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ORIGINAL ARTICLE

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Development of LVL frame structures using glued metal plate joints I: bond quality and joint performance of LVL–metal joints using epoxy resins

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Abstract Bond quality and joint performance between laminated veneer lumber (LVL) and metal plates were investigated. Commercially fabricated LVL made of Douglas fir veneer and bonded with phenol-formaldehyde resin as well as three types of epoxy adhesives were used. Various surface preparations and treatments were applied to ordinary steel, stainless steel, and aluminum plates to remove the weak boundary layer that is incompatible with the resin and form a stable adherend layer that is chemically and mechanically compatible with the resin. Small specimens were tested in shear to search the most suitable metal surface for bonding with LVL. Generally, shear strength obtained for the specimens bonded with aluminum plates was lower than those bonded with ordinary steel plates. Among them chemically treated (ChT) and roughened (R) surfaces have demonstrated superior performance. To investigate strength performance and bond quality, LVL beams jointed with metal plates were tested while bending. The best results were obtained for specimens bonded with zinc-coated metal plates, though good results were obtained also for ChT and R plates. However, the fracture proved to be fragile when no drift pins were used, even for high-performance surface treatments. The usage of drift pins was necessary to add toughness and avoid the brittle status of the fracture.

Key words Bond quality · LVL–metal joint · Epoxy adhesives

Introduction

Presently, the use of portal frames in timber structures is becoming more and more common, mostly because of their moment carrying capacity and ease of assembly. The portal frames are increasingly employing advanced-engineered products such as glulam or structural composite lumber [laminated veneer lumber (LVL) and parallel strand lumber (PSL)] characterized by structural stability and reliability. The main issue in the case of portal frames remains the joint, which governs the structural behavior. Several researchers have undertaken experimental and theoretical research on portal frames,[1–3] but a reliable, effective, economical structural joint is still needed.

The literature revealed several types of mechanical joint available for portal frames. Some of the most effective mechanical joints are nailed or screwed gusset plates, reported by many authors.[1,4,5] For better results Batchelar and Hunt[6] used composite side plates instead of simple plywood sheets or steel plates, gluing together plywood and thin sheets of steel. Other authors[7,8] conducted ample research on doweled joints with steel plates often placed between members or in slits. They obtained the good ductile and stiff properties necessary for moment resisting joints.

In comparison with mechanical joints, little has happened in the field of glued joints despite several favorable properties offered by them. A good example is the use of epoxied steel rods, which is presently receiving great attention. Numerous experiments[9–11] with epoxied steel rods have revealed the potential of these joints to create strong, reliable structural systems.

In this study, we have tried to combine and use both jointing methods – mechanical and glued joints – and apply them first at the LVL beams and later at the portal frames. Another challenge was the use of gap-filling glue instead of close-contact glue, which is normally used. The gap-filling type allows control of the glue line thickness, whereas with close-contact glue pressure must be applied.

The purpose of this experiment was to find the best metal surface suitable for gluing with LVL and to examine the bending strength properties of LVL beams jointed with glued metal plates. The whole test program was designated to research glued LVL–metal joints used as structural components, apply them at LVL portal frames, and evaluate the response of the structures during cyclic lateral loading.

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Materials and methods

Shear strength performance and bond quality of small LVL specimens

Commercially fabricated LVL, composed of 24 plies of 3-mm Douglas fir (*Pseudotsuga taxifolia* Poir) veneer and bonded with phenol-formaldehyde resin was used. Nominally 1125 × 75 × 75mm LVL 120E (JAS) pieces, obtained from the LVL manufacturer, were cut into small cube-like specimens with dimensions of 75 × 75 × 75mm. Then a 5.5mm wide groove was cut in the medial part of the radial section of each specimen (Fig. 1).

Aluminum and ordinary steel plates of 85 × 38 × 4.5mm used for shear tests were each divided into five groups depending on their surface preparation: rough surface (R), striated surface (S), plates with holes (D), chemically treated surface (ChT), and controls (C). The treatment followed generally the same procedure for all the plates, but different etching treatments were applied for aluminum and ordinary steel plates. The chemical treatment for aluminum plates consisted of (1) degreasing with lacquer thinner; (2) washing in cold water for 5min; (3) etching at 60°C for 30min with 15% H_2SO_4, 5% CrO_3, and 80% H_2O; (4) washing again in cold water for 5min and in hot water (40°C) for 5min; and (5) drying at 40°C for 30min. The chemical treatment for ordinary steel plates was as follows: (1) degreasing with lacquer thinner; (2) brushing with soap; (3) washing in hot water (40°C) for 5min; (4) drying at 120°C for 10min; (5) etching at 65°C for 10min with HCl (conc.) = 50 parts by weight (pbw), H_2SO_4 (30%) = 2pbw, CH_2O = 10pbw, and H_2O = 45pbw; (6) washing in hot water (40°C) for 5min; and (7) drying at 40°C for 30min. According to the literature,[12] these treatments are appropriate for bonding with epoxy resins.

Three types of epoxy adhesive, made by three different Japanese manufacturers, were used for all the tests performed in this experiment: low-viscosity epoxy resin (E250), high-viscosity epoxy resin (TE134), and "medium"-viscosity resin (R114) provided by Konishi, Oshika Shinko, and Dainippon Ink Chemical, respectively.

After gluing the metal plates inside the LVL grooves, some specimens were kept indoors for curing for 2 days at 15°C (t1;T1) and others were kept indoors for 7 days at 20°C (t2;T2). Altogether 80 specimens (two kinds of metal plates × five kinds of plate surfaces × two kinds of adhesives (E250 and TE134) × two directions of testing × two replications) were tested in shear and rolling shear; an additional 120 specimens [two kinds of plate surfaces (ChT and R) × three kinds of adhesives × two kinds of curing conditions × ten replications] were tested only in shear. Tests, performed on a universal testing machine, were conducted in one of the faculty's laboratories where the room temperature and relative humidity (RH) were about 10°–15°C and 50%, respectively.

Strength performance during bending and bond quality of LVL beams jointed with metal plates

Bending tests were carried out using LVL members (1000 × 270 × 89mm) and metal plates (540 × 270 × 5mm) as shown in Fig. 2. The following specimens were prepared: type A, two LVL members were glued together by means of a stainless steel plate with rough and chemically treated surfaces; type B, similar to type A but fortified with drift pins mounted on a square; types C, D, and E, jointed with stainless steel plates coated with zinc (type D was fortified with drift pins mounted on a square and type E mounted on a circle).

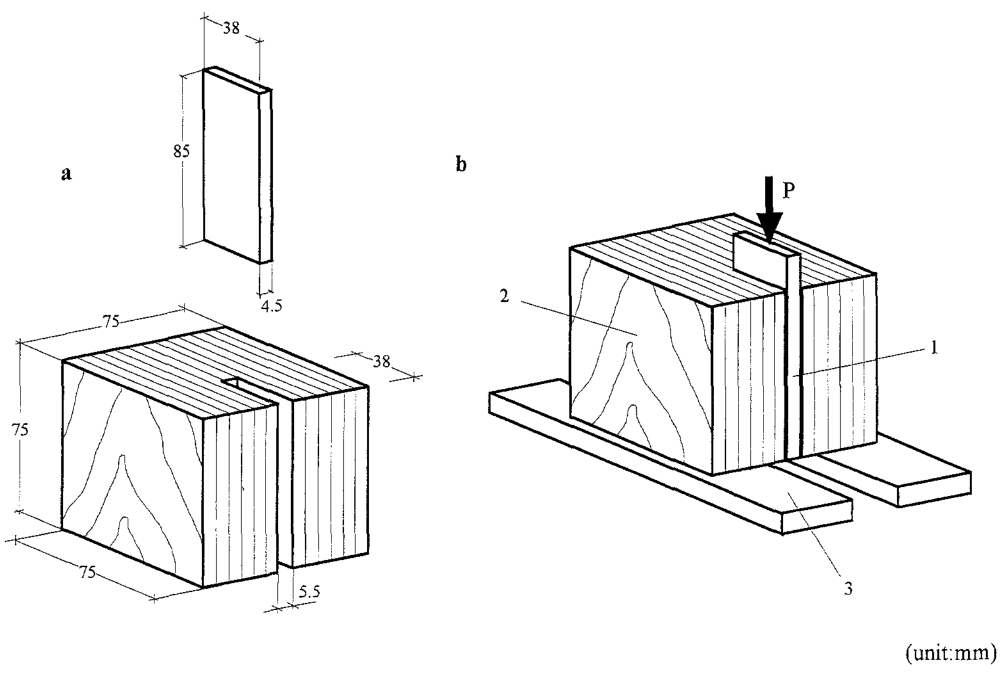

Fig. 1. Shape and size of laminated veneer lumber (LVL) specimens tested in shear. **a** Size of the metal plate and LVL specimen. **b** Test setup: *1*, metal plate; *2*, LVL; *3*, steel base

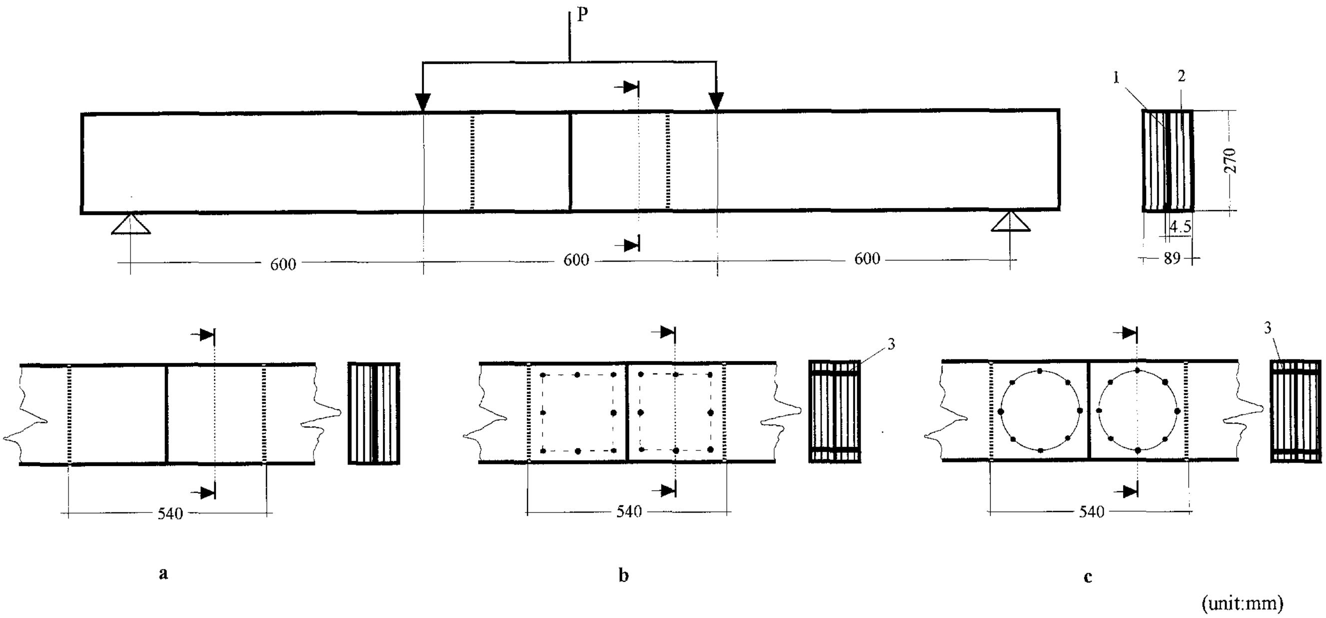

Fig. 2. Shape and dimensions of LVL specimens subjected to four-point loading, with 600 mm of pure bending section. Three models were used for this stage. **a** Specimens without consolidation (types A and C). **b** Specimens with drift pins mounted on a square (types B and D). **c** Specimens with drift pins mounted on a circle (type E). *1*, metal plate; *2*, LVL; *3*, drift pin. The thickness of the glue line was 1 mm for all specimens

Stainless steel plates with the following surface preparations were used.

1. *Plates with rough and chemically treated surfaces.* The plates' surfaces were first sanded with sanding paper No. 40 and then treated using the same chemical treatment used for the small specimens that were tested in shear;
2. *Plates with surfaces coated with zinc.* These plates were provided by Sumikin Kohzai Co. Their special mechanical plating treatment consisted of two coating treatments: (1) zinc coating: the surface was splashed with Zn-Fe alloy drops (macromolecules) after which the steel surface had gained zinc (5–15 g/m^2); and (2) chrome coating with the next component: CrO_3 32%; H_2SO_4 0.5 ml/l; HNO_3 0.5 ml/l, and the rest H_2O. After coating, the plates were oven-dried and then naturally dried. The plates were cleaned only with lacquer thinner before gluing in the laboratory.

A total of 14 specimens (two replications for each type, plus two more replications each for types C and D) were used. Specimens A, B, and half of C and D were glued with a low-viscosity epoxy adhesive; and the other half of C and D plus E were glued with a high-viscosity resin. The specimens were kept in a controlled-environment room for 7 days at 15°–20°C for curing, and then some of the specimens (types B, D, and E) were drilled and fortified with drift pins. Finally, they were simply supported at the end and subjected to a four-point bending test with the clear span distance between supports of 1800 mm and 600 mm of pure bending section. Total and lateral displacements were measured using displacement transducers, which were connected to an electronic data analyzer.

Results and discussion

Shear strength performance and bond quality of small LVL specimens

Shear/rolling shear strength

Shear strength and rolling shear graphs for specimens jointed with ordinary steel plates are shown in Fig. 3a,b. In all cases the chemically treated (ChT) and rough (R) plates had the highest strength; the striated plates (S) and the plates with holes (D) were sometimes stronger and sometimes weaker than the control (C). Based on the above results, it can be affirmed that ChT and R plates behaved best during the shear test; hence only these two types of plate were chosen for testing. Although similar trends were observed for the specimens jointed with aluminum plates (Fig. 3c,d), the results were inferior to those jointed with ordinary steel plates, and therefore aluminum plates were not used for the bending tests.

Failure mode

Four types of failure were observed. Type A represents 100% wood failure, meaning that the rupture took place entirely in the LVL. Type C represents interface failure; that is, the rupture occurred at the interface, between the metal plate and the adhesive. The percent of wood failure in this case is 0%. Types B1 and B2 represent an intermediate state of failure (wood failure was more than 50% for type B1 and less than 50% for B2).

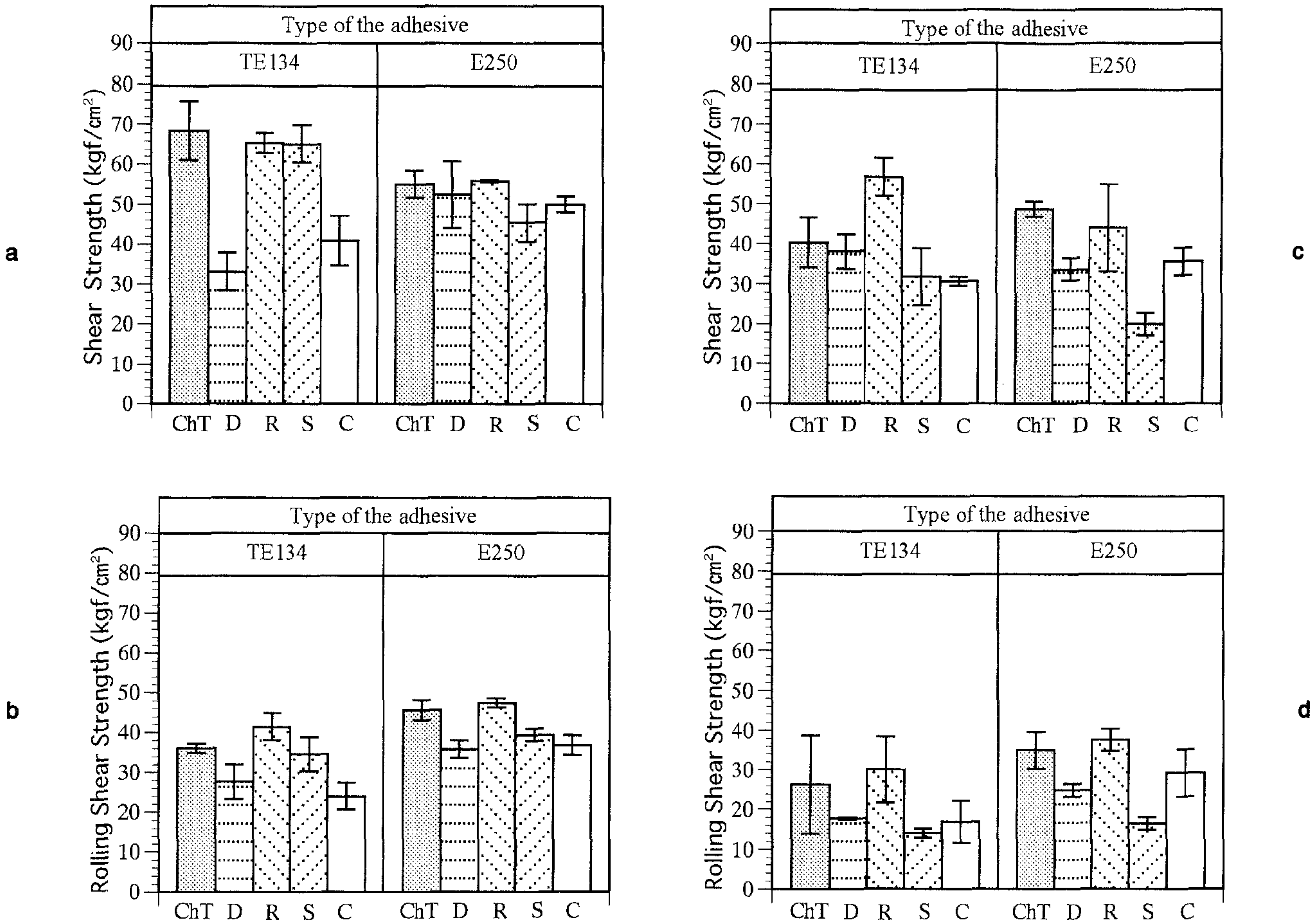

Fig. 3. Shear strength (**a**, **c**) and rolling shear (**b**, **d**) for ordinary steel plates (**a**, **b**) and aluminum (Al) plates (**c**, **d**) bonded with LVL. Low (E250) and high (TE134) viscosity epoxy adhesives were spread on different kinds of plate surfaces: *ChT*, chemically treated surface subjected to full treatment; *D*, plates with holes; *R*, rough surface (plates sanded with no. 40 sanding paper); *S*, striated surface degreased with lacquer thinner (Al plates were also brushed with soap and washed in hot water at 40°C for 5 min); *C*, control plates. The values obtained for each replicate were close, and their averages were plotted on the graphs. I-bars represent standard deviations

Among all the specimens tested in shear, 42% were A type, 26% B1 type, 19% C type, and 13% B2 type.

Figure 4 shows the wood failure percent for small specimens tested in shear. Slightly better results were obtained for rough-surfaced plates in comparison with chemically treated plates, proving that the two treatments were almost of the same efficacy (Fig. 4a). A higher percentage of wood failure was obtained for E250 and R114 resins compared with TE134 for both surface treatments. These results indicate that, in the case of E250 and R114, the strength of the adhesive was much better than the strength of the adherent, which failed first.

The curing conditions t1;T1 and t2;T2 exhibited an insignificant effect on wood failure for both surface treatments and for all three adhesives (Fig. 4b,c). However, E250 and R114 reached the highest degree of wood failure for the t2;T2 curing condition.

Influence of curing time and temperature, type of resin, and plate surface on shear strength

The influence of the plate's surface, type of epoxy adhesive, and the time and temperature of curing on shear strength is shown in Fig. 5. Like wood failure, the results were similar for the samples bonded with metal plates having the surface roughed and for those chemically treated. Lower shear strength was obtained for TE134 than for E250 and R114 resins (Fig. 5a). Similar results were obtained for the specimens kept at 10°C for 2 days and at 20°C for 7 days (Fig. 5b,c), probably because the adhesive was hard and stiff enough after only 2 days, though for epoxy it takes 7 days to cure completely.

Strength performance in bending and bond quality of LVL beams jointed with metal plates

Results for zinc-coated and chemically treated plates glued in LVL beams

Figure 6 shows the differences between chemically treated and zinc-coated specimens. Among the samples glued with E250 epoxy resin, the zinc-coated plates showed a higher moment in bending for both reinforced and nonreinforced samples. In the case of the specimens glued with zinc-coated plates, similar results were obtained for TE134 and E250

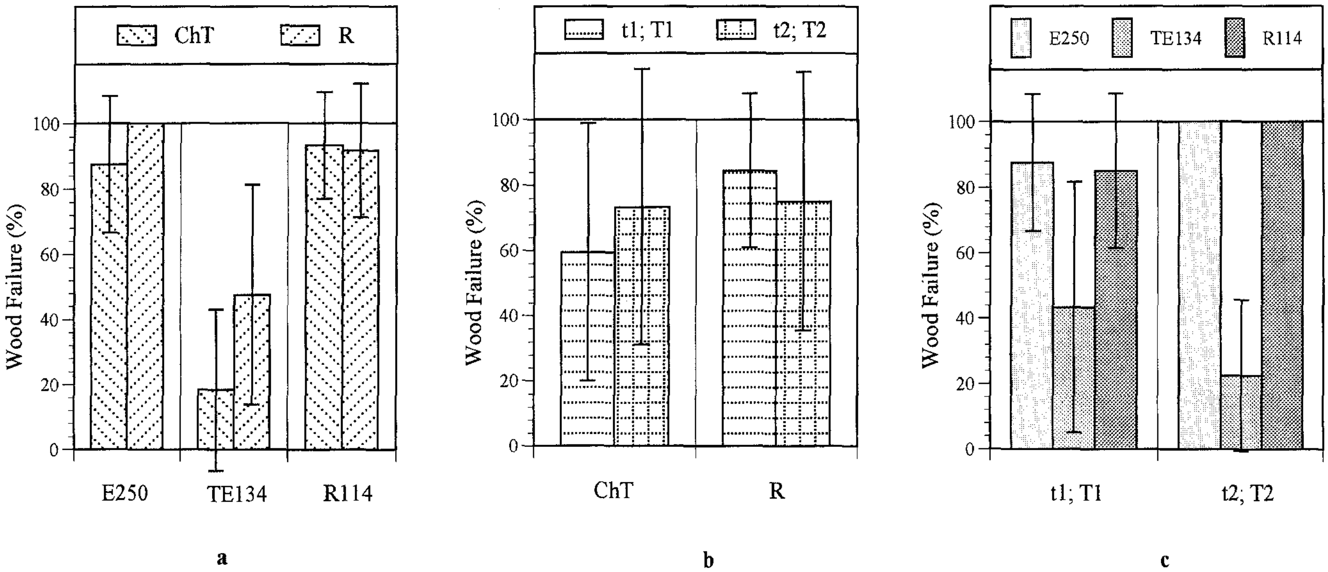

Fig. 4. Influence of the plate surface (**a**), type of epoxy resin (**b**), and curing conditions (**c**) on wood failure. See Fig. 3 for explanation of symbols. *t1;T1* and *t2;T2* represent curing conditions as follows: 2 days at 10°C and 7 days at 20°C, respectively. Each value represents the average of 10 specimens. I-bars represent standard deviations. The same results were used to construct bar graphs **a**, **b**, and **c**

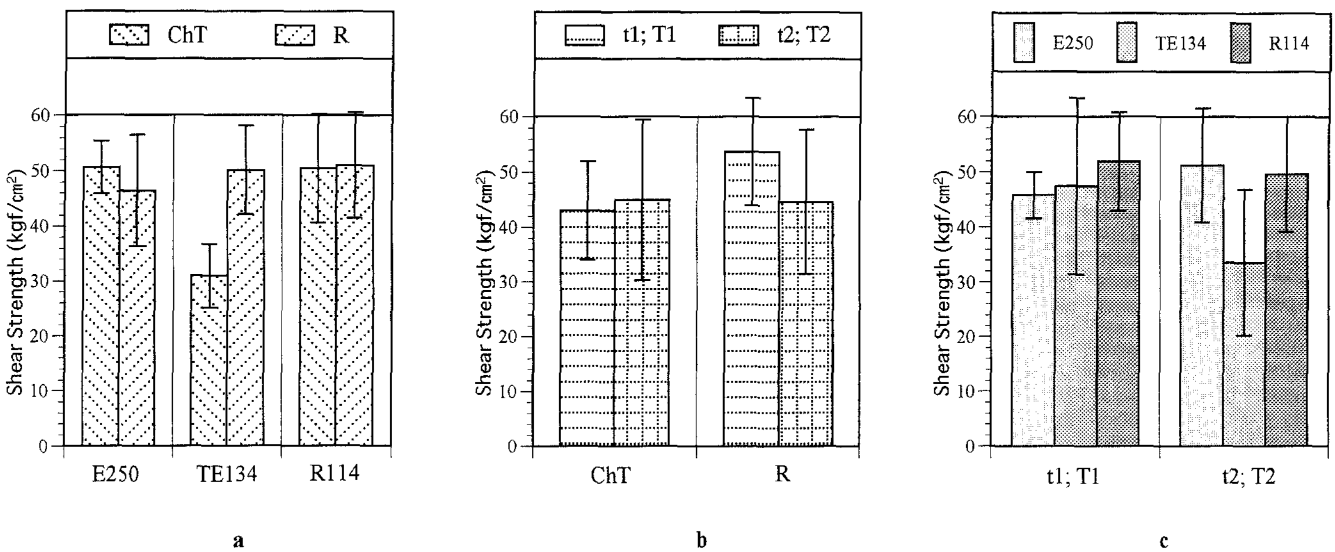

Fig. 5. Influence of plate surface (**a**), type of epoxy adhesive (**b**), and curing conditions (**c**) on shear strength. See Figs. 3 and 4 for explanation of symbols. Each value represents the average of 10 specimens. I-bars represent standard deviations. The same results were used to construct graphs **a**, **b**, and **c**

epoxy resins for both groups of samples, reinforced and nonreinforced. The maximum moment during bending was found to be higher for specimens having circle-like reinforcement than for those with square-like reinforcement, as well. For these specimens the adhesive secured the initial strength, and the drift pins took over the load-carrying capacity after the adhesive failed.

Failure mode of the LVL beams

After the failure, it could be seen that adhesion was far better in the zinc-coated plates than in the chemically treated plates. The fracture status was found to be brittle for most of the glued specimens.

Figure 7 shows the load-displacement relation for specimens C, D, and E, all glued with TE134. Different curves were achieved for the specimen without drift pins (type C) and for the specimens with drift pins (types D and E). The curve for type C shows an early, brittle failure with more than 50% reduction in strength at the first adhesive collapse. All the curves are linear-elastic up to 5500kgf when the adhesive failed. The drift pins took over the load in the case of specimens D and E, which had higher displacements. Specimens D and E had only a small reduction in strength at the first failure of the adhesive, and their failure occurred gradually, not suddenly as for type C. This was attributed to the drift pins, which were rigidly inserted in their drilled holes, without clearance. It was found that the drift pins deformed during the test and caused local crushing of wood fibers.

These results were obtained with two replications for each type of the LVL beam. Using a small number of specimens might presume lower reliability, but the unique results and findings of this study reflect the valuable results of these two replications. More experimental work is needed and represents the objective of additional prospective research to employ the findings of the present study.

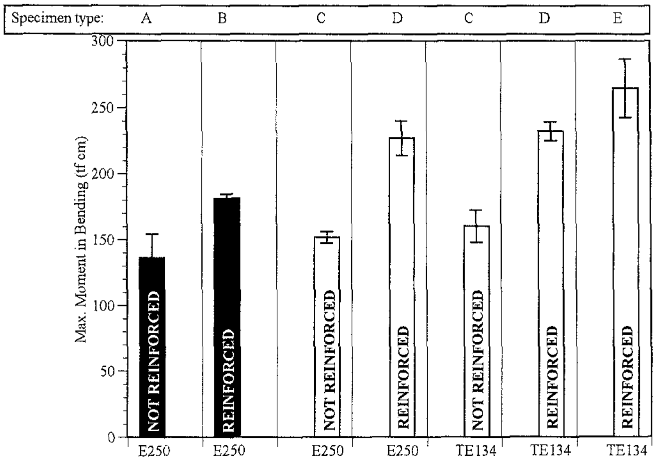

Fig. 6. Maximum bending moment for the types of specimens *A*, *B*, *C*, *D*, *E* glued with chemically treated (*filled bars*) or zinc-coated (*open bars*) plates using low (E250) or high (TE134) viscosity epoxy resins. See Fig. 2 for explanation of symbols: *A*, stainless steel plates with rough and chemically treated surfaces; *B*, same as *A* but fortified with drift pins mounted on a square; *C*, stainless steel plates coated with zinc; *D*, same as *C* but fortified with drift pins mounted on a square; *E*, same as *C* but fortified with drift pins mounted on a circle. The values obtained for the replicates were close, and their average was plotted on the graphs. I-bars represent standard deviations

Conclusions

Three major conclusions may be drawn from this study.

1. Surface preparation is the most effective way to ensure high bond performance and always involves at least degreasing and abrading. The best results were obtained with stainless steel coated with zinc plates.
2. Viscosity is of major importance when applying the adhesive, but it had no serious effect on joint strength.
3. The LVL–metal joints without drift pins proved to be fragile with brittle failure when tested during bending. The use of drift pins increased the toughness and strength of these joints.

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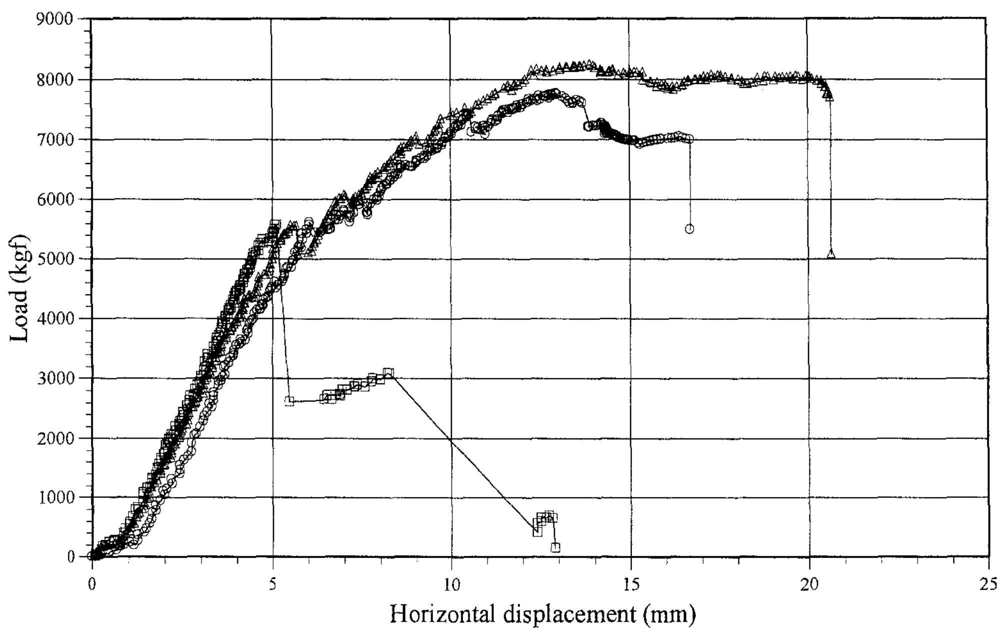
Fig. 7. Load–displacement relation of various specimens tested while bending. *Squares*, specimen type C; *circles*, specimen type D; *triangles*, specimen type E



References

1. Komatsu K, Kamiya F, Hirashima Y (1988) Full-size test and analyses on glulam two-storied portal frames. In: Proceedings of the International Conference on Timber Engineering, Seattle, pp 205–220
2. Ohashi Y, Sakamoto I (1994) Experiments and response analyses on three storied timber frame structures. In: Proceedings of the Pacific Timber Engineering Conference, Gold Coast, Australia, vol 2, pp 222–231
3. Komatsu K, Karube M, Harada M, Fukuda I, Hara Y, Kaihara H (1996) Strength and ductility of glulam portal frame designed by considering yield of fasteners in part. In: Proceedings of the International Wood Engineering Conference, New Orleans, vol 4, pp 523–530
4. Boult BF (1988) Multi-nailed moment resisting joints. In: Proceedings of the International Conference on Timber Engineering, Seattle, pp 205–220
5. Miyazawa K (1994) Timber shear walls and skeleton structures: analyses and experiments. In: Proceedings of the Pacific Timber Engineering Conference, Gold Coast, Australia, vol 2, pp 241–250
6. Batchelar ML, Hunt RD (1991) Composite plywood and steel gusset plates for moment-resisting joints in timber frames. In: Proceedings of the International Conference on Timber Engineering, London, vol 3, pp 104–110
7. Leijten Ad JM (1988) Steel reinforced joints with dowels and bolts. In: Proceedings of the International Conference on Timber Engineering, Seattle, pp 474–488
8. Yasumura M, Ohta H, Fukuda I (1996) Design of wood-framed building with shear walls and moment frames. In: Proceedings of the International Wood Engineering Conference, New Orleans, vol 4, pp 81–88
9. Buchanan AH, Deng XJ (1996) Strength of epoxied steel rods in glulam timber. In: Proceedings of the International Wood Engineering Conference, New Orleans, vol 4, pp 488–495
10. Gardener G (1994) Reinforced glued laminated timber system: epoxy/steel/timber composite material. In: Proceedings of the Pacific Timber Engineering Conference, Gold Coast, Australia, vol 2, pp 548–557
11. Buchanan AH, Fairweather RH (1993) Epoxied moment-resisting connections for timber buildings. In: Proceedings of the International Workshop on Wood Connectors, Madison, WI, pp 107–113
12. Lee H, Neville K (1967) Handbook of epoxy resins. McGraw-Hill, New York, pp 15–16