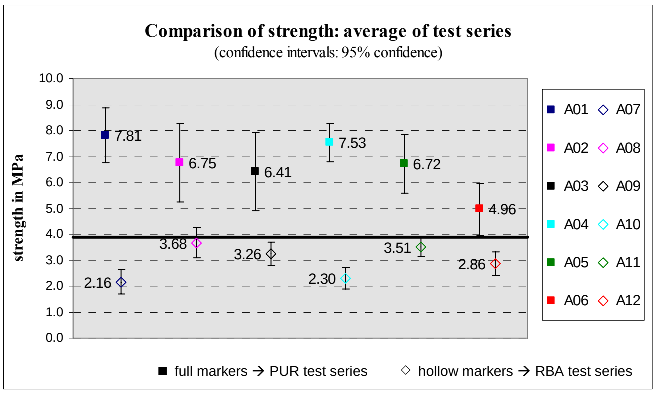

Figure 4: graphical comparison of the average strength of the test series

Figure 4 also shows the absence of overlap of the tolerance bars between each pair of test series. Further, the magnitude of these bars also demonstrate the higher variations experienced by PUR test series.

Figure 4 also enables identifying that PUR test series (A01 to A03, A04 to A06) experiences a linear decrease of strength in correlation to the device assisting the adhesive curing — the best performances being obtained with clamps, screws and nails respectively. With RBA test series, specimens manufactured with clamps and screws achieved the lowest and best performance respectively.

5.4 *Load-slip modulus*

In assemblies, which combined adhesive and mechanical fasteners, three distinct phases are expected for the slip modulus. Firstly, the slope is very steep and reflects the deformation of the glue line i.e. slip is negligible and full composite action can be assumed. Secondly, a major loss of stiffness occurs, signalling bond failure. Lastly, the mechanical fasteners, with about 50% of the peak strength, control the strength and slip modulus of the assembly. In this last phase, the connections experienced significant ductility. Such typical load-deformation curves, e.g. nail-glued specimens, are depicted in Figure 5. The initial untidiness of the curves corresponds to the specimens adjusting to the testing set-up.

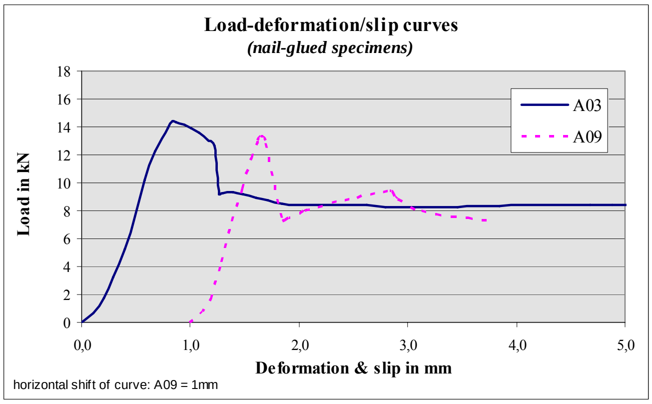

Figure 5: typical load-deformation curve of nail-glued assemblies

From the graphical depictions of the test results (Figure 5), the load-deformation curves characterise "trilinear" behaviours i.e. three consecutive sequences of distinctive stiffness. The results of the laboratory investigation also demonstrate that superposing the strengths of the adhesive and mechanical fasteners, as suggested by Pellicane (1992a; 1992b), is correct. Therefore, the strength and slip modulus of screw- and nail-gluing assemblies can be accurately approximated provided that the strength and moduli of the adhesive and the mechanical fasteners are known.

The load-deformation curves also indicate that adhesive and mechanical fasteners have very different strength and slip moduli. The first one is very strong and stiff with incremental ductility, while the second one has lower strength and stiffness but is very ductile. These differences of properties prevent them to work efficiently together. Therefore, adding the stiffness and strength of both connectors for design could be unsafe. For safer design, an "in succession" approach reflects the behaviour of the connections more accurately. This concept gives clear boundary to the superposition theory and enables safe design. Therefore before bond failure, the mechanical fasteners, which only make an incremental contribution to the strength and stiffness of the assembly, should be ignored i.e. the strength and stiffness of the assembly should only rely upon the adhesive properties. With this design scenario, the mechanical devices act as "backup" to the adhesive i.e. in case of bond failure the interlayers retain sufficient strength to avoid a sudden collapse of the whole structure.

6 CONCLUSION

Today's wood engineered products and structural adhesives enable constructing high performing structures. Associated with hybrid assembly techniques that combine mechanical fasteners and an adhesive, composite structures with large dimensions can be manufactured. Such composite systems enhance the capacity and reliability of wood solutions for structures and can generate new opportunities for use of timber in large constructions such as sport halls, warehouses and factories.

The properties of the connection (strength and slip modulus) have significant effects on the composite characteristics of the structures. With the presence of adhesive, full-composite properties can be expected in the interlayers. The current study on screw- and nail-gluing techniques, which focused on connections involving elastomeric and polyurethane adhesives and Australian softwood, identified such full composite properties in the assemblies. It also demonstrated that polyurethane adhesive meet the requirements of structural glue. On the other hand, rubber based adhesives should not be considered for structural use.

The trilinear curve of the slip modulus indicates that the screw- or nail-glued assemblies experience three distinct phase. Firstly, the strength and stiffness are governed by the adhesive. Following the failure of the latter (second phase), the mechanical fasteners govern the performance of the interlayer (third phase). Therefore in design, considering the strength and stiffness of the adhesive and mechanical fasteners successively, i.e. ignoring the contribution of the mechanical fasteners before the adhesive failure, represents a sound practice and should be preferred for safe(r) design.

The presence of mechanical fasteners in the connection generates ductile behaviour. This phenomenon, which happens after adhesive failure, is beneficial for the structural safety of the composite construction. Furthermore, the interlayers retain sufficient strength to avoid the collapse of the whole structure in the events of bond failure.

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