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Inductively cured glued-in rods in timber using Curie particles

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ABSTRACT

Commonly used adhesives for glued-in rods in timber engineering, cold curing two-component (2K) epoxies or polyurethanes, only harden relatively slowly (usually in hours to days), which is magnitudes of times longer than mechanical fastening. Additional constraints associated with aforementioned 2K adhesives arise from the fact that they usually necessitate some minimum temperature below which polymerisation can take place, respectively that pot life is strongly affected by (higher) ambient temperature; both limitations restrict the possibilities to bond onsite, depending on the location to a limited number of months of a year. Induction heating was investigated in the light of a potential timber engineering application, herein fast curing of glued-in glass fibre reinforced rods in timber. As none of the materials involved is susceptible to electromagnetic induction, metallic particles were mixed to a 1C epoxy. Induction of adhesives with particles has long been plagued by issues related to non-uniformity of heat distribution in the bondline, unless extensive temperature monitoring and control is exerted. To overcome these issues, metallic particles consisting of Mn–Zn-Ferrite, a Curie material that is not susceptible to induction heating beyond its Curie temperature, were used. The experiments showed that, by matching Curie temperature with the temperatures at which the adhesive cures, induction heating can be performed without any external control, thus freeing the process from monitoring equipment. Inductively cured glued-in rods reached shear strengths at the upper end of what is usually reported in literature. Compared to current practice of cold curing 2K polyurethanes or epoxies, the proposed method leads to bonded joints achieving full strength within minutes, instead of hours, or days, which represents a substantial gain in processing time, almost unaffected from outside temperature conditions.

1. State-of-the-art

Adhesively bonding is among the oldest joining techniques known to humans [1], including for structural [2], and architectural [3] purposes. For a large part of the 20th century, adhesive bonding, with the prominent exception of prefabricated glued laminated timber, has fallen in relative disdain for civil engineering applications. This is also true in timber engineering, where most load bearing connections are still realized using mechanical fasteners. However, in recent decades, bonding as a joining technique experiences a revival [4], in particular with the introduction of synthetic adhesives, as epoxies and polyurethanes. Bonding particularly suits the anisotropic and brittle nature of timber, which, in contrast to pinned connectors, does not interrupt fibres and allows for a much smother load transfer between loaded members [5]. Adhesives permit the structural connection of timber with a wide variety of other materials, as for example concrete [6,7] to form timber-concrete structures, steel [8] as a very convenient way to build up complex timber structures, or glass [9] to develop architecturally appealing structural elements. Within timber engineering, glued-in rods represent a particular class of bonded joints in which load is transmitted from timber elements by means of rods through a layer of adhesive; this specific type of joints is widely been investigated [10], in particular for retrofitting existing structures [11]. Standard practice is to employ metallic rods, usually textured, or threaded rods, to improve mechanical interlocking. However, for a series of reasons, including improved resistance to corrosion in humid or acid environments, lower weight, easier and faster handling and installation, and lower heat conduction into the joint in case of fire [12], fibre reinforced polymers (FRP) can be considered to act as glued-in rods. Most available studies focus on Glass-FRP (G-FRP) rods, and Carbon-FRP (C-FRP) bars with even higher strength are generally discarded because timber strength is the limiting factor [13].

Commonly used adhesives for glued-in rods in timber engineering, cold curing two-components (2K) epoxies or polyurethanes, only harden relatively slowly (usually in hours to days), which is magnitudes of times longer than mechanical fastening. Additional constraints associated with aforementioned 2K adhesives

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arise from the fact that they usually necessitate some minimum temperature below which polymerisation can take place; respectively that pot life is negatively affected by (higher) ambient temperature. Depending on the location, bonding onsite can only occur in a limited number of months of a year.

Adhesive curing can be accelerated by a series of methods, including UV light [14], radiation [15], microwaves [16]; however, the most widely used method remains increasing curing temperature. Temperature increase acts directly on the curing kinetics, and its effect is most commonly described using Arrhenius' Law [17]—which practitioners often apply in form of the rule of thumb that temperature increase of 10 °C halves the curing time. For smaller parts, or standardized parts manufactured in large numbers, temperature increase is very often achieved by oven curing; for the highly individualized and larger parts typically encountered in civil engineering, including timber engineering, oven curing is not an option, especially when manufacturing on-site.

In the context of fast curing adhesively bonded joins, discarding ovens and direct radiation (e.g. infrared lamps, lasers or heating sleeves), the most widely used techniques to generate heat is electromagnetic induction. If metallic adherends are considered, induction heating acts on them, and the adhesive is heated via thermal conductivity. If inductive heating is to be used on non-conductive adherends, it is necessary to ensure that the adhesive reacts to electro-magnetic fields; this is mostly achieved by adding appropriate susceptors; typically metallic particles, or electrically conductive meshes. Two classes of susceptors can be adjunct to the adhesive [18] : firstly, large(r) sized components, as for example plates, or more commonly meshes, embedded within parts to be bonded; secondly, significantly smaller sized components, usually particles, directly mixed with the adhesive. Compared to meshes, particles embedded in adhesives adapt easily to a large variety of geometric situations; accordingly, handling adhesives filled with particles does not require any specialized skills or equipment. Typical particle susceptors encountered are Magnetite (Fe_3O_4,[19]) and Maghemite (γ-Fe_2O_3, [20]); additionally, a series of specifically designed susceptor particles have been developed, one example being MagSilica® [21]. Further information related to induction heating can be found in [25], which addresses the influence of particle size, coil geometry, frequency of the alternating current etc.

Although adjunction of susceptors allows remotely located induction coils to induce thermal energy, associated methods have often been "*plagued by non-uniformity of heating of the bondline*" [18]. It was nevertheless used in a series of practical applications, as for example to accelerate the curing of adhesively bonded structural composite tubes [22] with diameters up to 92 mm ($3^5/_8$"), with Nickel–Zinc-ferrites susceptor particles. Mahdi et al. [23] have compared oven-cured and induction-cured adhesively bonded single lap joints, and shown that there is no significant difference in strength and fracture toughness. The authors used a 2K epoxy on G-FRP adherends, electromagnetic susceptibility was achieved by means of a stainless-steel mesh. Suwanwatana et al. [24] demonstrated that inductive-heating (using Nickel particles in poly-sulfones) can generate bond strengths of polymer–matrix composites comparable to those achieved in autoclave process; however, with the benefit of cycle times reduced with an order of magnitude. Recently, Vallée et al. [25,26] reported on the inductive heating of glued-in metallic using a 1C-epoxiy adhesive; induction heating proved functional, ultimately leading within 5 min to sufficient strength in the bondline to yield the steel bars in pull-out tests. However, the curing process had to be monitored, and induction power constantly adjusted (via thermocouples fixed on the rods) to prevent overheating of the adhesive. Glued-in G-FRP bars in beech, in combination with a Pre-Applicable Structural Adhesive (PASA®, a 2K epoxy) inductively cured were investigated by Adam et al. [27]. Although ultimately induction curing proved as efficient as oven-curing, leading to similar shear strength of the joint, it took the authors specific adaptation of the coil shape to keep temperature differences inside the adhesive layer within tens of degrees centigrade. Additionally, it proved necessary to control the induction power using embedded thermocouples within the adhesive layer.

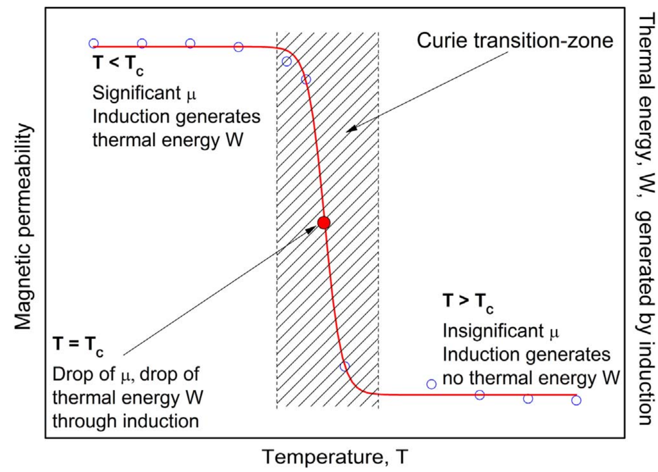

Fig. 1. Curie material; magnetic permeability drops significantly beyond a its Curie temperature, labelled T_C, which in turn significantly reduces its ability to generate heat by means of induction; note that depending upon the material considered, the drop from pre- to post-Curie behaviour occurs within a temperature range that differs in width.

All metals and alloys that exhibit magnetic properties lose the ability to be susceptible to external electromagnetic fields beyond a material specific temperature [28]: this temperature is labelled Curie temperature (T_C) in case of ferromagnetic materials; for antiferromagnetic materials, the analogous temperature is labelled Neel temperature (T_N). In the context of this paper, Curie and Neel temperature are used indiscriminately as the point beyond which a material loses its magnetic properties, and thus no longer generates heating if subjected to electromagnetic induction – this feature is schematically illustrated in Fig. 1. The loss of electromagnetic susceptibly is dependent on particle size [29–31], pressure [32,33] or applied strains [34] – however, corresponding influences do not occur under conditions relevant for practitioners. For practical considerations, the Curie temperature is a property of the particles.

For a large variety of alloys, Curie/Neel temperatures depend upon the relative contents of the components. To illustrate this on one example, Fig. 2 depicts for Ni–Fe-alloys the influence of the alloy's composition on the Curie temperature: at 30% Ni-content, T_C is roughly 100 °C, T_C increases up to 600 °C for a Ni-content of 70% [35]. Accordingly, it is possible to select specific Ni–Fe compositions to target any given Curie temperature (at least below 600 °C). The composition of an alloy does not only influence its Curie temperature T_C, but also (amongst others) its magnetic permeability μ. For illustrative purposes again, Fig. 2 shows that T_C and μ do not follow similar trends; for practical applications in which a specific performance is required, several parameters will have to be balanced for selecting the right susceptor alloy. It is tempting to take advantage of Curie temperatures in the context of inductive heating, since ideally the specific phenomena associated would act as a switch to the induction process, with shutting down the heating beyond T_C. Using Curie particles as susceptors would automatically lead to a substantial simplification of the process by reducing the sophistication of the technical equipment to monitor temperatures, respectively the skill of the induction operator.