Resin Bonded Timber Repair and the Preservation of Historic Timber Surfaces

A report on materials, construction and skills submitted by

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Contents

List of Illustrations

Sources as noted, except for:
[1] the author
[2] Zeuner (2003)
[3] Adams, Comyn and Wake (1984)

List of Tables

Synopsis

In considering the use of resins in the repair of historic structural timber, the conservation doctrine to use proven techniques has come into conflict with the need to retain historic fabric. Research and debate in this field continues unabated, with valuable developments in the materials science and by conservation organisations such as the Weald & Downland Open Air Museum. A resin-bonded timber repair method that preserves historic surfaces has been developed by the museum and forms the focus of this report: brevity prohibits the inclusion of comprehensive resin and timber material evaluations.

Assessment of the method was made against research performed primarily for new-build applications, but, with cautious adaptation and reliance on a small number of published papers, many of the findings are extensible to the repair of historic frames. Conservation principles, materials science, engineering quality and durability performance and practical aspects of in-situ access need to be considered.

It was determined that resin technology as a gap-filling adhesive is acceptably mature: there remains little foundation for the reservations regarding longevity and it better enables future repairs compared to traditional carpentry. It was concluded that resin-bonded timber repair should be considered as a viable technique alongside other methods of timber conservation.

1 Introduction

The principles of conservation are a constant test for repair methodologies, particularly in the field of structural timber repair. The doctrine to use only proven techniques is here in direct conflict with the need to retain historic fabric. The use of epoxy resins in conservation has had a very chequered history, created by early practitioners. This had led to great reluctance by many conservators to consider its use in current projects, although the increasing momentum of research during the past twenty years is showing that the technology is highly suited to timber conservation.

The need to conserve historic timber has led to increasingly sophisticated philosophies and repair methods. However, whilst principles of conservation might be widely accepted, the interpretation of conflicting philosophies leads to contentious battles as to whether certain methods are more acceptable than others. One of the most contentious repair techniques for timber is clearly the use of epoxy resin.

Resin as a timber consolidant or prosthetic has been used for many decades. Its early use (in the 1970's/80's) was highly experimental and often poorly executed by companies focused on profit rather than conservation. This justifiably led to resin repair receiving bad press and has led to a firmly established bias against the use of resin in today's conservation industry. However, research has continued leading to an improved understanding and innovative repair techniques. A method that deserves positive attention is that of 'resin-bonded timber repair' (RBT repair), chiefly developed by the Weald & Downland Open Air Museum and this report is primarily an appraisal of the technique.

2 Values of Historic Timber

The timber components in buildings, bridges, monuments and recovered nautical wrecks are central to their value in terms of appearance and as an archaeological record:

<u>Emotional Values:</u>

- delight of an authentic structure retaining a maximum of historic fabric
- patina and aesthetics – a unified image of an aging frame, uninterrupted from the 'interference' caused by new material.
- colour / finish
- historic graffiti and symbols carved into timber surfaces

<u>As a record:</u>

- carpenters' marks
- timber conversion methods: identified by marks left by: pit-saw; a see-saw 'V'; band saw; circular saw; axe and adze.
- carpentry methods: historic joints
- dating by dendrochronology

With the exception of dendrochronology, it is the timber surface that articulates these values, yet, when considering these in the context of repair, it is natural to call upon the ethics relating to 'façadism' of whole buildings: the importance of retaining a whole timber section is readily accepted, as is the unacceptability of reducing a historic building to a two-dimensional remnant. Nevertheless, it is presently much less apparent as to whether a conservator should retain historic surfaces when the bulk of the underlying timber is in need of replacement or support. Given the difficulty of this philosophical argument, it is helpful to compound the weight of two principles: firstly, to not prejudice future repair methods and, secondly, to minimise loss of historic fabric. When considered together they suggest that retaining surface should be given some priority. If one combines this viewpoint with the mistakes so often made by conservation experts, it would seem prudent to preserve the surfaces in case improved philosophies or repair are developed in the future.[1]

3 The Development of Structural Adhesives

Adhesives have been successfully used for many decades in the automotive, marine and aerospace industries, driven by many benefits including not damaging the items being joined, simpler joints with fewer components, being weather-tight and of high strength.[2] The majority of these applications concentrated on thin-film adhesives as a bonding agent rather than gap-filling materials. The application of resin in timber conservation primarily makes use of gap-filling adhesives and can be divided into three primary categories – as a prosthetic, a consolidant and solely as an adhesive.

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[1] It could be argued that timber-bonded resin repairs might in the future also turn out to be a conservation mistake. Even if proven true, the damage will be minimal due to the retention of historic fabric. This argument is examined in Section 5.

[2] Hutchinson and Hurley (2001), p.19

3.1 Prosthetics

A timber might have insufficient strength for is current purpose or a newly proposed use. Timber sections were often over-specified, yet it is common to find weakness due to defects such as knots and through decay. However, during an appraisal for adaptive re-use, it is common to find that strength of timbers is insufficient for the proposed load. Whilst poorly executed appraisals may over-specify load requirements and under-estimate strength, it is sometimes justifiable to specify that bridging beams and floor joists require strengthening.

Early attempts at repair using resins used the properties of epoxies to provide structural enhancement. More acceptable is the re-enforcement of the timber using rod of a suitable material such as steel or, more latterly, fibre-reinforced plastic (FRP) potted in resin [Figure 1].

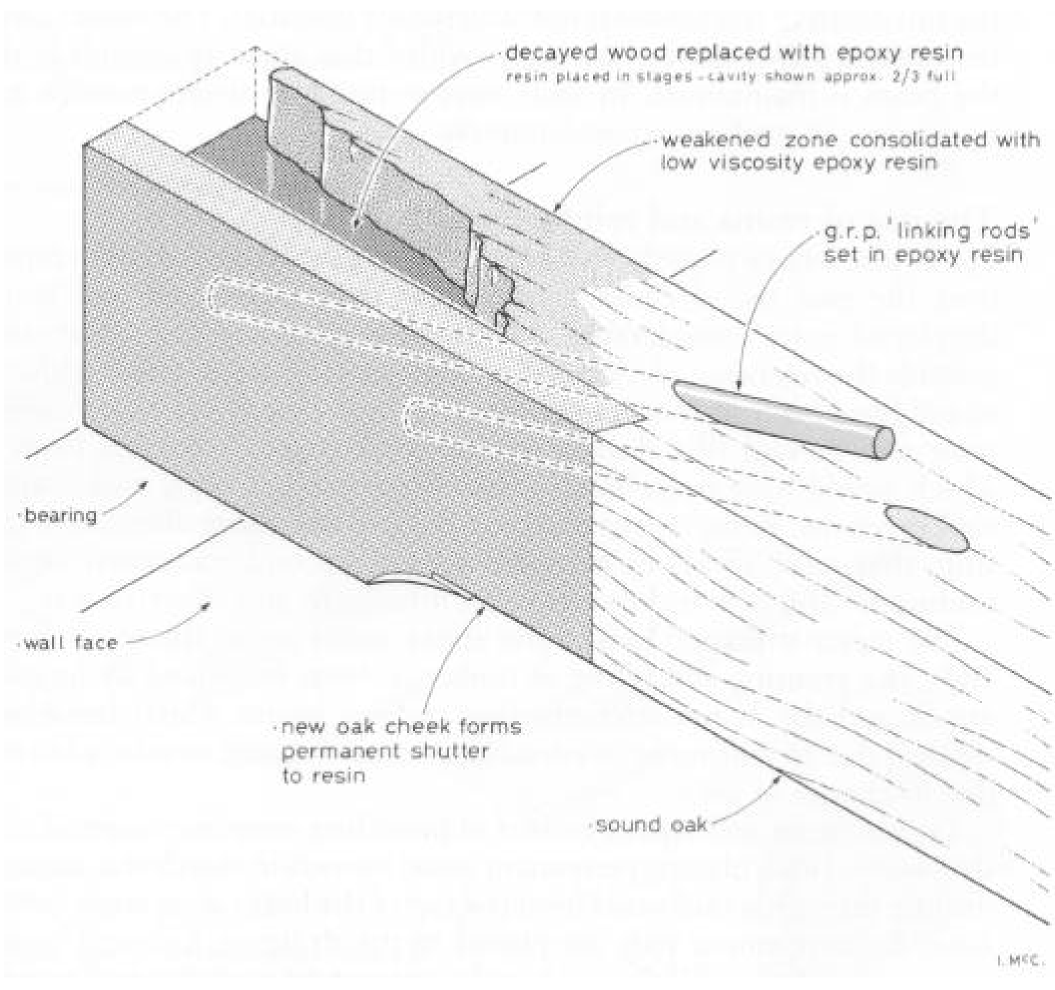


Figure 1. Shuttered FRP resin repair to beam end. From Ashurst and Ashurst (1988).

Latest variations call for FRP rods to act as dowels between sound historic timber and replacement treated timber of matching section. In this variation, the epoxy is reduced to an adhesive between the rod and timber.[3]

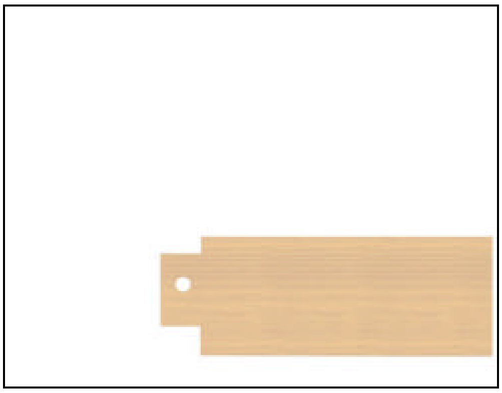
The most common application of this technology is remedial repair to beam-ends where integrity has been lost due to fungal decay or insect attack. The method has become sufficiently mature to justify batch manufacture of standard repair components. The technique is equally applicable to the repair of historical and recent structures and has therefore been able to attract substantial research grants.

3.2 Consolidants

Friable historic timber presents a particular challenging problem to the conservator. Much damage to the appearance of historic timbers has been done by defrassing, as is still too frequently specified in tender documents for historic building repairs. Even when it is accepted that frass and partially decayed fabric should be retained, the question of how to stabilise the material must be addressed. Today, the best policy is likely to be the 'do-nothing' option, but early attempts to manage the problem were done using resin consolidants. In interior work this can occasionally still be considered as appropriate, but use on external carpentry has many aspects of concern: it invariably changes the appearance of the timber;[4] gradual discolouration is caused by the ultraviolet components of sunlight; higher levels of moisture retained behind the consolidated material that may lead to accelerated and hidden decay of the timber section.

[3] This arrangement, with the epoxy as a thin adhesive layer, is important to the applicability of test and durability data to the RBT repair technique. This is discussed in Section 6.
[4] It is acknowledged that the most valuable of historic timbers may be consolidated by injecting resin below the surface, as described by Ashurst and Ashurst (1988) pp.24 - 29, but this is neither scalable nor economic for the vast majority of conservation scenarios.

a. Decayed rail with failed tenon.



b. New timber splice, with replacement tenon.

c. Splice bonded in behind historic surface

d. Appearance after reassembly

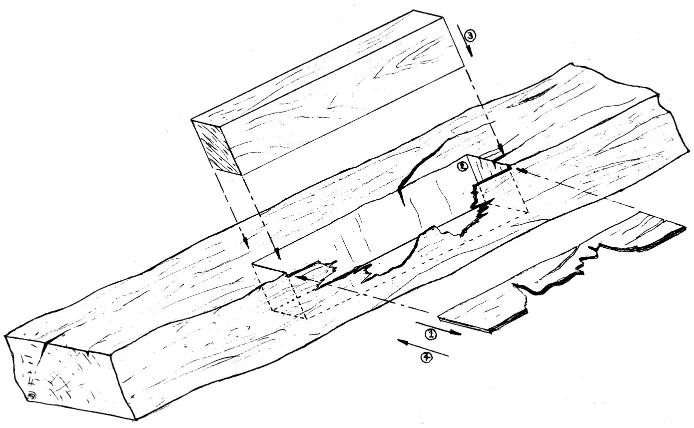
Figure 2. A resin-bonded timber workshop repair sequence for a decayed rail end and tenon.

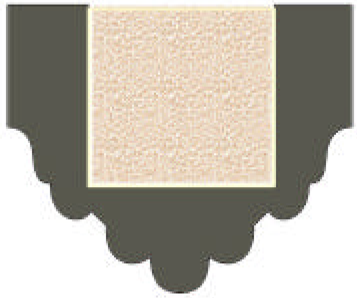
3.3 Gap-Filling Adhesives

The Weald & Downland Open Air Museum has led experimentation with timber repair since the 1970s and has evolved resin repair methods out of the basic prosthetic methods already described. These developments came from the desire to retain as much historic material as possible, especially the surfaces, and led the museum to substitute the bulk of the resin with new timber, effectively reducing the role of the resin to an adhesive. It was also found that the method could be extrapolated to circumstances where a given length of timber would have otherwise required replacement in order to restore structural capacity. In these cases, their method effectively retains the surface as a veneer, which is then reapplied to the new timber.

4 The 'Resin-Bonded Timber' Repair Method

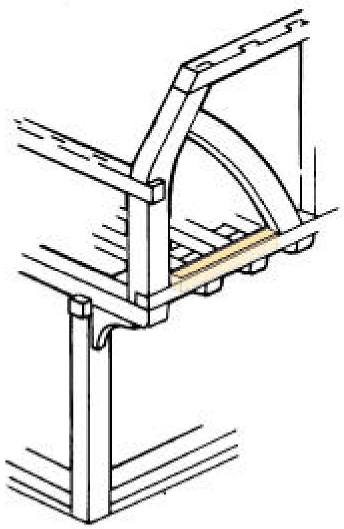
The principle is to splice in sufficient timber behind the historic timber surfaces to restore structural performance. This most frequently involves reinstating a decayed mortise or tenon [Figure 2].

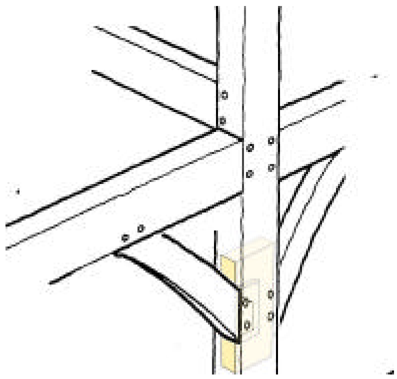




surface veneer reapplication

moulded beam





jetty bressumer repair [5]

post repair

Figure 3. Examples of in-situ RBT repair.

[5] Drawing adapted from Harris (1997).

Within the principle of Resin-Bonded Timber (RBT) repairs there are many variations, each one having a custom design guided by the specific situation [Figure 3]. Typical RBT solutions, in increasing degree of timber replacement, are:

1. timber flitch
2. single- or double-scarf
3. surface-only retention

A timber flitch lets in a cuboidal strip of new seasoned wood from an unseen face. At least one face of the timber is lost and therefore the least valued one should be sacrificed. The fluid nature of resin and its desire to drain out of a joint will be an additional factor determining which face is lost, ideally being the top. Flitches let in from the bottom or side may therefore require temporary shuttering to prevent loss of resin during its curing period.

New wood may be scarfed-in if the historic timber has decayed across its entire section at one point, typically an end. A single scarf or double 'V' scarf, with replacement mortises or tenons created as needed, is prepared in the traditional way except that the new surface is set back and the historic surface reapplied. The use of resin increases joint strength and secures the historic surface.

The most aggressive form of RBT is total replacement of the decayed member with either one or two of the historic faces reapplied using resin.

To ensure quality of resin bond, the surfaces of the timber must be properly prepared:

1. they must be adequately dry (<20% water content), ideally matching the expected in-service conditions.
2. surfaces should be cut flat
3. dirt and dust removed
4. 'wetting' the surfaces of the timber with resin may be required.
5. the resin adhesive must be applied to surfaces and the bond completed as soon as possible. A uniform adhesive thickness of 2-5mm is optimum.[6]
6. The joints should be lightly cramped to prevent movement until cured.

For single tasks, adhesives may be purchased ready for use, usually containing resin and hardener in separate tubes, which automatically mix in the correct proportions on application. This is quick and avoids the need for measuring equipment, incorrectly mixed product and tool cleaning. Unfortunately, adhesive from tubes is expensive and so manually mixed adhesives are available in larger quantities for frequent use or larger repair projects.

[6] Institute of Structural Engineers (1999), p.34 recommends the joint should be as thin as possible by squeezing with cramps or weights throughout the curing process. However, is important that cramping does not cause the epoxy to be squeezed out of the joint.

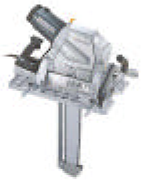
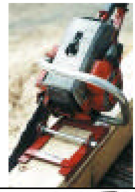
Power Tool		Uses
Circular saw – large diameter		Minimum width cut for cutting perpendicular and through an historic surfaces. Removal of historic surface veneer by cutting parallel to historic surface. Shallow slots from multiple passes.
Chain beam saw, guided chainsaw (or chainsaw mill in workshop)	  	Fast production of long slots – entry through least valued surface.
Chain mortiser with guide		Fast production of shorter slots and replacement mortises.
Reciprocating saw		Cutting through of defective tenons to enable timber to be removed (e.g. rails or braces).

Table 1. Power Tools for resin-bonded timber repairs (Images courtesy of Timberwolf Tools)

Working with hand tools in old oak is arduous and so the cavities and new timber for the repair may be shaped using power tools. The most efficient preparation of historic timber for RBT repair requires the use of circular saw, chain beam saw, chain mortiser and possibly a reciprocating saw [Table 1].[7] Essentially, this becomes obligatory equipment since oak becomes extremely impenetrable with age.

4.1 In-Situ Constraints and the Need for Innovation

The majority of repairs must be carried out in-situ to avoid unnecessary disturbance. However, the RBT repair method was developed for the workshop where a timber can be removed from the frame and laid flat on the bench or trestles. This inhibits immediate use of the museum's method for in-situ repairs due to reduced access, interference from other building fabric and the fixed orientation of the timber, all combining to prevent easy use of workshop power tools. This is the primary factor currently preventing adoption of in-situ RBT repair by the conservation industry.

Innovative methods are also required to control the liquid resin until it is cured. This may take the form of shuttering created from thin board, using heavy-duty tape, or inert putty-like plastic material.

Easier re-establishment of tenoned joints is facilitated by RBT since less disassembly is required compared to a traditional carpentry repair. For instance, a false-tenon may be bonded into the parent timber from the side using resin, then dropped down and across into the mortise. The resulting repair has both the appearance and the structural performance of a traditional mortice and tenon joint.

The loads being carried by a timber must be considered prior to in-situ repair and must form an integral part of the repair methodology. This applies equally to all repair techniques but it must be remembered that resin will require time to cure before supporting the dead weight of the repair splice and longer-still before taking up an applied load.[8] A combination of temporary vertical support, horizontal bracing and shoring may be required.

Cost is usually an unfortunate driving factor in deciding repair technique. In the majority of situations, the cost of RBT is likely to be higher than other methods. For the most prominent of repairs on any building and discrete locations in more important buildings, the incremental cost may not be of such concern. However, complex joints or situations where dismantling for a traditional repair is disruptive, it is conceivable that RBT may be a more economic option.

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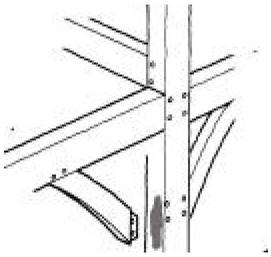
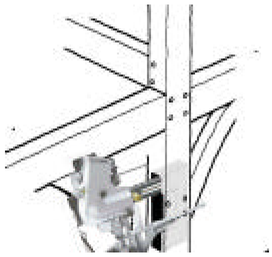
[7] A shallow slot can be cut using multiple parallel passes of a circular saw, but is impractical for most situations where the repair is at the end of a timber or a deep mortise is required.

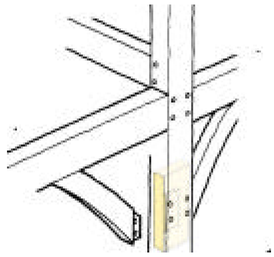
[8] The cure process is explained in Section 6.1. Cure times are specified on the manufacturers' datasheets.



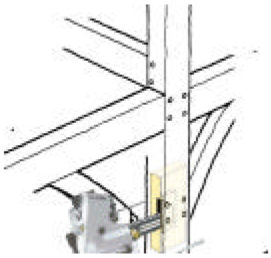
1. brace unpegged and removed from decayed post



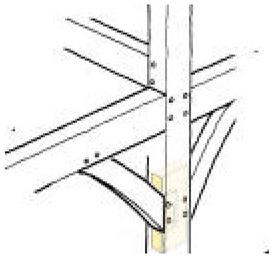
2. slots cut in post, *behind* surface, using chain mortiser.



3. Timber splices set in epoxy resin and shuttered during curing.



4. new mortise re-cut in spliced repair to accept brace tenon



5. brace reinstated and pegged

Figure 4. An example of an in-situ RBT repair sequence

Progress might be achieved if the slots could be created in-situ more simply. The limitations are presently the difficulty in setting up guided chainsaws or chain mortisers in-situ. It is realistic to propose that new tools are designed especially for the purpose of in-situ repair. For example, a right-angled mortiser with shorter chain would ensure the tool projects perpendicular to the frame, the significance being the necessary clearance around the timber is reduced to the depth of the chain. In effect, this is an adaptation of a mini chain carver. Further tooling improvement might come from a clamp-on guide that takes support from a vertical frame and connects to it using the internal sides of the timbers.[9] The development of specialist tools need not be prohibitively expensive assuming a sufficiently large market of timber conservators exists or can be created. Ironically, such a market cannot develop unless the techniques are first devised using expensive custom-made prototypes.

It is therefore apparent that further work is required to refine the RBT technique for in-situ repairs. However, with some much-needed innovation, it is predicted that the method should enable new conservation benefits.

[9] For example, by using thin cramping plates, each side of which slot into the gaps between timber and infill panel, hence causing minimal damage to the timber.

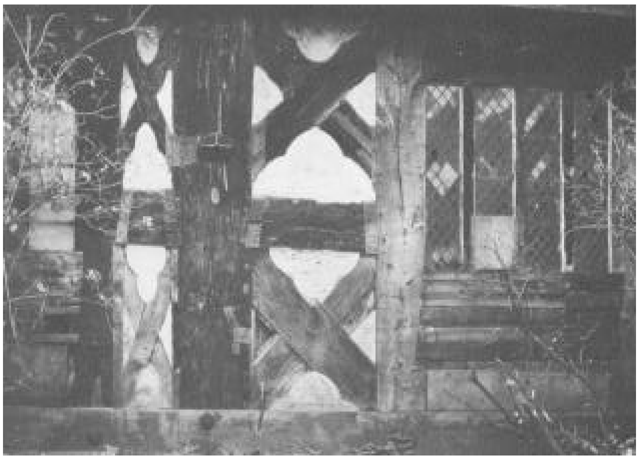


Figure 6. The cumulative impact of multiple carpentry repairs. From Feilden (1982).

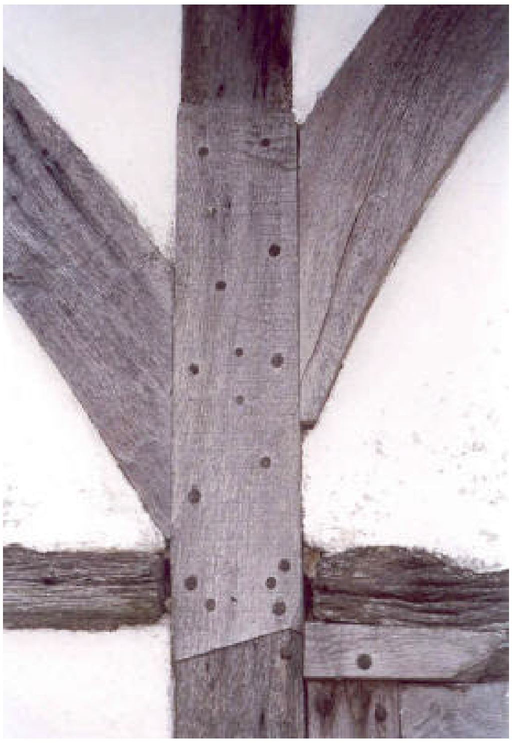


Figure 5. The aesthetic impact of carpentry repairs.

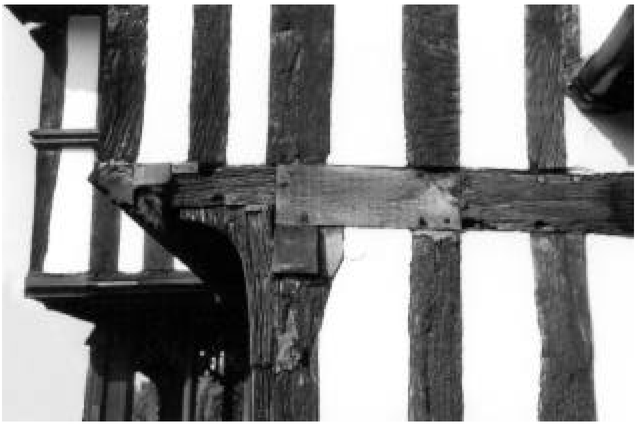


Figure 7. Carpentry repairs draw the eye's attention away from the frame as a whole.

Figure 8. An RBT mortise repair to a rail. New timber is set back behind the retained historic surface.

Figure 9. An RBT V-scarf repair with surface veneer reapplied. The perpendicular cuts by circular or band saw are just visible.

5 Qualitative Assessment

Inexperienced conservators have very polarised views on resin repair. The technique is either condemned as being an unproven technology that is over-relied upon and being no compensation for the craftsmanship of a skilled carpenter. The other reaches for the epoxy compound whenever a decayed timber is discovered. Skilled conservators will select the most appropriate solution to each individual repair situation. This should be based on the principles of repair.

An prerequisite for meaningful appraisal is the clarification of two common areas of confusion. Firstly, it is important not to consider ‘resin’ as a single technique since it encompasses several different methods, each one having different applications, advantages and disadvantages. Only RBT repair is under scrutiny here – resin as a prosthetic and consolidant are beyond the scope of this report. Secondly, it must be remembered that best practice has not always been followed in the industry and that adhesive technology is continually advancing, consequently requiring the careful treatment of early repairs (i.e. not placing too much weight on outdated techniques) when analysing their performance.

5.1 Minimal Loss of Historic Fabric

As discussed in Section 2, the timber surfaces hold much of the value of a framed building. These components are vulnerable to the slow processes of decay yet sections may be instantly lost in their entirety if removed during repair. Given that we are now able to dramatically extend the lifetime of our buildings through new conservation methods, the extrapolated effects of cumulative part-replacements must be considered. In the past, part-replacement was a necessity in order to retrain stability of a building but the development of new repair techniques is reason for questioning the over-use of traditional carpentry joints.

As a tool to aid examination, it may be useful to quantify the *relative* values of surfaces and internal bulk, which then enables comparison of various repair methods.

Let, v_s = value per unit length of timber surface
v_b = value per unit length of timber section (excluding its surfaces)
v_T = total value per unit length
L = length of repair
n = number of the four surfaces lost in repair.

If, for the purposes of this example, the surfaces are stated to be three times more valuable that the internal bulk (v_s = 3, v_b = 1), then the relative fabric *loss*, Äv_T , of the repair methods can be calculated as illustrated in Table 2.[10]

Repair scenario of Figure 5 …	…as a traditional carpentry repair	…as an RBT repair
Äv_T (= $nv_sL + v_b L$)	4 x 3 x 0.85 + 1 x 0.85	1 x 3 x 0.65 + 1 x 0.65
Äv_T	<u>11.05</u>	<u>2.6</u>

Table 2. Comparison of relative loss of value caused by timber repair.

The above is a useful framework to enable the quantitative comparison of techniques yet it must be noted that it would be erroneous to use this criterion independently of other conservation principles. However, it clearly illustrates that more value is lost through a traditional carpentry repair than an RBT repair.[11]

5.2 Aesthetics

The effects of decay add much interest to old buildings: the 'parasitic sublimity' that John Ruskin fought so hard to retain; the meandering of shakes and wany edges. A traditional carpentry repair in time may reproduce these values in itself, but in the short- to medium-term it does much to detract from the beauty of a unified ancient frame. There is also an unresolvable problem when attempting to mate a repair piece with the weathered corners of historic timbers: if the repair is set back from the edges it appears to be undersized; if it is cut to the same size as the historic timber then its edges stand proud [Figure 5, Figure 6 and Figure 7]. The repair of a member *behind* its historic surface using timber-resin minimises these discontinuities [Figure 8].

5.3 Honesty of Repair

The need for an honest repair is primarily for the benefit of the few archaeologists, building historians and conservation experts and can be contrasted with the aesthetics that benefit the large number of local and national stakeholders of our heritage. Since experts would never be fooled by repairs such as those of Figure 8 and Figure 9, there is little concern that they cannot be classed as entirely honest.

5.4 Reversibility of Repairs

A disadvantage of an RBT repair is that it is not reversible. This prohibits an improved repair method being used for the same defect at a future date. It is therefore clear that the method should only be used where structural capacity of a decayed or defective timber must be restored and preferred techniques are to either utilise a 'do nothing' approach or make use of steel straps, either exposed or hidden.

[10] The carpentry repair is longer (~0.85m) than the RBT repair (~0.5m).
[11] This conclusion is consistent regardless of numerical values used.

Where it is decided that repair is necessary and the quantity or appearance of steel is deemed undesirable, then the choice is generally between traditional carpentry, reinforced resin or RBT repairs. Carpentry is often taken as the default, but it too is irreversible. A fringe benefit of RBT over traditional carpentry is that it might be possible to modify the repair at a later date since the bonded joint creates a composite that performs structurally in a similar way to a conventional timber: the composite can be drilled, sawn and the timber surfaces planned. Such treatment is not possible with a traditional carpentry repair since further alteration by sawing or drilling would invariably weaken it severely or cause complete failure.

6 Quantitative Assessment

The performance of a repair depends on the short- and long-term properties of the resin materials, the timber-resin bondline and joint design.

6.1 Materials Science and Engineering

Resin is a general term referring to organic polymers – long chains of carbon-based compounds with hydrogen, often with oxygen, nitrogen, sulphur or a halogen (e.g. chlorine). Long polymer chains (with a series length of >200) create either ‘thermoplastic’ or ‘thermosetting’ plastics, the latter formed by cross-linking of chains created as an irreversible process. The ‘polymerisation’ of a thermosetting polymer is called the ‘curing’ or ‘hardening’ process and is typically achieved through the addition of a second reactive compound – a ‘curing agent’.[12] The degree of cross-linking increases with time and determines many of the properties of the cured resin. The curing is often possible at low ambient temperatures, often down to -5°C.[13]

After mixing with the hardener, the period during which the resin is workable is termed the ‘open time’ and a joint must be completed during this period. As cross-linking changes the properties of resin it begins to ‘gel’, representing the initial cure. Cross-linking then continues until a solid is formed and then for a significant duration afterwards. Strength therefore increases over time and the final strength is usually limited by the ability of the curing agent to bond with the polymer. Curing can also be enhanced by increasing molecular activity by heating it beyond the original cure temperature and by ensuring a sufficient quantity of hardener is available for the reaction.

Epoxies are a specific category of thermosetting resin and those typically used in construction are usually synthesised from bisphenols or epichlorohydrin.[14] Epoxies have the following generic properties:

- high versatility
- long shelf-life

[12] Heating can also initiate polymerisation of some resins.
[13] A more comprehensive introduction to resins is given by Hurley (2000), pp. 23-33.
[14] ibid., p.32.

- low fire risk
- low odour
- wide usable temperature range
- cure down to –5°C
- slow cure rate
- low cure shrinkage
- excellent adhesion
- tough

Joints for epoxies have been categorised into three types: [15]

- thin bonds (gap <1.5mm)
- thick bonds (gap 1.5mm)
- grouts and mortars

Thin bonds rely on the close fitting of the materials to be joined, usually achieved by pressure, and so are most suitable to workshop conditions. Thick (gap-filling) bonds are more suitable to structural carpentry, especially that involving irregular historic timber. A typical adhesive used in RBT repair is the gap-filling resin diglycidyl ether of bisphenol (DGEB) incorporating a diluent, and hardener trimethylhexane-1, 6-diamine.[16] Properties can be modified by mixing several types of resin, the addition of diluents and by the inclusion of fillers to change viscosity and increase volume without reducing strength.

6.1.1 Properties of Epoxy

Table 3 shows the properties of a typical epoxy. A comparison has been made to European Oak since the majority of repairs in the UK will be to historic oak frames, using oak as a the splice timber.

Property	Epoxy	European Oak (at 12% moisture content)
Density (kgm^{-3})	1500	500-1000
Tensile modulus parallel to grain (GPa)	4	8-16
Shear Modulus (GPa)	1.5	-
Tensile strength (MPa)	30 - 65	97 (parallel to grain)
Shear Strength (MPa)	25	10-18 (parallel to grain)
Coefficient of thermal expansion parallel to grain (10^{-6} °C^{-1})	30	3-5

Table 3. Typical properties of epoxy and European Oak

[15] Bainbridge (2001), p.2
[16] A diluent is a substance added to modify the viscosity of an epoxy.

It can be seen that the properties are sufficiently matched for an epoxy to be considered a compatible material for use in repair. The most significant difference is the mismatch between thermal coefficients. This results in a differential strain across the bond-line. As a result, shrinking and swelling of the timber due to changes in temperature can cause a shear stress along the glueline. The problem of differential strain is worse still for changes in water content, influenced both by temperature and by relative humidity. It is therefore important that the repair is performed in an environment close to that expected in service. Cracks along the bondline can occur if this precaution is not observed.[17]

Water is often regarded as the most worrying agent that may affect the properties of an epoxy and its interface with timber. In a very humid environment the strength of the bulk adhesive will often fall with time, but this effect is limited to extreme conditions.[18] Water ingress is dictated by Fick's laws of diffusion and therefore its effects follow the Arrhenius equation. This is helpful in enabling thermal activation energies to be associated with water-induced defects, thereby allowing easier prediction of durability from accelerated life tests. In theory, defects induced by water could include stresses caused by swelling, the formation of adhesive cracks, creation of small cavities and the modification of a crack tip caused by some other factor.[19] In practice, tests have shown moisture content below 18-22% at the time of adhesion causes negligible effect, although slight reduction in overall joint strength for higher moisture levels has been observed in oak.[20] It is also likely that a 'critical water concentration' applies, above which the adhesive strength does start to markedly decrease. However, this critical point is likely to be at approximately 60% RH and is so of limited concern except for repairs in extremely exposed environments.[21]

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[17] A test method for adhesive timber joints is described by BS EN 203: 4 (1992). The issue has been characterised by Davis (1997) and Harvey and Ansell (2000).

[18] Broughton and Hutchinson (2001), p.181.

[19] Adams, Comyn and Wake (1984), pp.211-219.

[20] Wheeler and Hutchinson (1998), p.10. Further, it was shown that at higher moisture levels the failures were not in the adhesive or on the bondline, but within the timber. This was particular pronounced in oak, possibly attributed to acidic substances leeching out during the exposure to extreme moisture.

[21] Adams, Comyn and Wake (1984), pp. 315-316 discusses the hypothesis of a 'critical water concentration', including experiments performed on aluminium-epoxy joints showing a 60% roll-off point.

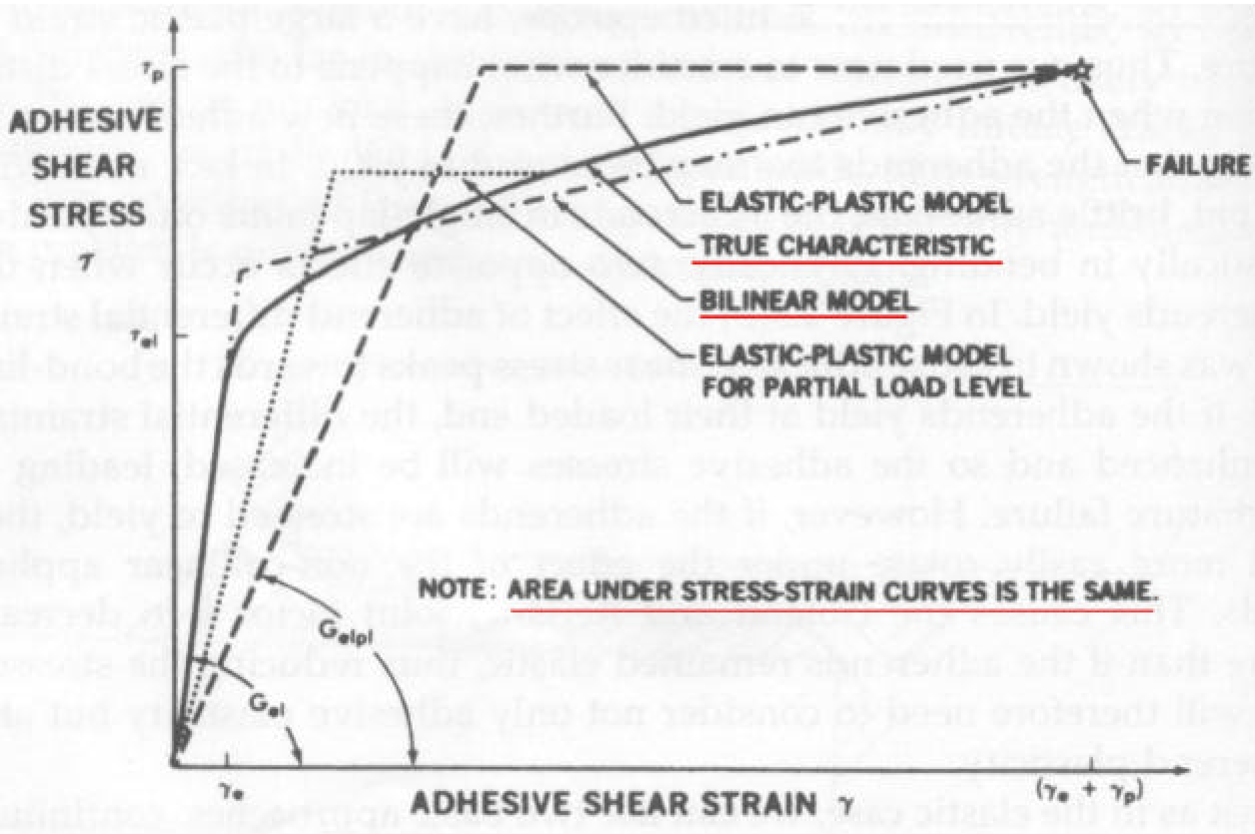


Figure 10. Bilinear approximation to stress strain characteristic.

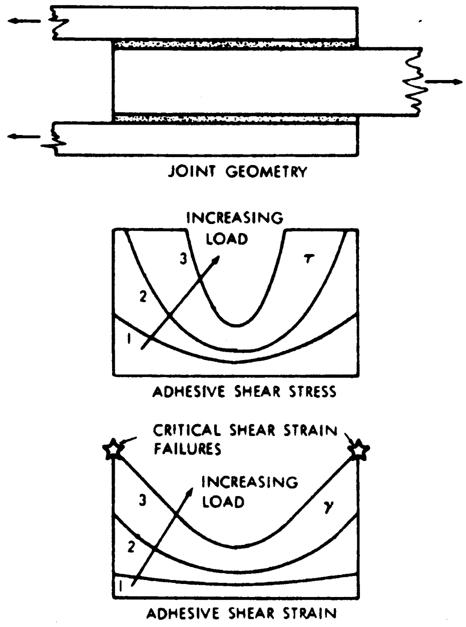


Figure 11. Development of shear stress and strain in a double-lap joint with increasing load.

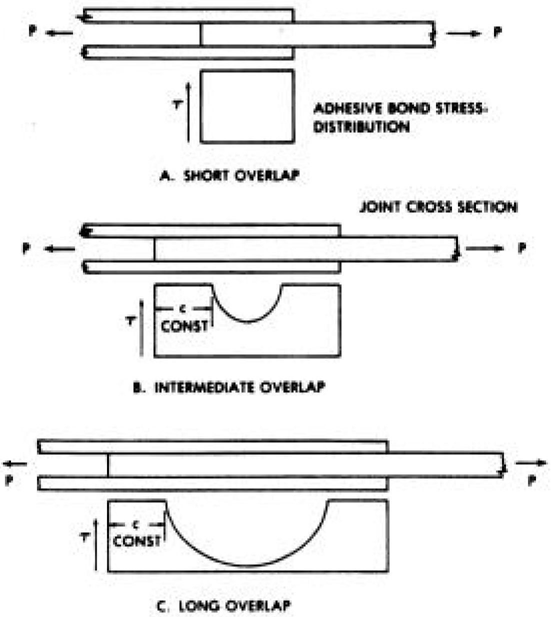


Figure 12 Effect of joint length on stress in plastic and elastic regions.

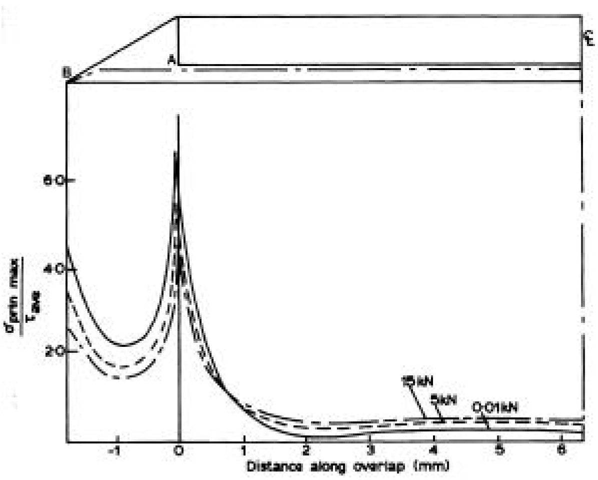


Figure 13. The stress at timber end, A.

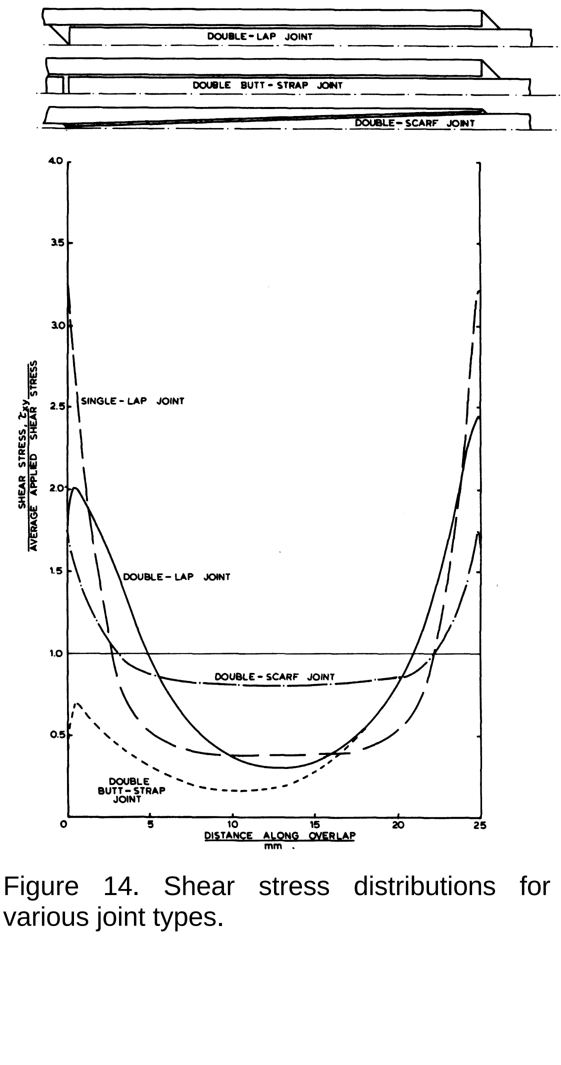


Figure 14. Shear stress distributions for various joint types.

6.2 Performance Attributable to Joint Design

A common concern when using resin to repair historic joints is that the flexibility of the joint may be lost. This would disrupt the flexible nature of a frame thereby increasing stresses in other parts of the structure. However, with RBT repairs, the joints are not modified and the technique actually facilitates the re-establishment of broken tenons. The extent of the resin is limited to the length of the bondline and so it should not affect the traditional performance of the structure.[22]

Rather than being considered as inflexible components, both adhesive and timber may have a significant 'plastic strain to failure' performance. This deformity can affect the way in which the joint performs under load. If the adhesive is taken to behave as a bilinear approximation to its elastic-plastic characteristic curve, then the stress along various types of joint may be analysed [Figure 10].[23] Applying this model, for example, to a double-lap joint, the shear stress and shear strain profiles along the length of the joint can be calculated [Figure 11]. This suggests that the maximum stress is at the end sections of the lap and increasing the load will result in the critical strain acting at the joint ends. The model also demonstrates that increasing the joint length decreases the stress and the length of the central elastic region: it does not decrease the stress in the plastic regions at the ends of the joint [Figure 12].

End effects must also be considered. It has already been shown that that the maximum stress acts at the joint ends and if the end is modelled as having a simple elastic timber and adhesive fillet, a peak stress is found to exist in the adhesive at the corner of the timber [Figure 13].[24] The magnitude of this stress may be reduced by modifying the corner of the timber lap: a curve or tapering of the timber at its extremity improves the situation with respect to this type of adhesive failure.[25]

[22] The behaviour of an RBT repair retaining only an historic veneer can be viewed differently: it can be considered that the veneer is approaching the dimensions of a 'thin film' and so the overall performance becomes similar to that of a complete timber replacement.
[23] The term bilinear refers to approximating each of the two parts of the curve – elastic and plastic – as linear. Adams, Comyn and Wake (1984), pp.42-44 suggests using this model devised by L.J. Hart-Smith.
[24] If the equivalent analysis is done using the more accurate plastic-elastic model, then it has been found that there is good correlation between predicted and measured failure loads. Adams, Comyn and Wake (1984), p.73.
[25] ibid. pp.95-97.

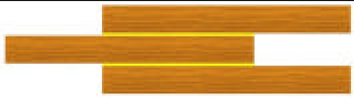
RBT variant	Joint Model	Diagrammatic representation
timber flitch	Double lap joint	
scarf	Double scarf	
surface-only retention	Non-structural	

Table 4. Modelling of RBT variants.

For the purposes of modelling, the three varieties of RBT repair discussed in Section 4 can be described as shown in Table 4. A comparison of shear stress distributions [Figure 14] shows the effect of scarfing the joint is to considerably reduce the adhesive end stress.

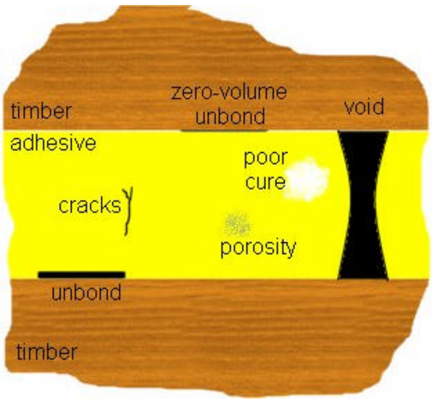


Figure 15. Adhesive defects.

Defects will affect the strength of a joint. Cracks may result from problems with curing, such as from thermal shrinkage during cure or from an excessive applied load. Insufficient cure can result from incorrect mixing or incorrect formulation of the resin and these may act locally or throughout the adhesive. Voids are a problem caused by air trapped during mixing, application of the adhesive, or during bonding. A specific form of void is called a ‘surface unbond’ in which the void lies along the timber-adhesive interface. A ‘zero-volume unbond’ is an area where the adhesive and timber are in contact but has insignificant strength as a result to a surface defect such as lack of timber preparation or contamination and this has the same effect as a surface unbond [Figure 15].

Modelling therefore shows that the adhesive stress can be minimised by increasing the joint and bondline area by extending the length of a joint, avoiding right-angled ends to the timber and by using a scarf joint instead of a lap joint. The various types of adhesive defect must be avoided through careful preparation and application in order that maximum strengths are achieved.

6.3 Quality and Durability Testing

Although resins have been used in construction for more than thirty years, there is still limited data to answer the questions of how strong a gap-filling adhesive joint will be, how long it may last and what secondary effects the resin may have. Some aspects of the technology where information can be transferred to structural repair are:[26]

- Testing: methods adapted by other industries are applicable
- Durability: degradation and failure mechanisms are well understood
- Process control: documentation systems are mature, including training
- Failure analysis: procedures are directly applicable from other industries.

For example, the large number of repairs in aircraft and marine structures has overall been found to be reliable, despite compromises made with materials and curing management.[27] These data cannot be directly correlated to historic timber repair but provide an indicator to acceptable performance in buildings.

Established test methods and good data exists for 'thin bond' adhesives such as described by the 1992 standard BS EN 203-1 (1992) describing test methods for load-bearing thin-bond adhesives, and BS EN 203-4 (1992) providing a shear test procedure.

More recently, improved test data specific to building repair have become available and from research on beam-end replacement. TRADA Technology (2002) discusses an ongoing project to define classification standards and create a user selection guide for thick-bond adhesive joints. They have also considered testing samples with deliberately induced faults in order to further characterise the process envelope. Similar experiments could be devised with RBT test samples. Other research has tended to focus on bonded-in glass fibre reinforced plastic (GFRP) rods, with particular attention to rod pull-out characterisation.[28] The shear test results and identification of performance-modulating factors are likely to have aspects that correlate with the performance of RBT bondlines. The research concluded:

- Glueline thicknesses of at least 2mm give better joint strength.[29]
- Failure load increases with joint length.
- Adhesive selection is important.
- Tests perpendicular and parallel to the grain produced similar failure loads.
- High moisture content (in softwood) significantly decreases the failure load.

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[26] Hutchinson and Hurley (2001), p.82.
[27] ibid. p.78.
[28] Harvey and Ansell (2000)
[29] This Harvey and Ansell (2000) recommendation to have thicker gluelines of at least 2mm differs from the procedure given by Institute of Structural Engineers (1999), p.34 which recommends ‘the glueline [to be] as thin as possible’ and their table on p.25 suggests a target glueline of 1mm is acceptable.

The TRADA research has also summarised possible problems affecting the initial quality of the joint as:

- the timber is not blown clear of swarf.
- gap-filling adhesive is insufficient to give a continuous bond and has voids because the insertion of adhesive has not been from bottom to top of the slot
- the adhesive is inadequately mixed
- mixing of base resin and hardener are in the wrong proportions
- a portion of the adhesive drains from a horizontal or vertical hole
- considerable burning of the historic timber by power tool action
- the effect of excess chainsaw oil on the surface of the timber to be bonded is presently unevaluated and as such poses a risk to bond integrity.

6.3.1 Interaction with Timber Treatments

Biocides may interact with the adhesive, especially where solvent carriers are used. The effects of common preservatives on softwoods had been found in some cases to have a negative impact in accelerated durability tests as measured in terms of bond shear strength and delamination failures.[30] This was particularly significant with pre-treatment (i.e. bonding of treated wood) and less so with post-treatment. It is therefore advisable to review any known previous treatments prior to making a repair on historic timber. This raises the problem of not knowing the treatment history of an historic building. However, the concentrations of preservative carriers are likely to diminish with time, which counter-balances the probability of uncertainty of treatment history.
It was also established that post-treatment has less effect on the bond that pre-treatment, so resin repair should not prohibit timber treatments as long as the adhesive has had sufficient time to cure.[31] However, there has been no study of these effects on historic hardwoods and so remains an area in need of further research.

6.3.2 Moisture Retention

The possibility of increased moisture within the historic timber due to adhesive impermeability is of concern as it may encourage fungal growth and subsequent decay. Experiments of this nature have not yet been undertaken.

[30] Tascioglua, Goodellb and Lopez-Anido (2003).
[31] Institute of Structural Engineers (1999), p.34 summarises this advice.

Models are becoming available that combine heat-air-moisture transfer in timber ('HAM' simulations) with fungal growth modelling.[32] Such a combined model may be able to quickly predict the performance of the timber-resin interface with respect to fugal decay, chiefly the wet rot coniophora puteana. Empirical data from accelerated life tests may also be of use, although it is likely that the acceleration is limited by the optimum and maximum temperatures that support growth. Presently, in the absence of such data, one can refer only to case studies:

1. The Weald and Downland Open Air Museum reports that they have not experienced failure of any of their resin repairs, including the crude early attempts of 20 years ago.[33]
2. Charles Bentall of Carpenter Oak & Woodland performed remedial work to a building requiring removal of an earlier RBT repair of an externally exposed post. Sectioning and inspection of the bondline showed it to be in good condition with no evidence of fungal decay.
3. TRADA's inspection three years after resin repairs were carried at Milton Hall, Canterbury, showed now degradation or debonding.[34]
4. Inspection of 14 year old repairs to The Old Hospice, St Albans, showed no sign of degradation.[35]

[32] Clarke, Johnstone, Kelly, Mclean and Nakhi (1997) created a tool to predict mould growth by combining mould growth models and environmental conditions. Hukka and Viitanen (1999) created a model of the development of mould growth on the surface of softwood subjected to changing environmental conditions.
[33] Zeuner (2003).
[34] Mettem and Milner (2000), p.37.
[35] ibid. p.38.

6.3.3 Accelerated Life Tests

Whilst there are currently no standards for testing the thick-bond RBT, segments of the BS EN 302-1 (1992) can be immediately useful. Such is the designation of standardised environmental stresses, as summarised in Table 5. The Standard views these tests as ‘preconditioning’ prior to testing. However, if useful failure rate data are created (i.e. one or more failures), it is often more useful to approach this from the opposite viewpoint: the tests are used as pass/fail criteria for each population of sample joints. The stresses are then applied with pass/fail ‘readouts’ performed at regular time intervals rather than only at the end of the stress. Through this methodology, the rate of acceleration (i.e. ‘acceleration factors’) can be determined, which in turn enables the real-life durability of the joints to be modelled.[36]

Designation	**Treatment**
A1	7 days in standard atmosphere [20/65]
A2	7 days in the standard atmosphere [20/65] 4 days soaking in water at (15 ± 5) °C Samples tested in the wet state
A3	7 days in standard atmosphere [20/65] 4 days soaking in water at (15 ± 5) °C Drying for 7 days in standard atmosphere [20/65] Samples tested in the dry state
A4	7 days in standard atmosphere [20/65] 6 h in boiling water 2 h soaking in water at (15 ± 5)°C Samples tested in the wet state
A5	7 days in standard atmosphere [20/65] 6 h in boiling water 2 h soaking in water at (15 ± 5)°C Drying for 7 days in the standard atmosphere [20/65] Samples tested in the dry state
The standard atmosphere [20/65] is defined as a temperature of (20 ± 2)°C and a relative air humidity of (65 ± 5)%.	

Table 5. Standard precoditioning treatment prior to sample testing. From BS EN 302-1 (1992).

The LICONS project (Low Intrusion Conservation Systems for Timber Structures) performed limited accelerated durability testing. Temperature/humidity cycling and the effects of wood swell and shrinkage where assessed against the following indicators:[37]

- shear bond strength
- resistance to delamination
- peeling performance (wedge test)

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[36] Nelson (1983).

[37] LICONS is a consortium including TRADA, sponsored by the European Commission Research Directorates General, aiming to provide techniques for the safe, cost-effective, restoration and repair of structural timber through systems that combine structural adhesives and FRPs. TRADA Technology (2002).

The overall finding was that the bonds are extremely durable to effects of moisture. They also concluded that life prediction is best achieved through observation of real-life observations [c.f. Section 6.3.2]: prediction based on accelerated tests is complex since it relies on knowledge of failure modes and the underlying failure mechanisms.
Omitted from LICONS durability tests were the effects of sunlight. It is known that epoxies may discolour with exposure and therefore an accelerated test using ultraviolet radiation would broaden the understanding of adhesive performance.[38] However, problems associated with UV are unlikely in an RBT repair since only the edge of the bondline is exposed.

Integrating durability data borrowed from other industries, the emerging real-life timber repair observations and the limited experimental life test data, it may be concluded that that the durability of adhesive bonds and RBT repairs will be comparable to other timber repair solutions.

[38] Early prosthetic repairs to external timbers at the Weald and Downland Open Air Museum tended to discolour significantly with exposure to sunlight.

7 Conclusion

Special attention to the aesthetics and archaeological evidence of historic timber surfaces is required during conservation. This has led to the development of resin-bonded timber repair that uses modern epoxy adhesive technology. Benefits include minimal loss of historic fabric, maximum retention of historic surface, it is an honest repair and reduces the zone of irreversible repair compared to traditional carpentry methods.

The RBT technique is currently limited by difficulty in applying it to in-situ repairs and innovative tools are needed if widespread adoption by the industry is to be achieved.

The performance of epoxy bonds has been well characterised by the construction industry and the material is highly suited to structural repair in the hands of a trained and skilled contractor. Concern over durability emanating from a few heritage bodies has recently been abated by experimental data that is extensible to historic timber and by emerging data from old epoxy repairs. However, durability needs to be further substantiated by research specifically addressing moisture effects and fungal decay of historic hardwoods.

In the short-term, the application of resin-bonded timber repair will be limited to the workshop by the issues with in-situ tooling. In the longer term, the ethics of timber conservation are likely to drive development of the technique and compel the skilled conservator to embrace it as a welcome addition to the repair method portfolio.

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