"New joining techniques for hardwood species"

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ABSTRACT

The joining techniques for hardwoods have progressed and continue to progress towards the increasing use of binders more friendly towards the environment, either less expensive or of improved performance up to the total elimination of gluing by the new technique of wood friction welding. After a brief overview of the resins used to-day for the structural gluing of timber, such as resorcinol resin of ever decreasing resoprcinol content, fast-setting separate application "honeymoon" adhesives based either on melamine or on resorcinol and one component polyurethanes, wood welding without adhesives will be the most important objective of the presentation. The two types of wood welding in operation, namely linear vibration welding and rotational dowel welding, will both be presented with the structural assemblies already achieved. These structures contain 100% wood , thus they are totally natural. The limitations, advantages and disadvantages of such a joining system will be discussed and compared to joining by gluing.

RESUME

Les procédés d'assemblage par collage des bois feuillus ont progresses et continuent à progresser vers l'utilisation de résines plus propres pour l'environnement, moins chères ou plus performantes jusqu'à arriver à l'élimination totale du collage et des colles par la toute nouvelle utilisation du soudage bois. Apres une brève liste des les résines utilisées aujourd'hui pour collage structural du bois, comme colles à la résorcine de plus bas niveau de résorcine, colles rapides lune de miel à application séparée soit de melamine soit de résorcine, et polyuréthanes monocomposants, le soudage du bois sera la cible plus importante de la présentation. Les deux types de soudage bois, par friction linéaire et rotative, donc sans aucune utilisation de colle, seront presentes, avec la réalisation d'assemblage de différentes structures en construction. Ces assemblages contiennent 100% bois et rien d'autre donc ils sont totalement naturels. Les limitations, avantages, et désavantages de ce système d'assemblage seront discutes et compare à l'assemblage par collage.

HONEYMOON ADHESIVES

Honeymoon fast-set adhesives for glulam were first devised in the 1970s (Baxter and Kreibich 1973, Caster 1973, Kreibich 1974, Pizzi et al 1980) and were commercialized for the first time in South Africa at the beginning of 1980. Several variations have been developed since the original pure synthetic phenol-resorcinol-formaldehyde (PRF) ones (Caster 1973, Kreibich 1974, Pizzi et al 1980, Pizzi and Cameron 1984, Cameron and Pizzi 1989), from the totally tannin-resorcinol-formaldehyde (TRF) ones (Pizzi et al 1980, Scopelitis and Pizzi 1993), to the ones in which half PRF and half tannin solution are used (Pizzi et al 1980, von Leyser and Pizzi 1990) these three types being the ones ever since commercialized in South Africa, to the ones developed in New Zealand in which half PRF and half an ammonia-based accelerator are used (Parker et al 1991), to those in which of the profiles uses instead of tannin a a pH soya hydrolysate (Steele et al 1998) and finally to those in which the PRF is substituted altogether by MUF resins (Properzi et al 2001), all of these types being commercial. PRF honeymoon adhesive systems have component A presenting a pot-life of 2 to 2.5 hours, but systems presenting pot-lives as long as 48 hours also having been developped and used commercially in the past (Bakelite AG 1993).

Recently, the increased interest in the use of more natural, environment friendly materials has again brought to the fore interest in honeymoon adhesive systems based on half PRF resin applied to one surface to be bonded (profile A) and half tannin extract solution applied on profile B. The interest was based not only on (i) the low cost of the system due to half the amount of resorcinol used in relation to traditional PRF adhesives but also (ii) on 50% of the adhesive being composed of a natural environment-friendly non toxic material such as tannin and finally (iii) on its capability of performing well and at cheaper cost also in the new concept of wet and green gluing (Na et al 2005).

Addition of flavonoid tannin extract to the PRF component A of a PRF/Tannin honeymoon fast set adhesive system for glulam and fingerjointing yielded (PRF+Tannin)/Tannin adhesive systems in which the total percentage of natural material can be as high as 65% (2/3) of total adhesive resin solids without any loss of either long term performance or of fast rate of curing.

Table 1. Results achievable with honeymoon fast setting adhesives on beech wood strips

Component A	Component B	Strength (% Wood failure)		
		Dry (N)	24 h cold soak (N)	6hBoil (N)
100 PRF	100 Tannin	2553 (0)	2071(35)	2351 (51)
90 PRF + 10 Tannin	100 Tannin	3244 (50)	2066 (10)	2105 (80)
80 PRF + 20 Tannin	100 Tannin	3156 (15)	2108 (10)	2143 (65)
70 PRF + 30 Tannin	100 Tannin	2734 (70)	2468 (50)	2571 (76)
50 PRF + 50 Tannin+5%NH_3	100 Tannin	2613 (22)	1764 (50)	1707 (70)
40 PRF + 60 Tannin	100 Tannin	2242 (0)	605 (0)	1059 (3)
BS 1204-1 requirement		≥2500	≥2000	≥1500

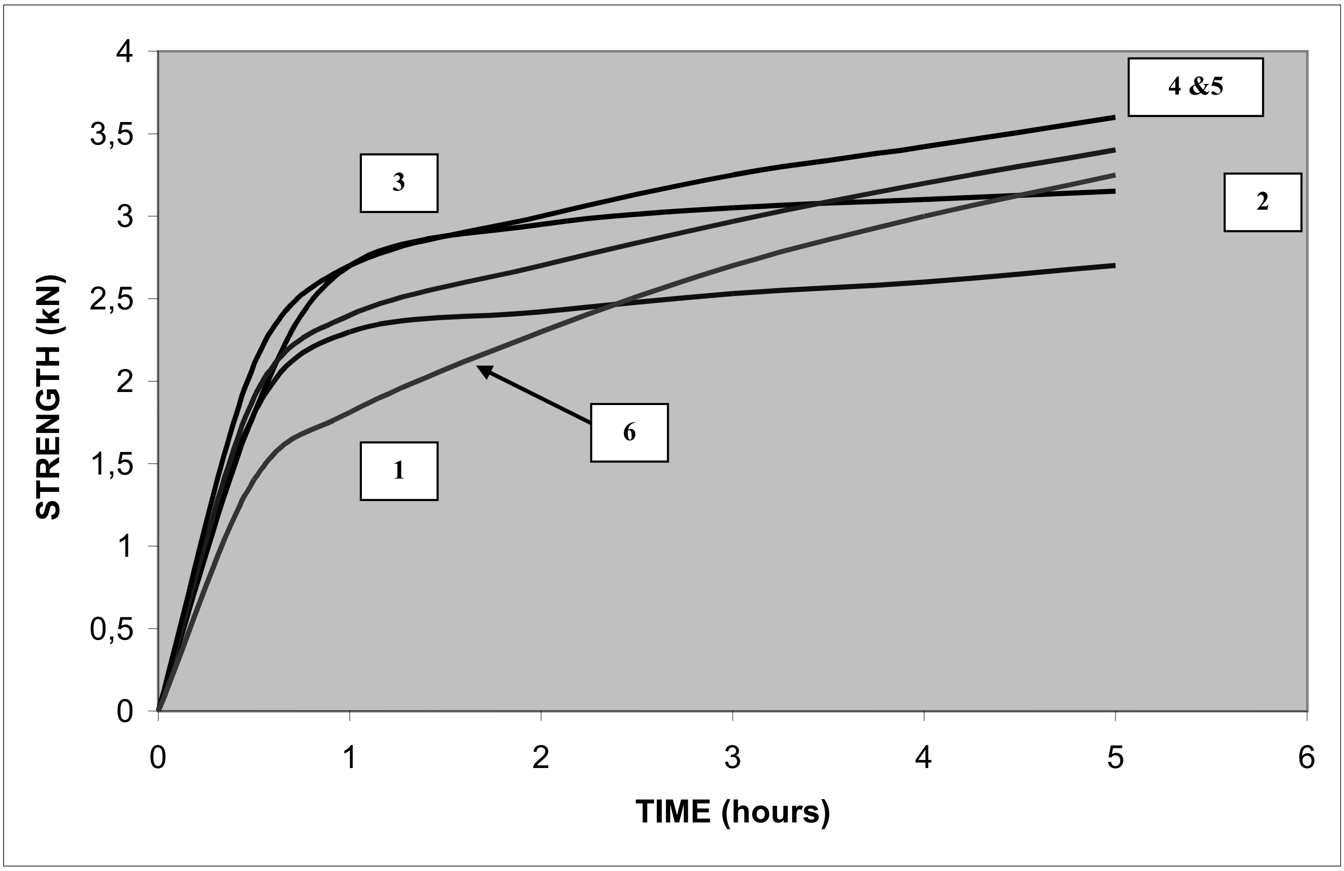


Fig. 1. *Curves of dry strength increase as a function of time of beech strips bonded according to BS1204-part 1(1982) with experimental honeymoon separate application fast set adhesives. (1) 100 PRF+100 Tannin honeymoon adhesive control, (2) (90 PRF + 10 Tannin) +100 Tannin , (3) (80 PRF + 20 Tannin) +100 Tannin , (4) (70 PRF + 30 Tannin) +100 Tannin , (5) (50 PRF + 50 Tannin) +100 Tannin + 5% NH_3, (6) (40 PRF + 60 Tannin) +100 Tannin .*

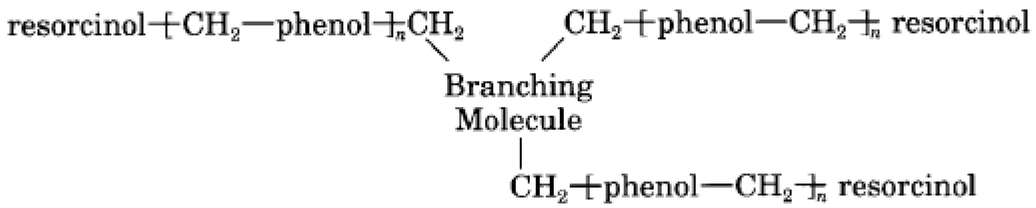
The results obtained after 7 days ageing from beech strips tested according to EN 302-1 when the honeymoon adhesive Component A was progressively changed from 100% PRF resin to respectively , 90% PRF + 10% Tannin, to 80% PRF + 20% Tannin, to 70% PRF + 30% Tannin, 50% PRF + 50% Tannin and to 40% PRF + 60% Tannin are shown in Table 1. These show that for a PRF resin studied for the european market, in which percentage wood failure is not taken into account (both in BS 1204 and the newer EN 302), a honeymoon adhesive systems for glulam and fingerjointing in which a total of 65% natural material and only 35% synthetic PRF resin are used can satisfy well the requirements of the norm. It is interesting to note that percentage wood failure is relatively low, while average joint stength is particularly high, as acceptable in european-type standards. This is sometime the case for PRF adhesives developed for the european market, this being due to their relatively lower viscosity and different rheology than the same adhesives developed for other markets where percentage wood failure is instead required by other standards. The results in Table 1 also show that as the proportion of tannin in component A, thus premixed with the PRF adhesive, increases both strength and especially wood failure improve, again due to the tannin-induced change of rheology of the system. Increase of the proportion of tannin much over 2/3 of the total resin solids starts to affect the performance of the resin as quite clearly shown in the last cases in Table 1 in which the total tannin is up to 75%-80% of total resin solids, even if a further acceleraator such as amonia is added,. At these low PRF proportions while dry strength is still good both wet strength and especially percentage wood failure show considerable deterioration of bond durability. It must be pointed out that the use of different PRF formulations, better apt to maximize wood failure (Scopelitis and Pizzi 1993) would also allow this increase in the relative proportion of natural material for systems needing to satisfy standards such as north american ones conceptually different from european ones.

The usefulness of honeymoon fast set adhesives depends on their high rate of curing allowing the reaching of the standard requirements in a much shorter time than traditional PRF adhesives. The results in Table 1 are not enough to indicate if the addition of tannin to the PRF in component A still allows to maintain this essential characteristic of the adhesive. Thus, in Fig. 1 are shown the curves of increase of dry strength of beech joints as a function of time for the same adhesive combinations of Table 1. These indicate that the rate of curing tends to increase once the tannin is added. Thus, 10% tannin addition just increases the initial rate of curing but the curve does then settles to the same rate of increase than that of the control honeymoon adhesive. However, in the case of 20% and 30% PRF substitution by tannin in component A not only a much faster initial rate of strength increase results, the BS 1204 requirements being reached in about 40 minutes for the specific PRF used, but hardening settles also to a later faster rate of curing. It must be pointed out that such a result was achieved when the specific PRF used had even a rather longer than usual pot-life of 5 hours. The trend is still maintained at 50% tannin in component A, but it is not maintained when the percentage tannin in component A increases to 60% (thus 80% of the total adhesive system). The last case in Table 1 show a curve (Fig. 1) that is relatively slower in the initial hardening phase, hence in the phase that most characterize honeymoon fast set adhesives, but a relatively fast subsequent increase. The difference in trend of this curve in Fig. 1 clearly indicates that the adhesive does not behave as should be expected from a honeymoon fast set systems, confirming the poor results shown for this case in Table 1.

These resins are equally suitable for green gluing as already described in previous work (Na et al 2005) and the component B tannin solution can also be substituted with a soya hydrolysates as reported by other authors (Steele et al 1998). Use of ammonia accelerators in component B in the same manner as Greenweld (Parker et al 1991) will be suitable for applications in which the PRF resin has been partially substituted by tannin in component A.

Synthetic PRFs of lower resorcinol content

Phenol-resorcinol-formaldehyde (PRF) resins of good adhesive performance, and of resorcinol content much lower than in traditional PRF cold-setting adhesives, were prepared by introducing small amount of urea as a branching unit during preparation of the resin. Resorcinol contents as low as 10% were obtained by this methgod while still maintaining an acceptable pot-life and performance of the resin. Resorcinol contents as low as 8%, still with good adhesive performance, were obtained, although the pot-life obtained tended to be too short. GPC, NMR and FT-IR analysis has shown that the small amount of urea branching units used leads to the reduction of the resorcinol content mostly by rapid doubling of the average linear length of the PF intermediates and of the final PF oligomers. Tridimensional branching in the liquid resin, contrary to what could be thought, does occur but it does not appear to greatly contribute. Reduction of resorcinol content is achieved simultaneously by two mechanisms: (1) the decrease of resorcinol percentage on resin solids due to the rapid lengthening (doubling) of the average oligomers length, and (2) the need for these resins to operate at lower solids content, due to the increased viscosity obtained during their preparation.



Comparison of Honeymoon PRF, MUF anf one component PUR

In Fig. 2 is shown the increase of strength as a function of time of the dry (12% e.m.c.) joints bonded with the three different adhesives. Of the three adhesives tested the faster increase in strength is that of the commercial PRF honeymoon which reaches the strength requirements of the standard after approximately 30 minutes. The single application polyurethane and the experimental MUF honeymoon reach the value of strength required by the standard in respectively 1hour 45 minutes and in 2 hours. Some other differences in behaviour are noticeable too: the difference in maximum final strength are in the order of 6.3 MPa, 6 MPa and 5.4 MPa for the polyurethane, PRF and MUF bonded joints, this being in line with the reported increasing order of rigidity (MUF more rigid than PRF more rigid than PU) of the glue line induced by their respective values of viscoelastic dissipation of energy of the three types of adhesive. The PRF and MUF honeymoon already presents noticeable values of percentage wood failure at the first attainment of the strength standard, namely 35% for the PRF and between 40%-75% for the MUF, while the PU for the same elasic creep rasons outlined above presents 0% wood failure at the 4 MPa limit and only starts to present noticeable percentage wood failure much later at a higher strength value of the joint.

The behaviour changes somewhat in the bonding of wet timber at 22% or much higher (>50%) moisture content (Fig. 3). All the three adhesives present strength increase rates as a function of time which are slower, with the polyurethane being the faster of the three, followed by the PRF and then by the MUF. The strength value of the polyurethane-bonded wet joint passes the requirements of the standard much earlier than the other two and this would be expected in an adhesive that is set by the reaction of its residual isocyanate groups with water.

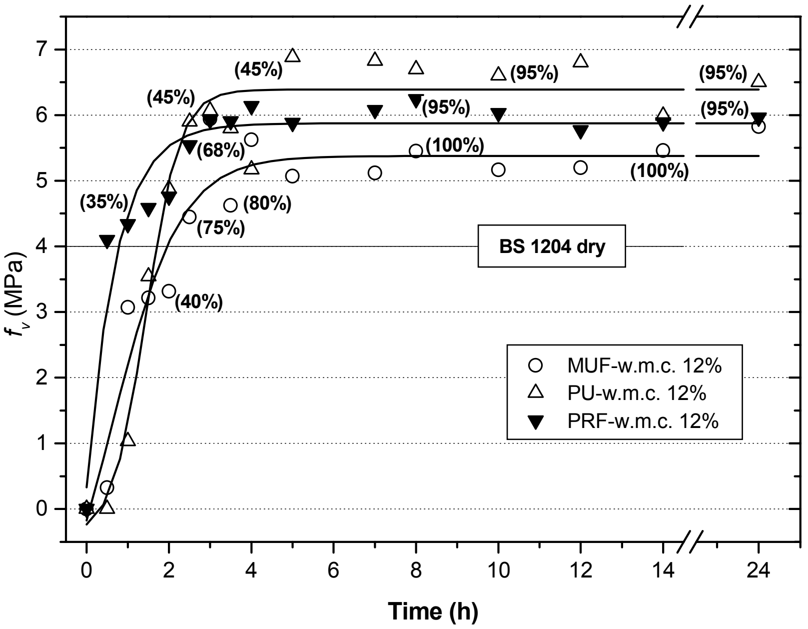


Fig.2. – *Tensile Strength increase as a function of time of beech joints (BS 1204, Part 1) bonded with PRF- and MUF-based separate application honeymoon adhesive systems and with single polyurethane (PU) adhesive system using beech wood of 12% equilibrium moisture content (e.m.c.).*

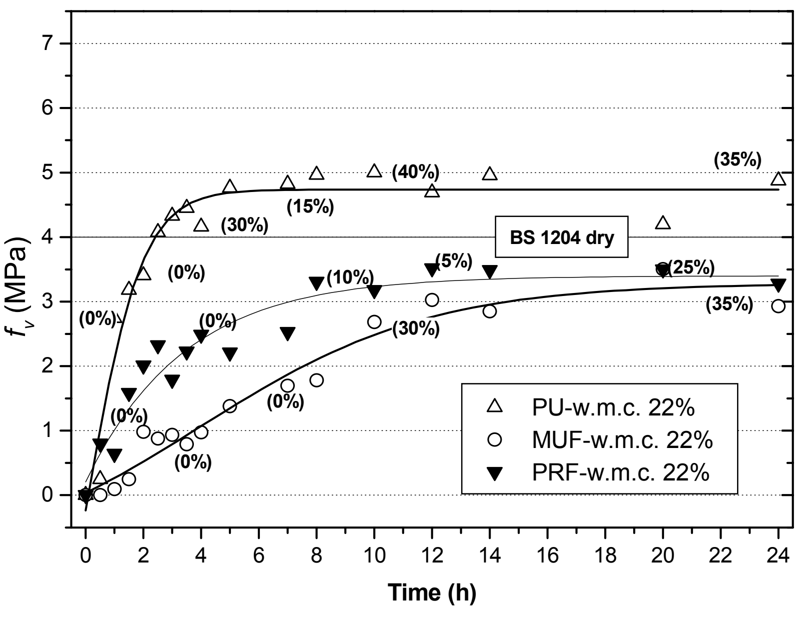


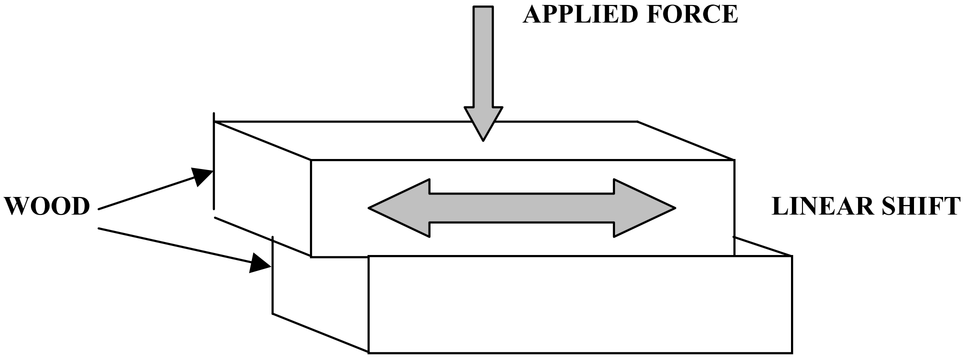
Fig.3. – *Tensile Strength increase as a function of time of beech joints (BS 1204, Part 1) bonded with PRF- and MUF-based separate application honeymoon adhesive systems and with single polyurethane (PU) adhesive system using beech wood of a high 22% equilibrium moisture content (e.m.c.).*

Wood Welding

Linear vibration welding

Thermoplastic welding techniques which are widely used in the the plastic and car industries have recently been applied also to joining wood, by melting a thermoplastic polymer between the two wood surfaces to be joined . A variety of techniques such as ultrasound, mechanical friction and others have been used to melt the thermoplastic polymer in situ.

However, the same mechanical techniques at the interface of two solid wood surfaces in the absence of any thermoplastic material, or any other binder, yields joints of considerable strength[1-3]. The equipment used for the mechanical vibration welding of wood in absence of an adhesive is the same type of equipment as used for frictional welding of metals. The figure below shows the characteristic linear vibrational movement of the type of industrial metal welding machine used as well as the frictional shift and force applied to the two pieces of wood during welding.



Linear welding of wood can gives bonding results satisfying the relevant standards, while orbital welding gives much lower results. Some of the parameters that influence welding of metals with the same type of equipment also influence wood welding. Thus, the influence on the final bond of the vibration welding time, the contact holding time after the welding vibration had stopped, the welding pressure exerted on the surfaces, the holding pressure after the welding vibration had stopped, and the amplitude of the shift imparted to one surface relative to the other during vibrational welding are of importance. Welding frequencies of 100 Hz are used. The newer techn,ology uses 150 Hz. The joint tensile strength depends on vibration amplitude, showing some good bond strength for 3mm vibrational amplitude. The joint tensile strength depends on welding pressure, values of 2 to 2.3 Mpa giving the best results. The joint tensile strength depends on welding time, but less markedly than on welding pressure. In general combinations of 1.5 to 3 seconds welding time and 4-5 seconds holding time give strong joints presenting strength in excess of 10-12 MPa and sometime of the order of 15 MPa . The relevant European Norm for these types of joints requires strengths equal to or higher than 5 MPa.

The strong joints obtained are not capable of satisfying specifications for exterior joints as they show very poor resistance to water. These joints can then only be considered for interior applications such as for furniture and for interior grade wood joints. Furthermore the technique at this stage is only usable for solid wood joints and perhaps joints between premanufactured panels presenting the same type of characteristics as solid wood, such as oriented strand board (OSB). The technique constitutes however has considerable interest for its low cost and in the implementation of totally environment friendly wood joints in joinery and furniture manufacturing.

The mechanism of mechanically-induced wood vibration welding has been shown to be due mostly to the melting and flowing of some amorphous, cells-interconnecting polymer material in the structure of wood, mainly lignin, but also hemicelluloses. This causes partial detachment, the "ungluing" of long wood cells, wood fibres, and the formation of a fibres entanglement network in the matrix of molten cell-interconnecting material which then solidifies. Thus, a wood cells/fibres entanglement network composite having a molten lignin polymer matrix is formed. Scanning electron micrographs show the detail of the type of composite formed in the bondline of a solid wood joint.

During the welding period some of the detached wood fibres which are no longer held by the interconnecting material are pushed out of the joint as excess fibres. Cross-linking chemical reactions also have shown and confirmed to occur (the most likely one of these identified by NMR appears to be a cross-linking reaction of lignin with carbohydrate-derived furfural and furfural self-polymerization. These reactions, however, are relatively minor contributors during the very short welding period. Their contribution increases after welding has finished, explaining why some holding time under pressure after the end of welding contributes strongly to obtaining a good bond.

Rotational Dowel Welding

High speed rotation-induced wood dowels welding, without any adhesive, is shown here to rapidly yield wood joints of considerable strength. The mechanism of mechanically-induced high speed rotation wood welding is shown here to be due, as already observed in vibration welding, to the temperature-induced softening and flowing of some amorphous, cells-interconnecting polymer material in the structure of wood, mainly lignin, but also of hemicelluloses and consequent high densification of the bonded interface. Wood species, relative diameter differences between the dowel and the receiving hole, and pressing time were shown to be parameters yielding significant strength differences; while relative orientation of the fibre grain of the dowel in relation to the fibre grain of the substrate, relative rate of rotation within a limited range and the use of rough or smooth dowels did not have any significant influence. The welded contact area is sufficient to yield strength results comparable to or even slightly higher than that obtained by PVAc adhesive bonding.

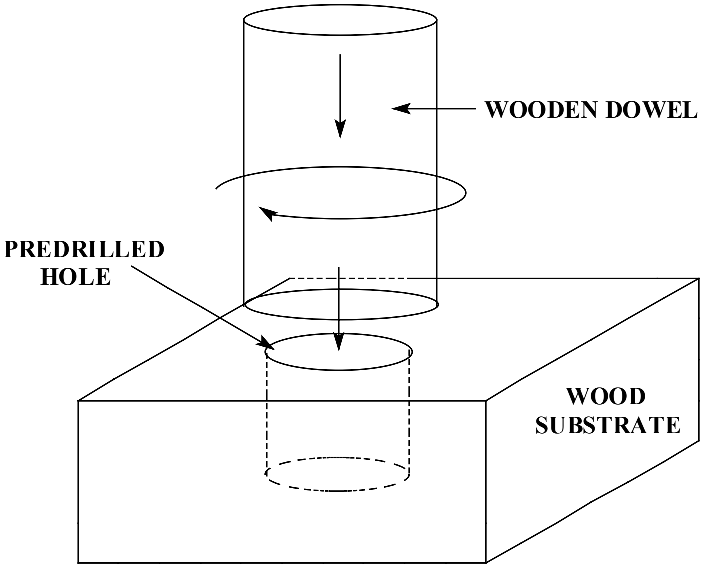


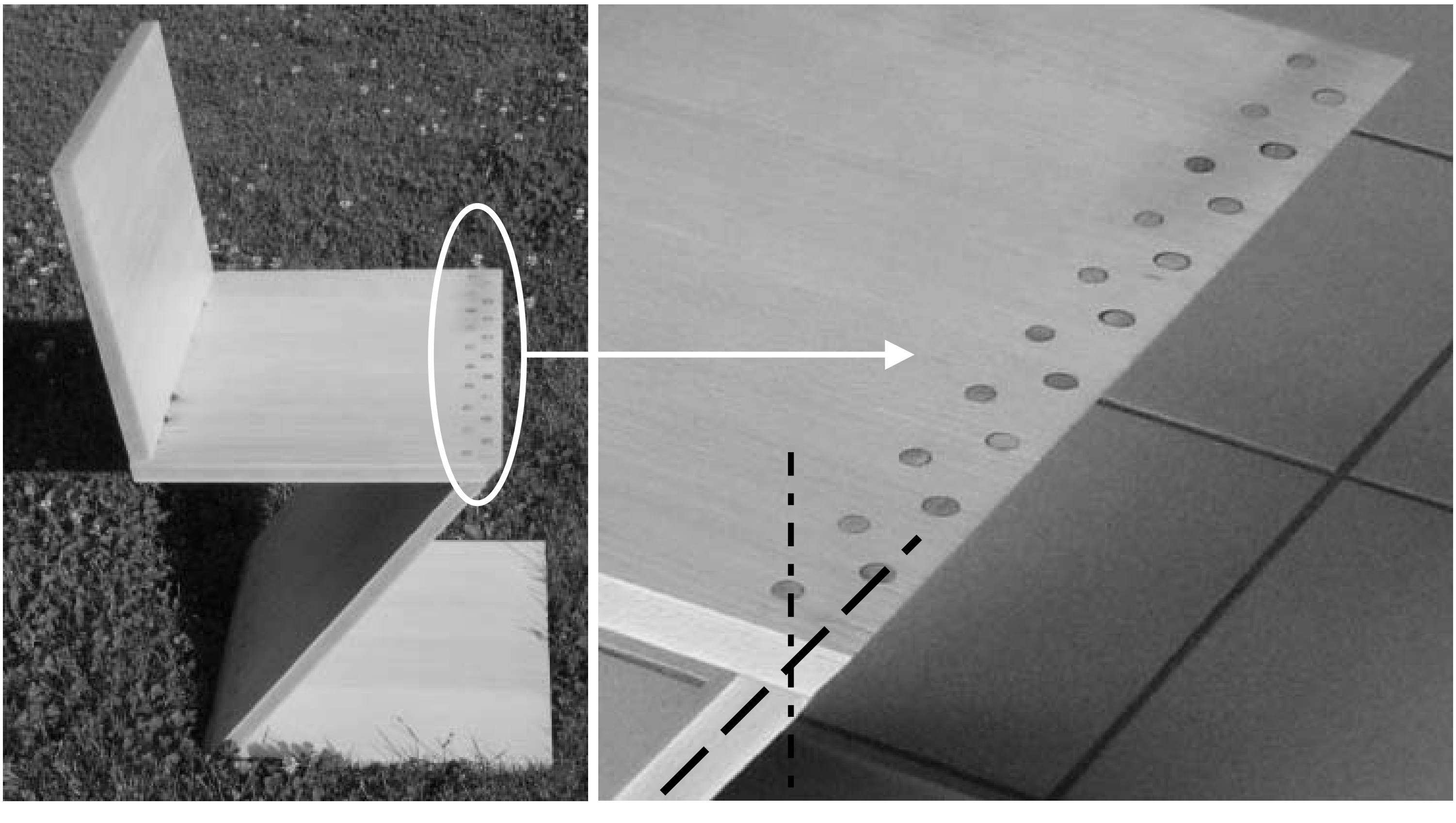
Table 2. Average tensile strength results for dowels inserted to 20 mm depth in single beech blocks, tested dry and after 24-h cold water soak, and comparison with PVAc glued dowels

	Dry (N)	24 h cold water soak (N)
Welded dowels (*a*)	1979 ± 103	1746 ± 153
PVAc-glued dowels(*b*)	1844 ± 177	1286 ± 224

*a*After 3 s welding.
*b*After 24 h clamping.

High-speed dowel rotation welding was used to manufacture a full-scale 400x400x22 cm raised access floor, hence an applicable civil engineering structure, to demonstrate that scaling up of the welding technique is feasible. This was coupled with obtaining a more light weight floor assembly at equal stiffness by maximizing the rigidity of the suspended floor while minimizing the number of timber boards used to build it, and maintaining its vibration frequency high and its level of vibration low. Several assembly and connection combinations of two and three boards linked through welded wood dowels were tried to determine the resistence of the cross-over joints that had to be used in the building of the floor. Deformation under 4 points static load of the floor was carried out to determine displacement under load and the floor vibration behaviour was determined by the use of accelerometers. The fundamental first natural frequency measured does satisfy well the requirements specified by Eurocode 5.

The application of recently developed rotational dowel welding techniques (Pizzi et al 2004, 2006, Kanazawa et al 2005, Ganne-Chedeville et al 2005, Bocquet et al 2007) can be applied to the manufacture not just of normal furniture but also of furniture that otherwise could have not been manufactured without metallic or other special supports. The example at hand and presented here is the minimalist chair devised by dutch architect Gerrit T. Rietveld (1888-1964). For the first time it was possible to build this type of chair without neither metallic nor angle supports, by just using rotationally welded wooden dowels and presenting a clean angle joint.



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