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FRONT COVER
Garofalo, *Saint Augustine with the Holy Family and Saint Catherine of Alexandria* (NG 81), (detail of PLATE 4, p. 23).

TITLE PAGE
Garofalo, *The Virgin and Child with Saints William of Aquitaine, Clare (?), Anthony of Padua and Francis* (NG 671), (detail of PLATE 3, p. 22).

The Mechanical Behaviour of Adhesives and Gap Fillers for re-joining Panel Paintings

CHRISTINA YOUNG, PAUL ACKROYD, ROGER HIBBERD AND STEPHEN GRITT

The primary aim of this research is to study the behaviour of adhesive/filler mixtures used to re-join thin panels that may subsequently move as a result of changes in the external environment. Moisture uptake and loss in panel paintings lead to expansion and contraction of the wood, and further change in the curvature of each section of panel is often associated with this dimensional change. If the panel is constrained by a cradle or framing system, then splits in the wood and separation or failure of the panel joints can occur. Joints and old repairs in the wood are often the weakest points in the support and are the most likely sites for failure.

The installation of air conditioning, resulting in more stable environmental conditions, has made this kind of damage to the panels less frequent for paintings within gallery collections. However, the National Gallery contains a considerable number of paintings on wood and a good deal of time is devoted to reducing the vulnerability of these objects to possible damage caused by climatic changes. Furthermore, many paintings treated by conservators – for example those treated at the Courtauld Institute of Art by the authors of this study – return to uncontrolled environments, such as churches. It is therefore important to re-examine the properties of adhesives and gap fillers that are commonly used in the structural treatment of panel paintings.

The most appropriate structural conservation treatment for a panel painting will depend on the nature of the damage, the type of wood and panel construction, the surrounding ground and paint layers, and the environment to which the painting is likely to return. In general, for situations where there are hairline cracks or where two parts of a panel can be brought back into immediate contact, a thin line of adhesive is introduced. If wood has been lost, or removed, or if large deformations have occurred, it may not be possible to fit the individual planks back into their original configuration and hence gaps may be present. In cases where the split or gap between adjacent panels is large (greater than 1 mm) it is necessary to re-join the panels with an adhesive bulked with filler. In many cases, the adhesive/filler mix serves to fill the void (possibly including worm holes) and hold the panels together as a single structural entity. Usually, after treatment, the panel will be mounted in such a manner as to support its weight and allow a certain degree of free movement of the wood with the aim of preventing further damage. However, most systems introduce some restraint, even if minimal.[1] Constraint primarily induces a bending force on the panel joints, although tensile and shear forces may occur because of uneven distortion within the panels (see Appendix). Similar forces can also occur during the handling of unsupported panels.

In some cases a damaged panel painting will have partial cleavage of a joint with original paint covering the undamaged section. It is preferable not to cause separation of the joint with consequential damage to the original paint. Thus, realignment and repair of the cleaved section may be constrained by the original joint and surrounding wood. In brief, if treated panels change dimensionally or geometrically, tensile, compressive, shear and bending forces can be exerted on the joints and hence on the filled gap.

The ideal joint

In general, manufacturers' data for adhesives show that shear strength is higher than the peel strength.[2] Hence, the strongest type of joint is a lap joint that puts the adhesive in shear when forces act on it and minimises peel at the edges of the bond (FIG. 1). The length of the glue line in a lap joint is increased so that most of the adhesive will be elastically rather than plastically deformed to ensure minimal permanent deformation.[3] Adhesion is dependent on both the chemistry and the surface texture of the surfaces to be adhered. Surface preparation to eliminate weak boundary layers is important, and for good adhesion the surfaces of the materials to be joined must be free of loose layers and, ideally, provide a 'mechanical key'.

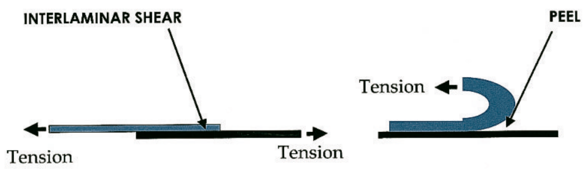


FIG. 1 Diagram of shear and peel forces.

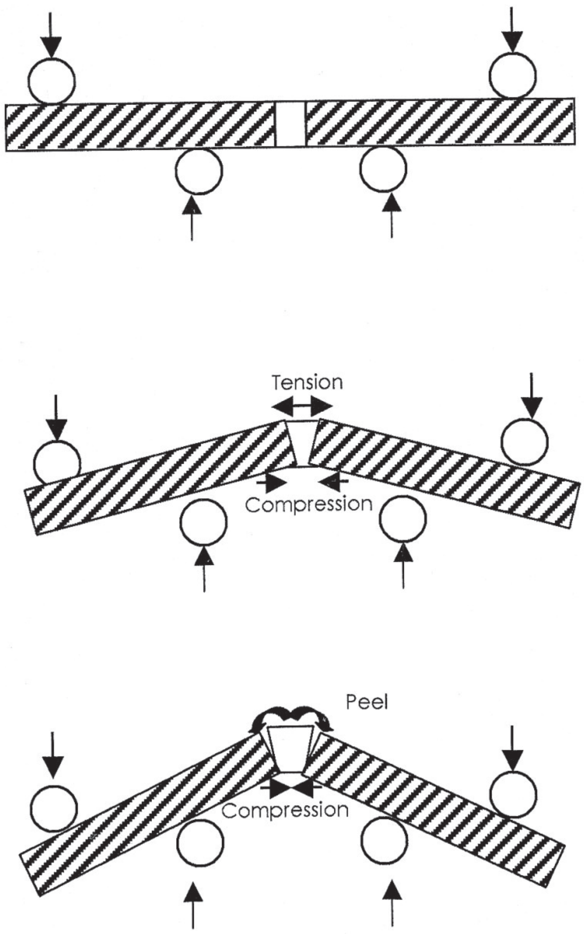


FIG. 2 Diagram of tensile and compressive forces on joint.

In contrast to this ideal practice, most European panels of the Renaissance and Baroque periods were originally constructed of several planks that were simply glued and butt jointed and sometimes reinforced with dowels, fabric strips or battens.[4] The bonding edges have small surface areas in relation to the size and weight of the individual planks and hence the joint will be highly stressed. In the case of a simple butt joint on a restrained panel painting, bending will create peel forces at the edges of the joint, tensile on one side and compressive on the other (FIG. 2). There may also be shear forces acting if one side of the join is restrained relative to the other. The actual contribution from each force will depend on the movement of the wood surrounding the joint. The wood around the join can be severely degraded at the edges by worm damage, fungal attack, splintering, fatigue and remnants of old adhesive from previous treatments. Some of these factors reduce the strength and elasticity of the wood and will affect re-adhesion. Thus, this type of join is far from ideal. As a minimally invasive approach is a desirable criterion for treatment, modification or removal of the original wood to provide a better bond design is not an option.

The ideal adhesive

The mechanical properties of the adhesives required for panel painting conservation will vary from case to case. However, in general the following criteria apply:

- The peel and shear strength should be commensurate with, but not stronger than, the wood surrounding the joint, so that there is a low risk of causing failure within the original panel. This is counter to the normal criteria for adhesive selection for structural applications.
- The elastic modulus should be high enough so that the adhesive is loaded below its yield stress. At the same time, the adhesive should be sufficiently flexible to allow the panels to respond to the environment without a build-up of stress around the joint. In practice, the balance between elastic modulus and flexibility is hard to achieve.
- Under continuous load, creep should be minimised.
- The adhesive should fail in a ductile manner and be resistant to rapid crack growth.
- It should have a good ability to wet the surface of the wood.
- It should possess good handling and curing characteristics, in particular, an adequate working time, without an unduly long curing time. (There may be a conflict between handling characteristics and good wetting properties.)

The ideal filler

Ideally the adhesive/filler mix will be a homogeneous mixture. The filler serves a number of functions when mixed with the adhesive. In handling, it bulks out the adhesive (increasing the viscosity) to give a stiff paste, which helps to prevent the materials from flowing out of the gap during application or curing. It reduces the percentage shrinkage when added to adhesives with a volatile component. Additionally, it allows the cured mixture to be sanded or carved and provides a surface that will accept either a simple surface fill or the direct application of retouching media. The filler will also affect the mechanical properties of the cured adhesive, altering its cohesive strength and modulus. The actual values will of course be dependent on the ratio of filler to adhesive and it should be possible to alter the ratio to suit a given application. Hygroscopic fillers may allow the joint to contract or expand with varying relative humidity. If the sensitivity differs greatly from that of the adjoining panel then this will set up internal stresses that can lead to failure. It is perhaps preferable that the filler is inert and that the adhesive accommodates hygroscopic movement in the original wood.

The structural, and hence the mechanical, properties of the filler mixture are essentially the same as those for an ideal adhesive. The final mixture should also meet basic criteria for conservation materials, that is, it should be:

- inert to humidity and temperature change, in terms of stiffness, strength, and resistance to fracture
- reversible
- physically and chemically stable in both the short and long term
- resistant to fungal and bacterial attack
- non-toxic

The choice of adhesives and fillers to be studied was based on issues arising from treatments of panel paintings carried out in the conservation studios of the National Gallery and the Courtauld Institute, and also upon conversations with conservators who regularly repair panel paintings.[5] The rationale behind a given conservator's preferred system comes from many years of practical experience and from observations of the treatment of failed repairs. In practice, panels may require treatments for a combination of different problems, such as checks or splits along the grain, failed joints with varying gaps and worm damage. The same adhesive may be used for each type of failure but with varying amounts of filler. It became clear during the discussions that conservators used and modified their chosen filler mixtures but could not objectively assess how the type or quantity of filler affected the mechanical properties of the adhesive. The handling properties were key criteria when choosing their systems; also important was any technical information that could be obtained from the literature. The data available from manufacturers of adhesives is based on standard (ASTM) tests that satisfy the criteria for engineering applications. However, these are not directly applicable for panel painting joints. Furthermore, the literature on adhesives with fillers is minimal.

Although there are publications in the conservation literature outlining the practical problems of re-joining panel paintings and listing the equipment devised to assist in the processes, there is little information on the technical performance of the adhesives employed for this purpose.[6] A great deal of published information on wood adhesives is available from the timber industry but this tends to concentrate on the fabrication of composite boards, such as blockboard and plywood, or the gluing of joints in modern furniture. Some of this information is useful in understanding the general behaviour of certain adhesives but it has limited relevance to the conservation of easel paintings and other wooden artefacts.[7]

The adhesives that have been employed in conservation range from traditional natural materials, such as animal or fish glues and casein adhesives, to commercially manufactured synthetic resins: polyvinyl acetate emulsions (PVA), urea formaldehyde (UF), and epoxy resins.

Animal skin and bone glues have been used for centuries in the construction of many wooden objects, including easel paintings, and continue to be employed in their repair.[8] In the National Gallery's collection there are panel paintings with original joints, made with animal glues, which remain intact even after five hundred years or more. These are a testament to the durability of the materials within certain limits and their long-established record of performance is one of the prime reasons why they continue to find favour. Another reason is that they remain reasonably reversible, unlike the synthetic products. Their drawbacks, however, are also well established: they are prone to attack by fungi, bacteria and insects; their mechanical and adhesive properties alter according to fluctuations in humidity; traditional preparations have uncomfortably short working times because they are normally applied hot and the increased viscosity on cooling makes them difficult to handle.

Other natural adhesives, such as fish glues and casein glues, were not tested in this study. Fish glues, although they share similar disadvantages to animal glues, are thought to impart greater flexibility and since commercially prepared formulations remain liquid at room temperatures they have better handling properties. However, because of their limited use as gap-filling adhesives they were not included in these trials. Casein glues have a long history of use as woodworking adhesives, and are still employed in panel painting conservation in Italy and Germany.[9] They are less reversible than animal glues and remain, to some degree, sensitive to environmental change.[10]

PVA resins were first proposed for the structural conservation of museum objects in the early 1950s and a variety of these commercially prepared adhesives have since been used for the structural repair of panel paintings as well as other wooden artefacts.[11] The National Gallery uses Evostick Resin W. Generally, these materials have good working properties and give strong adhesive bonds that are thought to impart some flexibility to the join. Dried PVA emulsions may be swelled with water, particularly with the addition of ethanol, but in the case of easel paintings, these solvents are likely to damage the surrounding paint and ground layers and swell adjacent wood.[12] Also, because they are difficult to remove mechanically from a tight joint, they are in effect irreversible. Ageing studies have been carried out on several types of PVA woodworking adhesives which have shown a tendency towards increasing embrittlement, yellowing and reduced solubility under heat and light ageing.[13]

UF resins have been used as adhesives for wood conservation since the late 1940s and as consolidants from the early 1950s.[14] A UF resin, Extramite, has been used by the National Gallery Conservation Department for panel repair. This is a commercial wood-bonding adhesive, which is designed to provide a strong waterproof bond. It is applied in an aqueous form and, once cured, it is insoluble in solvents and is difficult to remove even by mechanical scraping.

Epoxy resins are the only other class of resin adhesives to have been commonly used for panel painting conservation. Since they provide strong joints with a variety of substrates, and have been shown to have some good gap-filling properties when used with an appropriate filler, they have been widely adopted in the conservation field, not only as adhesives but also as consolidants.[15] First mentioned in the conservation literature in 1952, they were subsequently investigated for repairing panel paintings in 1954 by Arthur Lucas and Norman Brommelle at the National Gallery.[16] That investigation concluded that traditional animal glues were better suited for the purpose on the grounds that they possessed better handling properties and were more reversible. Since the mid-1950s an improved range of epoxies have become available and have been applied to a large range of museum objects. Studies on the effects of ageing on epoxies have expressed concern over the pronounced yellowing of these resins on exposure to heat and light.[17] This is of considerable concern when they are employed as consolidants for ethnographic and archaeological objects, where they are likely to remain visible on the surface, but is a lesser concern when re-joining panel paintings as the resin is not exposed at the picture surface. Some cured epoxy resins can be swelled by solvents, but such solvents are likely to damage paint layers and, as is the case with the other synthetic wood adhesives, they are difficult to remove.[18]

Barclay and Grattan's work on fillers for wooden artefacts gives valuable information on some of the properties of adhesives and gap fillers.[19] The results are pertinent to the materials used for treating easel paintings, but the aims are not directly applicable to re-gluing panel joints with gaps. Normally, gap fillers for ethnographic objects and wooden sculptures do not function as an integral part of the structural repair, as they do in re-joining panels, but are simply intended to fill losses in the surface. A variety of filling materials both natural and synthetic have been used in panel paintings conservation. Natural materials, such as chalk, wood dust, cellulose powder, rye flour and coconut fibres, have been favoured, although glass beads and glass or phenolic microballoons may be used with epoxy resins to improve their gap-filling properties.[20]

The focus of the study presented here is to understand how thin wood panel joins repaired with gap fillers behave where some constraint to movement is present. In addition, the behaviour of hairline joints under the same circumstances is assessed.

Experimental procedure

A four-point bend test was chosen as it provides a controlled method of exerting a constant bending moment on a panel joint.[21] Both the joint itself and the wood either side of the joint experience the same bending moment (see Appendix) and hence it is possible to ascertain whether the filler or the wood fails first for the same bending force. The test also allows one visually to inspect the peel action of the bond at the edges and the nature of the failure. The load at which the joint fails demonstrates the 'practical' properties that might be expected for each adhesive and type of filler in a real situation. The strength and flexibility of the joint, the nature of the failure modes (shear, peel, tensile, compressive), and whether the failure is cohesive or adhesive,

TABLE 1 Adhesives

Hide glue: proteinaceous aqueous glue
Standard concentration for this application:
20g hide glue in 100ml of warm water

PVA: non-waterproof Evostick Resin W Polyvinyl Acetate Emulsion [23]
Standard concentration: direct from the bottle

UF: Humbrol Extramite.[24] Contains approximately 5% China clay and wood flour. Designed to give gap-filling properties up to 1 mm without any additional filler.
Standard concentration:
1 part Extramite, 2 parts water by weight

Epoxy: Araldite 2014. A grey epoxy paste [25]
Manufacturer's data: lap shear strength on aluminium at 18°C 25 N/mm2. Peel strength on aluminium at 23°C 3 N/mm
Standard concentration:
2 parts resin, 1 part hardener by volume

TABLE 2 Fillers

Rye flour: Neil's Yard Healthfoods organic

Wood flour: Sieved National Gallery wood dust

Cellulose powder

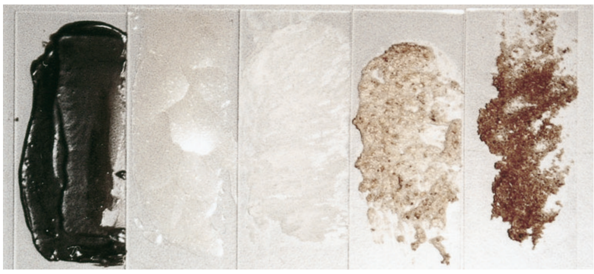
Coconut flour: Imported broken coconut shell. Particle size 150–3 microns

Microballoons. SP Systems hollow phenolic resin spheres. Particle size 50 microns. (Not normally used with polyester or vinylester resins because they can be subject to styrene attack which may cause the spheres to collapse.)

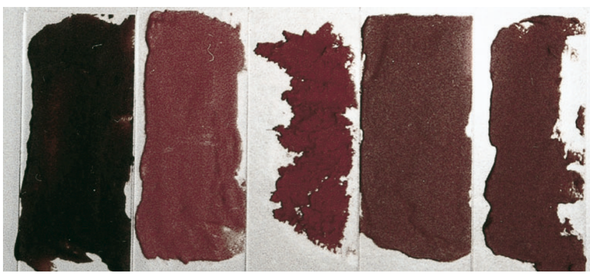
can all be assessed using this test.

Standard ASTM testing procedures have not been adopted as they do not represent the loading conditions of a wooden panel with a simple butt join. For a complete understanding, separate tests on the adhesives and fillers are also required.

PLATE 1 Filler mixtures after curing.



Araldite 2014 | Extramite: water 20g: 10ml | Cellulose powder: Resin W 2.09g: 5ml | Rye flour: Resin W 0.71g: 5ml | Wood floor: Resin W 0.91g: 5ml



Coconut flour: Resin W 1.28g: 5ml | Microballoons: Resin W 0.63g: 5ml | Microballoons: Resin W 1.27g: 5ml | Coconut flour: Microballoons: Resin W 1: 1 (0.78g): 5ml | Coconut flour: Microballoons: Resin W 1: 1 (1.37g): 5ml

Sample preparation

The test samples were chosen to represent panel joints with both hairline cracks and large voids or ill-matching joins where a filler is required to bulk out the gap. The panel samples were constructed from 5 × 50 × 50 mm naturally aged oak blocks, all approximately radially cut from a single piece of oak, and are representative of some Netherlandish and Dutch panel paintings. All joints were made with the growth rings parallel to the join. The adhesive and fillers used are listed in Tables 1 and 2 and the adhesive/ filler combinations tested are listed in Table 4. An empirical guide to their handling and carving properties is also included in this last table.

Adhesives were used in standard concentrations, as indicated in Table 4, and each filler mixture was added to 5 ml of adhesive dispensed from a syringe. Sufficient filler was added to produce handling properties ranging from a stiff and workable paste to a less viscous mixture which had some degree of flow. PLATE 1 shows the filler mixtures after curing. The amount of filler added was calculated by weight. Low-tack Scotch Tape was attached to the edges of both surfaces of each wooden block (FIG. 3). This prevented penetration of the adhesive into the faces of the wood. An additional strip of tape was attached to each pair of blocks on the underneath faces to align them 2 mm apart. This also prevented loss of adhesive and any excess seeping out of the join when using low-viscosity mixtures. In all samples the adhesive was first brushed along the edges to be adhered to improve wetting of the surfaces. This priming adhesive was applied in the normal concentration except in the case of the Resin W where a dilution of 5 ml water to 2 ml

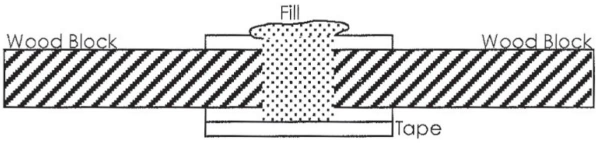


FIG. 3 Diagram of sample preparation.

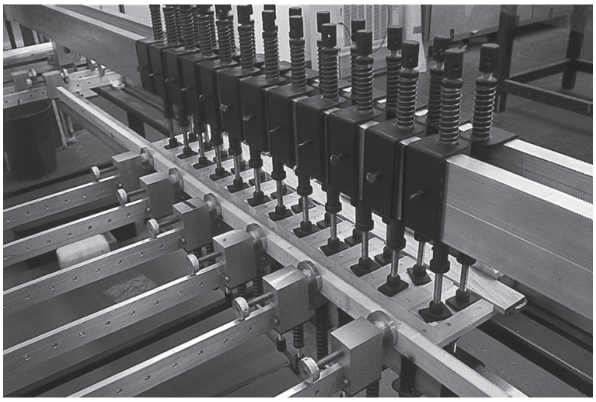


FIG. 4 Photograph of Teflon jig in gluing jig.

Resin W was used. The blocks were then clamped in a Teflon jig to maintain alignment (FIG. 4). A palette knife was used to apply the mix so that the gap was overfilled. After 24 hours the blocks were removed from the jig and the additional tape across each pair of blocks peeled away. The blocks were placed upside down and left to ensure complete curing of the adhesive. Excess filler was pared away carefully with a chisel and the protective tape removed. In some samples it was found that air bubbles formed beneath the excess filler. These corresponded to the samples with the greatest initial quantities of water, such as the low viscosity Resin W filler mixtures. Blocks were conditioned at 55% RH and 20°C for a minimum of two weeks before testing. For comparison samples were made with 2 mm gaps filled with adhesive without the addition of filler (see Table 3). With the exception of the Araldite paste, in practice the low viscosity of a pure adhesive is unsuitable for this application and good fills were hard to obtain.

TABLE 3 List of Pure Adhesive Joins

5ml of adhesive	Gap size
Hide glue	Hairline
Extramite	Hairline and 2 mm
Resin W	Hairline and 2 mm
Araldite 2014	Hairline and 2 mm

Samples of each pure adhesive in the standard concentrations were also prepared to produce a thin glue line in a hairline joint (see Table 1). The wooden blocks were prepared as described above and the adhesive applied to both surfaces of the join. The samples were laterally clamped together in the Teflon jig and further clamps were placed directly on top of each block to ensure good alignment across the join. After 24 hours the samples were removed from the jig, the tape peeled away and excess adhesive pared away with a scalpel.

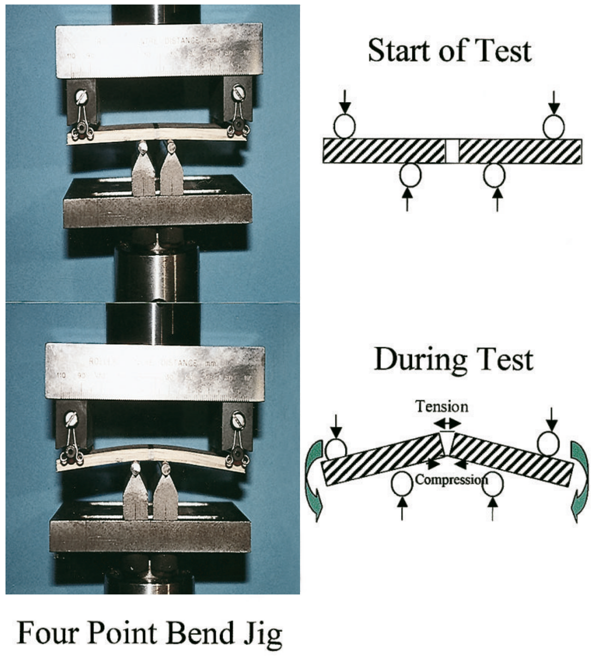


FIG. 5 Photograph of Instron and four-point bend jig.

Tests

The bending tests were performed on an Instron 4301 test machine at 55% +/- 3% RH and 20 +/- 2°C. The four-point bend jig consisted of two sets of rollers, one set fixed to the lower static crosshead of the test machine and the upper set attached to the top-moving crosshead (FIG. 5). The top and bottom rollers were at different separations (100 mm and 150 mm). The samples were supported on the bottom rollers of the four-point bend jig. The moving crosshead was then lowered at a speed of 2 mm/min, so that the upper rollers pressed down on the top face of the sample, creating a bending moment. The displacement of the top rollers, the compressive force, the temperature and relative

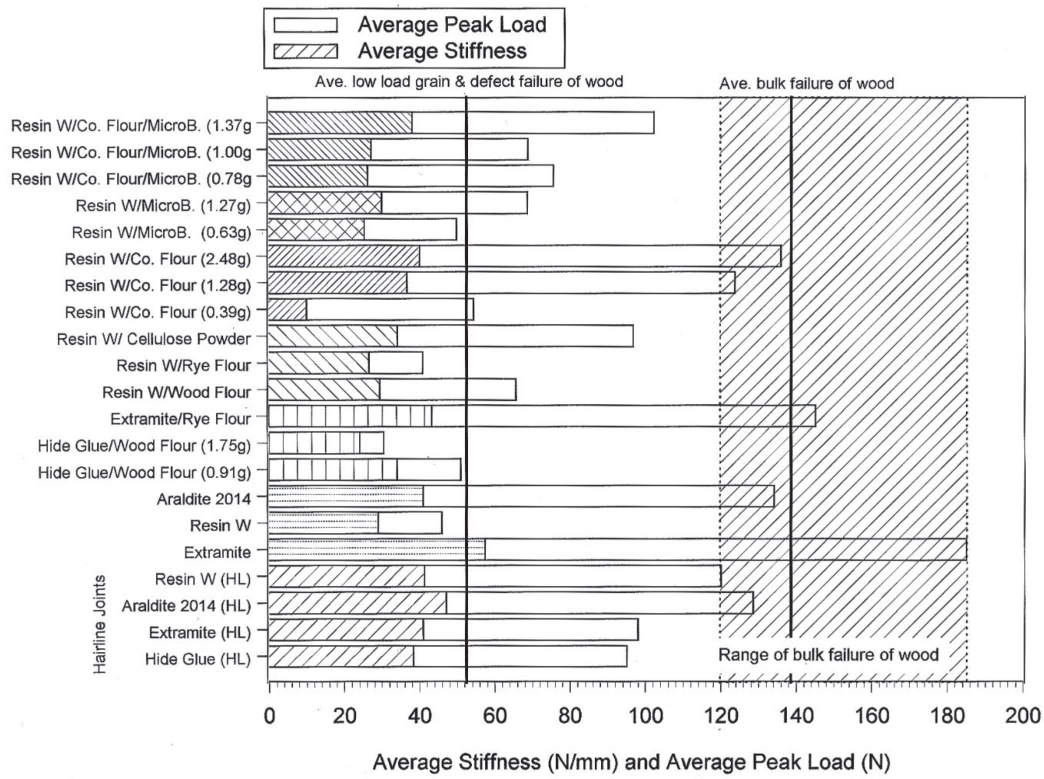


FIG. 6 Summary bar chart of peak bending loads and stiffness.

humidity were logged during the test. A CCD camera with 50 mm macro lens and fibre optic illumination was used to capture real-time video of the tests. The video was used to confirm the mode of failure and aid in the post-failure analysis.

Results

Depending on the ease at which good-quality joints could be repeated for each type of adhesive/filler between three to eight samples were tested. A summary of the results is given in FIG. 6. This gives the average stiffness and peak loads at bending failure for all the samples. The stiffness of the samples was calculated by taking the gradient of the initial linear section of load-displacement curves. For some of the very flexible adhesives, it is not possible from these tests to distinguish the transition from elastic to plastic deformation (the yield point). There was no distinct linear region of the load-displacement curve and so the measurement of stiffness is less reliable.

In a number of tests failure occurred in the wood at a very low load, usually along the grain and close to one of the rollers. This indicated that there was an inherent weakness or defect at such points and so the measured stiffness did not necessarily represent the true stiffness of the wood or the adhesive. These results have therefore not been included in the analysis. The averaged peak load for this type of failure is 53N and is shown in FIG. 6 as a vertical line.

For samples where the wood failed at high loads, away from the joint in the bulk of the wood, the stiffnesses have been calculated and included in the average for each type of joint. The averaged peak load for this type of wood failure is 139N and is shown in FIG. 6 as a vertical line. The range of these values is shown as a shaded region.

For samples where failure occurred along the adhesive interface with the wood (adhesive failure) or within the body of the adhesive (cohesive failure) the stiffness and peak load values have been calculated and averaged for each type of joint. These values are shown as a bar chart in FIG. 6. Wood 'removal' is indicative of damage to the wood at the wood/adhesive interface. Such damage will have occurred if any wood is visible on the fracture surfaces of the adhesive.

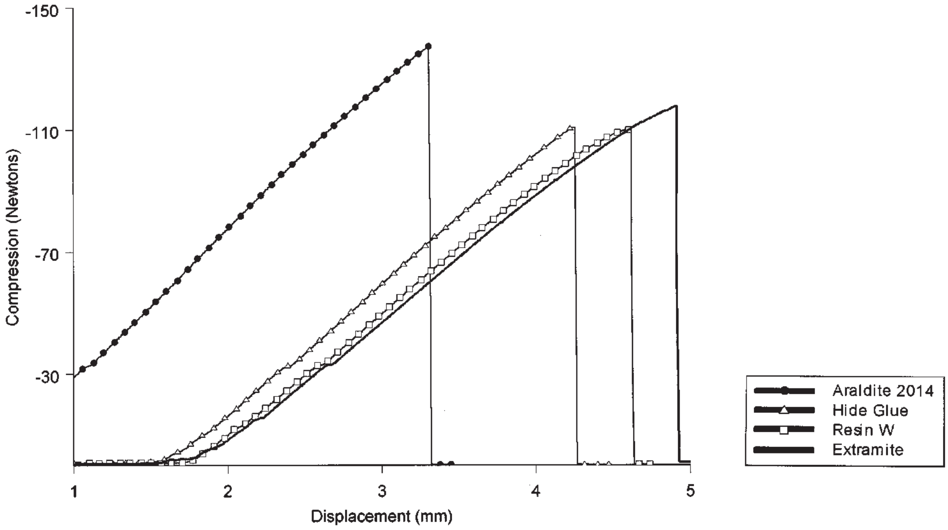


FIG. 7 Typical load-displacement curves for pure adhesives with hairline joints.

Hairline joints

Pure adhesives

Typical load-displacement curves for these tests are given in FIG. 7. In a hairline joint the adhesive layer is very thin and therefore any flexibility within the elastic region of the adhesive should make a negligible contribution to the change in the stiffness of the sample. Thus, for a good-quality joint the measured stiffness of the sample may be considered to be the same as a continuous piece of wood. In the case of Extramite and Araldite 2014 the wood failed before the joint and hence the stiffness for the wood was calculated from the low load gradients of these joints. These gave a value of 41 Nmm^{-1}; this stiffness is equivalent to a Young's Modulus 0.98 GPa which is relatively high for an oak stiffness modulus (typically 0.6 to 1.1 GPa) taken across the grain.

Araldite 2014 is designed as a strong structural adhesive and as expected the wood failed in all the Araldite samples. In two out of the six samples the fracture appeared to have initiated at the adhesive interface and then ran into the wood. In the four other samples the wood failed away from the joint, leaving it intact with no sign of cracking. The tests of the Extramite joints all resulted in brittle cohesive and adhesive failures and in all cases there was

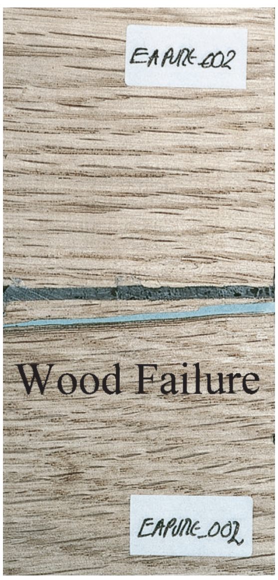


PLATE 2 Failed joint – Araldite 2014.

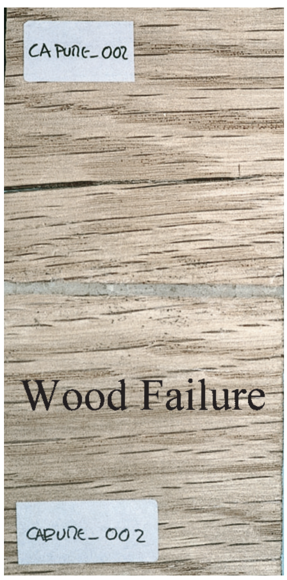


PLATE 3 Failed joint – Extramite.

wood damage at the adhesive/wood interface. The overall stiffness was also commensurate with that of the wood.

Resin W samples had an average stiffness of 38 Nmm^{-1} and an ultimate strength below that of the wood. Failure modes were the same as for Extramite. Post-failure inspection of the Resin W joints showed an inconsistent glue line between samples that was evident in the wide range of peak failure loads. It is likely therefore that the lower stiffness was a result of the non-continuous glue layer between the samples. The hide glue joints resulted mainly in brittle adhesive failure at an average value of 85N and a stiffness of 38.5 Nmm^{-1}. Inspection of the fractured surfaces showed consistent joints (confirmed by the narrow range of failure loads) with good wetting resulting in small amounts of wood removal at the interface. The lower stiffness values may result from yielding and failure of the glue at an early stage in each test. Resin W and hide glue gave the most flexible joints with fracture occurring in the joint rather than in the body of the wood. However, in both cases wood damage occurred.

2 mm filled-gap samples

Pure adhesives

As would be expected, the pure adhesive-filled gaps produced very uneven joints with the exception of the Araldite, which is designed as a combined filler and adhesive. It was not possible to produce 2 mm wide joints with pure hide glue. Despite the poor quality of the joints, the samples were tested in order to make comparisons. The Resin W had significant gaps in the joints and failed cohesively at relatively low loads of 30N and 61N. Given the poor joints, it was difficult to achieve a reliable stiffness measurement but a value of 29 Nmm^{-1} was recorded in one test. Araldite produced good-quality stiff joints (41 Nmm^{-1}) where failure of the wood occurred in all cases: two away from the joint and one that began at the wood adhesive/interface but then moved into the bulk of the wood (PLATE 2).

The Extramite also produced very stiff joints, with effectively no change from the hairline joint results. Quality was low with gaps in the glue line and shrinkage cracks running across the joint after curing (PLATE 3). However, the adhesive in this type of failure was still stronger than the wood, and in all cases the wood failed first at a position away from the joint. One joint produced the highest load recorded in any of the tests.

Adhesives with fillers

Typical load-displacement curves for these tests are given in FIG. 8. In contrast with the pure adhesive, Extramite with rye flour did not develop shrinkage cracks on curing. Joints were consistently strong and with a stiffness similar to an unjointed panel. Failure of the wood occurred in all cases.

The hide glue/wood flour mixture produced consistent joints and results, probably because of the good wetting achieved. Stiffnesses were substantially lower than the hairline joints and the overall strengths were very low at an average of 30N. All the failures were adhesive and predominantly ductile.

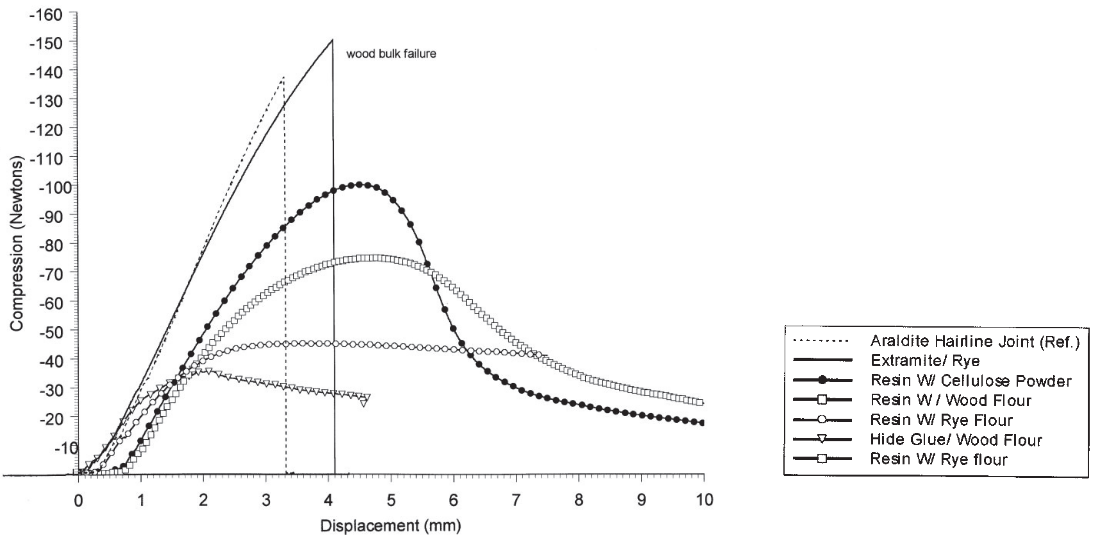


FIG. 8 Typical load-displacement curves for fillers with 2 mm gap.

PLATE 4 Failed joint – Resin W/Cellulose powder.

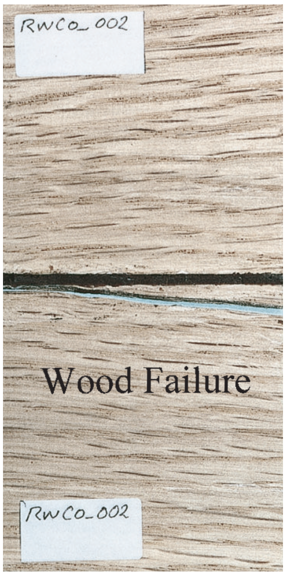


PLATE 5 Failed joint – Resin W/Coconut flour.

Resin W with wood flour had a low stiffness of 30 Nmm^{-1} with a low bending failure of 66N. The adhesive failure was cohesive and ductile occurring across the centre of the joint. Resin W with rye flour had even lower stiffness at 27 Nmm^{-1} and lower bending failure at 41N. As before, failure was cohesive and ductile within the joint. Resin W with cellulose powder gave inconsistent joints with higher stiffness of 34 Nmm^{-1} and a transitional ductile/brittle failure which removed wood from the interface (PLATE 4).

Resin W with 0.39g coconut flour had just sufficient bulk to produce a consistent joint. These particular samples had the minimum two weeks between construction and testing, whereas the majority of the samples had one month. Thus, it is possible that the stiffness values obtained are unrepresentative. The data sheet for Resin W recommends that the setting time should be between 1 hour and 24 hours under pressure at 20°C and 65% RH. However, this is assumed to be for a hairline join. In the case where the adhesive is being used in bulk the curing time must increase. Empirical observations show that Resin W hardens with age, and under artificial ageing there is a marked increase in stiffness. Further investigations are required to establish whether this is a continual process from initial application without a defined curing time. The stiffness value was very low at 10 Nmm^{-1}. The joints failed at an average load of 54N. Increasing the

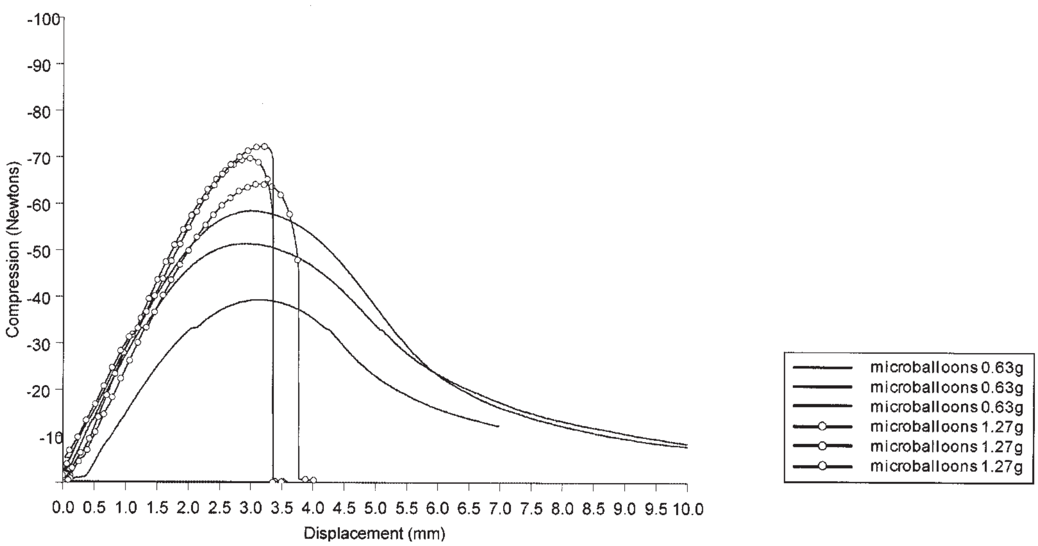


FIG. 9 Load-displacement curves for Resin W/Microballoon mixtures.

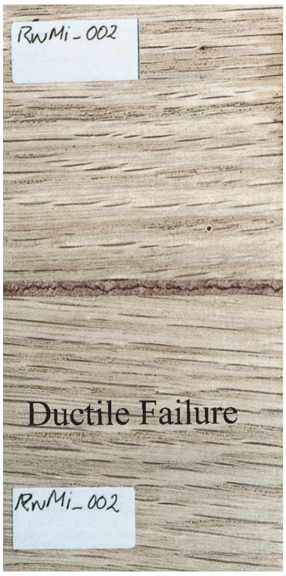


PLATE 6a Failed joint – Resin W/ Microballoons (0.63g).

PLATE 6b Failed joint – Resin W/ Microballoons (1.27g).

amount of coconut from 1.28g to 2.48g produced progressively stiffer joints (37 Nmm^{-1} and 40 Nmm^{-1} respectively). Strength also dramatically increased to averages of 124N and 136N. The results are comparable to the Araldite and Extramite/rye flour results and, as with these combinations, both Resin W/coconut filler mixtures resulted in failure of the wood rather than the adhesive (PLATE 5).

Resin W and microballoons gave joints that were very consistent and predictable. Stiffnesses were relatively low: 25 Nmm^{-1} for 0.63g /5ml of resin and 30 Nmm^{-1} for 1.27g/5ml. All failures were cohesive and occurred in the centre of the joint without removal of wood. As can be seen from the graph in FIG. 9, the 1.27g mixture results in a stronger joint (69N compared to 50N) that fails in a brittle manner. A photograph of the two mixtures shows (PLATE 6) the different form of the cracks for the ductile and brittle failure of the fillers. Employing the maximum workable quantity of filler produced a medium-strength joint.

Resin W with coconut and microballoons resulted in joints that were intermediate between those with the pure fillers. The joints were stronger and stiffer than those with only microballoons. Strengths ranged from 69N to 102 N and stiffness from 26 Nmm^{-1} to 38 Nmm^{-1}. As can be seen from the load-displacement curves in FIG. 10, all failures were within the joints, ductile at lower concentrations (0.78g/5ml and 1.00g/5ml) and brittle at the higher. The fractures were a mixture of

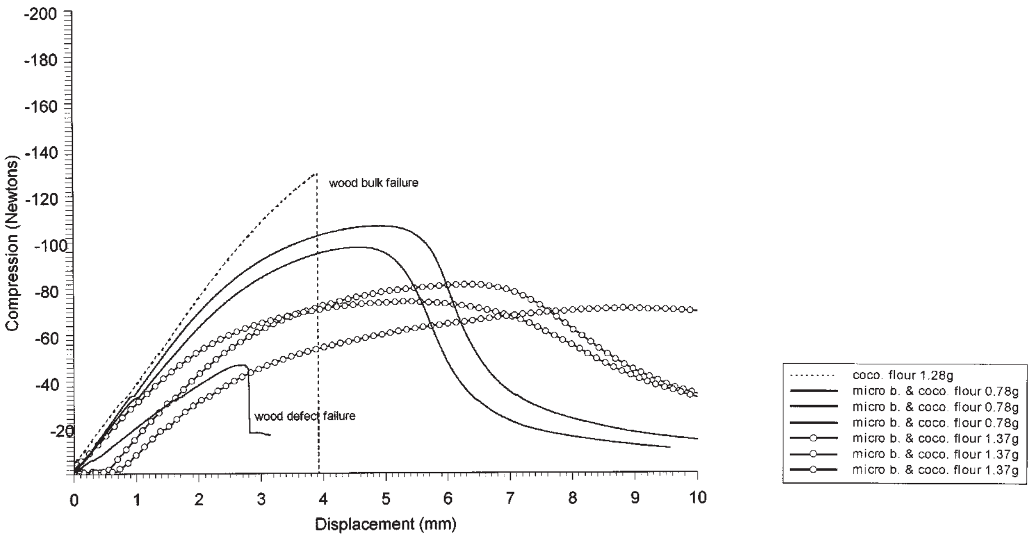


FIG. 10 Load-displacement curves for Resin W/Microballoon/ Coconut flour mixtures.

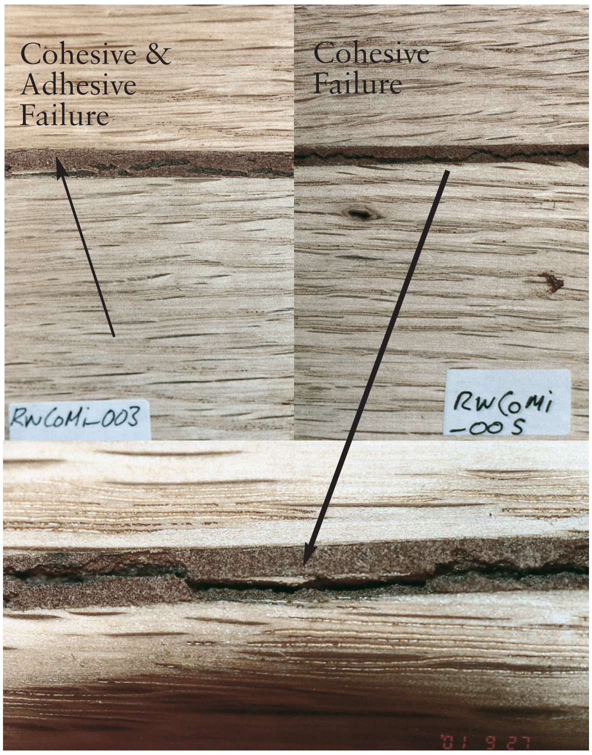


PLATE 7 Failed joint – Resin W / Microballoon / Coconut flour mixtures.

adhesive and cohesive failure (PLATE 7).

The handling and carving properties of the various adhesive filler/mixtures are quantified in Table 4. The best combination of both properties was found with Resin W with microballoons, coconut flour, and their mixtures. Some materials, for example Resin W with cellulose powder, handled well but were difficult to pare down after curing.

Conclusions

All the adhesives used in the hairline joints resulted in either bulk failure of the wood or some wood removal at the adhesive interface. The stiffnesses for all the adhesives were very similar. However, the ageing effects on Resin W and the influence of extreme humidity conditions on hide glue will alter their mechanical properties.

Araldite 2014, Extramite with and without rye flour, and Resin W with a high proportional of coconut flour were all stronger than the wood. They had equivalent stiffnesses to, or were stiffer than, the wood. If panel paintings conserved with these adhesives are then subject to bending loads, failure in the wood may occur.

Other epoxy resins used in conservation and in boat construction and repair are thought to have some of the appropriate properties, when combined with fillers such as microballoons or fibres. These are being investigated in the next stage of this work.[22]

TABLE 4 Adhesive/Filler Combinations

5ml of adhesive	Filler	Handling properties 1(poor)–5(good)	Carving properties 1(poor)–5(good)
Hide glue	0.91g Wood flour	2	2
Hide glue	1.75g Wood flour	1	2
Extramite	approx. 0.7g Rye flour	3	1
Resin W	0.91g Wood flour	3	2
Resin W	0.71g Rye flour	3	3
Resin W	2.04g Cellulose powder	3	2
Resin W	0.39g Coconut flour	2	3
Resin W	1.28g Coconut flour	3	5
Resin W	2.48g Coconut flour	5	4
Resin W	0.63g Microballoons	3	4
Resin W	1.27g Microballoons	5	5
Resin W	0.78g 1:1 Coconut flour: Microballoons	4	5
Resin W	1.00g 1:1 Coconut flour: Microballoons	5	5
Resin W	1.37g 1:1 Coconut flour: Microballoons	4	4

Hide glue with wood flour, Resin W with rye flour and Resin W with a low proportion of microballoons were weaker than the wood, even when it failed due to defects. The strength and stiffness of hide glue with wood flour depended on the amount of wood flour. All the hide glue-based joints failed adhesively at the wood interface while Resin W with wood flour joints failed cohesively within the adhesive. These fillers were much less stiff than the wood. They may be preferable, therefore, for very weak and degraded wood if the panel is not subject to large changes in relative humidity as this will alter the properties of the joints, possibly resulting in premature failure. If slightly stronger joints and stiffer joints are thought necessary the Resin W wood flour combination could be used, but the joint quality was variable and Resin W with microballoons and coconut flour gave more consistent joints with better overall handling and carving properties.

The hygroscopic nature of the filler mixtures has not been specifically addressed in this research. Materials such as wood, rye and coconut flour are likely to respond to moisture even within an inert mix. This could lead to contraction and expansion with changing moisture content, which could be considered beneficial if the response is similar to the panel. Conversely, the joint properties could change in such a way as to render the joint vulnerable to damage.

The Resin W mixtures with a very low quantity of filler invariably remove some wood at the interfaces. This is probably due to their viscosity, and hence their ability to wet the surface, which produces a very good bond with the wood fibres.

After testing, many of the Resin W samples creep back to an almost flat configuration. In some cases, partial reforming of the bond seemed to have occurred, requiring significant manual bending force to break the join. This supports the idea that the Resin W had not fully cured. Further work is needed to assess the curing and ageing properties of Resin W with fillers.

Mixtures of Resin W with coconut and microballoons can be tuned to give a wide variety of stiffnesses and strengths. Microballoons ensure failure within the joint. The coconut flour increases the strength and stiffness but should be used judiciously (if used in high concentration) as it can result in wood removal or wood fracture. Microballoons on their own can provide a consistent flexible join with a predictable cohesive failure. Cohesive failures where the fractures are entirely within the adhesive are less likely to lead to wood damage.

Suppliers

Araldite: Vantico Ltd, Duxford, Cambridge CB2 4QA
Extramite: Humbrol Ltd, Marfleet, Hull HU9 5NE
Resin W: Evode Ltd, Common Rd, Stafford ST16 3EH
Hide Glue: AP Fitzpatrick, 142 Cambridge Heath Rd, London E1 5QJ
Microballoons: SP Systems Ltd, St Cross Business Park, Newport, IOW PO30 5WU
Coconut flour: Hallmark Adhesives, Units 55 and 56, Hillgrove Business Park, Nazing Rd, Nazing, Essex EN9 2HP
Rye flour: Neal's Yard Health Foods, Neal's Yard, London WC2H 9AS
Wood flour: Sieved band-saw sweepings from the National Gallery Conservation Department

Appendix

Glossary of Terms in the Context of the Research

Peel strength The force required to peel apart (at a constant angle) two materials bonded by adhesive.

Shear strength The force required to cause separation in a plane parallel to the direction of tension for two materials bonded one on top of the other.

Bending force A force which by rotation about a fixed point in the material causes it to bend.

Ductile Used to describe a material which has a large amount of plastic deformation before failure.

Brittle Used to describe a material which has a very small amount of plastic deformation before failure.

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