THE IMPORTANCE OF BONDING – AN HISTORIC OVERVIEW AND FUTURE POSSIBILITIES

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ABSTRACT

An adhesive is a substance that has the capability to hold materials together. The manner by which adhesives are able to serve this function is due to a surface attachment that is resistant to separation. A bond occurs when the adhesive molecules adsorb onto a solid surface and chemically react with it. Adhesives have a very large importance for most industries, both for structural and for non-structural use. In this paper, an overview of the use of adhesives in different industries is presented – with focus on the building industry and on structural use. Not surprisingly, the use of structural bonding has increased considerably during the last decade. The main reasons for this are probably a combination of lower cost, more need of lightweight structures, development of more durable adhesives and improved structural adhesive performance. Additionally, adhesives often provide better load transfer than welded structures.

In this paper, an overview of the use of adhesive in the service of man is presented. The overview is brief, but nonetheless gives an idea of the possibilities of adhering materials by bonding. The paper briefly discusses the use of adhesives in the aerospace, automotive and marine industries, but focuses on the construction industry. Finally some ideas about “sticking things together” tomorrow are presented.

KEYWORDS

Adhesives, structural bonding, joints, construction industry, organic.

INTRODUCTION

Natural adhesives have been known pre-historic times. Two stones dating back at least 36,000 years have traces of a sticky black substance that was once used to attach them to a handle. In a chemical analysis the glue-like material was identified as bitumen. Archaeologists studying burial sites of prehistoric tribes dating to about 4000 B.C. found foodstuffs buried with the deceased in broken pottery vessels that had been repaired with sticky resins from tree sap. Archaeologists have also uncovered statues from Babylonian temples that have ivory eyeballs glued into eye sockets. This tar-like glue has been known for almost 6000 years. Egyptian carvings dating back 3,300 years depict the gluing of a thin piece of veneer to what appears to be a plank of sycamore. Flour paste was used to bond together papyrus fibers that were then used as fabrics. Beeswax, tree pitches and bitumen were used as protective coatings and adhesives. Egg whites were used to bind manuscripts at one time and wooden objects were bonded with glues made from fish, horn, and cheese. The period of time between 1500-1000 B.C. gave further proof that glue had become a method of assembly. Paintings and murals showed details of wood gluing operations. A casket removed from the tomb of King Tutankhamen shows the use of glue in its construction. A study of history shows the use of glue fell into disuse until about 1500-1700 A.D. when adhesives were used in the building of furniture. Some of the greatest furniture and cabinet makers of all times used adhesives in their products--names still recognizable today like Chippendale and Duncan Phyfe. Another notable name in history who may owe his notoriety, at least in part to adhesives in Genghis Khan. Around the year 1000 A.D., Genghis Khan overcame all attackers because of the exceptional power and range of the weaponry his men carried. Bows were made from laminated lemon wood and bullhorn bonded with an adhesive whose formulation has been lost to antiquity. During the 18th century, the technology of animal and fish glues advanced. In the 19th century, rubber and nitrocellulose based cements were introduced. In about 1700, the widespread use of glue brought about some rapid changes in the history of adhesives. The first commercial glue factory was started in Holland to manufacture animal glue from hides. About 1750, the first glue patent was issued in Britain for fish glue. Patents were then rapidly issued for adhesives using natural rubber, animal bones, fish, starch and milk protein (casein). By 1900, the U.S. had a number of factories producing glue from the aforementioned bases.

The Industrial Revolution caused an explosion in technical breakthroughs which resulted in new materials becoming available for use in formulating adhesives. The first plastic polymer to be synthesized was cellulose nitrate, a thermoplastic material derived from the cellulose of wood. Its first use was in the manufacture of billiard balls, which had been made of ivory. The era of plastics began with the introduction of Bakelite phenolic, a thermoset plastic, in 1910. Within a year, adhesives using phenolic resin were on the market. The 1920's, 30's and 40's saw many new plastics and rubbers produced synthetically; many out of urgent necessity, developed during World War II. Although adhesives have been known for a very long time, most of the technology of adhesives has been developed in the last 100 years.

Adhesives may be classified as either organic or inorganic materials in a number of different ways; for example by origin, by method of bonding, by end use or by chemical basis (Mays and Hutchinson, 1992). Table 1 gives an overview of a general classification of organic adhesives. Even though focus will be placed on structural adhesives, some different adhesives are briefly discussed in general terms below.

Table 1 Organic adhesive classification, after (Mays and Hutchinson, 1992).

Group	Type	Source	Use
Animal	gelatin	mammals, fish	can labels
	casein	milk	plywood, blockboard
	albumen	blood	
Vegetable	starch	corn, potatoes, rice	paper, packaging
	cellulose	cellulose	leather, wood, china
Mineral	asphalt/bitumen	earth's crust	road pavements
Elastomeric	natural rubber	tree latex	carpet making (rare)
	synthetic rubber	synthetic	tyre, fabrics, bookbinding
Thermoplastic	PVA	synthetic	wood and general
	polystyrene	synthetic	model making
	cyanoacrylates	synthetic	plastics, metals, glass, rubber
	liquid acrylic	synthetic	structural vehicle assembly
Thermosetting	formaldehyde (urea/phenol)	synthetic	chipboard and plywood
	unsaturated polyesters	synthetic	glass fiber, resin mortars
	epoxy resins	synthetic	structurally, metal to metal, concrete
	polyurethane	synthetic	semi-structural uses with plastics, metals wood and sandwich panel construction

Animal Glues are made from the protein extracted from the bones, hide, hoofs and horns of animals by boiling. The extract is cooked to form a gelatin material. The gelatin can then be reliquified with heat, which gives it quick setting properties. Its major use has been in the wood and furniture industry. Animal by-products from meat processing have been the source of supply for this type of glue. Fish glue is a similar protein-based glue made from the skins and bones of fish. An exceptionally clear adhesive can be made from fish and was the first adhesive used for photographic emulsions for photo film and photo resist coatings for photoengraving processes. Casein glue is made from a protein isolated from milk. The extraction process creates an adhesive that is waterproof. Its first use was in bonding the seam of cigarette paper.

Glues made from vegetable starch, which is a carbohydrate extracted from vegetable plants such as corn, rice, wheat, and potatoes are probably better known as paste. Major uses of these materials include bonding of paper and paper products (such as bookbinding, corrugated boxes, paper bags, wallpaper paste) and as a sizing in textiles. The laundry uses starch on your shirt collars, to stiffen and give shape to your shirt. Cellulose adhesive is made from a natural polymer found in trees and woody plants; it is the adhesive used on the cellophane wrapper on cigarette packs and the adhesive on decals placed on windows.

Elastomeric adhesives are adhesives made by combining one or more rubbers or elastomers in a solvent. These solutions are further modified with additives to improve the tack or stickiness, the degree of peel strength, flexibility, the viscosity or body. Rubber-based adhesives are used in a wide variety of applications such as: contact adhesive for plastic laminates like counter tops, cabinets, desks and tables. Self sealing envelopes and shipping containers use rubber cements. Solvent based rubber adhesives have been the mainstay of the shoe and leather industry. Furthermore, silicone adhesive is a rubber-like polymer called polydimethylsiloxanes. Silicone rubber adhesives are made from a complicated process that turns elemental silicon metal made from sand (silica) into a rubbery polymer. Because of its exceptional properties, silicone adhesive has been used in some exotic applications such as the soles of the boots worn by the first astronauts to walk on the moon.

The family of thermoplastics includes cyanoacrylates which are extremely rapid curing adhesives known as instant adhesive or Super glue. A cyanoacrylate adhesive is a very rapid curing adhesive also from the acrylic family tree, but having a completely different cure system. When a drop of cyanoacrylate adhesive is put on the surface of a part, the acid stabilizer molecules react with water molecules present on the surface of the part from the relative humidity in the air. The reaction of the water and acid causes the acid stabilizer to be neutralized. The cyanoacrylate molecules then react with each other and form polymer chains without cross-linking. Cyanoacrylates begin to form polymer chains immediately on contact with the water vapor on the surface of the part. If parts are moved during initial contact, the polymerization process and polymer chains are stopped. The process must start again at a new catalyzed site. The versatility of these adhesives makes them highly useful in all industries. Some of the larger application areas are in electronics for printed circuit board wires and components, and in medical technology for disposable plastic medical devices.

Hot melt adhesives are another thermoplastic polymer that are tough and solid at room temperature, but are liquid at elevated temperatures. The origin of hot melts probably started with the use of sealing wax used to seal documents and letters with a signature ring or stamp, but the art of hot melts was not pursued until the 1960's.

Anaerobic adhesives also belong to the family of thermoplastics. They are derived from methacrylates, a monomer related to the acrylic more commonly known as Plexiglas. The basic ingredient in anaerobic adhesives is a monomer from the acrylic family, a special liquid of small molecules which can combine chemically to form a polymer or group of molecules. Anaerobic adhesives are very versatile and are used in a wide variety of applications. The very first application of an anaerobic adhesive was to lock and seal a screw in the carburetor of an automobile engine. Today, anaerobic adhesives not only lock all types of threaded fasteners, they are used to seal pipe fittings, retain bearings, pulleys, and gears to shafts as well as sealing flanged surfaces and replacing gaskets. The major users of these adhesives are the automotive, truck, construction and farming equipment companies. The actual market for these adhesives is anywhere that fasteners, gaskets, bearings or any mechanical device needs to be secured or sealed.

Unlike thermoplastics, thermosetting adhesives do not melt or flow on heating but become rubbery and loose strength. The molecular chains present in thermosetting adhesives undergo irreversible cross-linking during curing (Mays and Hutchinson, 1992). The most familiar thermosetting adhesives are the family of epoxies. Epoxy adhesives have only been available commercially since the Second World War. Epoxies are adhesive systems made by a complex chemical reaction. Various resins are made synthetically by reacting two or more chemicals. The resultant resin can then be reacted or cured by the addition of another chemical called a hardener, or catalyst. The basic epoxy resin systems are further modified to change their physical properties by the addition of such things as flexibilizers for impact resistance and flexibility, diluents or solvents to reduce the viscosity. Fillers and reinforcements like glass fiber, alumina, silica sand, clay, metal powders and flakes may be added to change properties such as heat and electrical resistance, fire resistance or retardance, and strength and adhesion to certain substrates or materials. Epoxy adhesives can bond a wide variety of high strength substrates, particularly metals. They have been used to replace some traditional metalworking methods of joining like nuts and bolts, rivets, welding, crimping, brazing and soldering. High strength epoxies are used to construct rotor blades of helicopters and attach aluminum skins to the struts of aircraft wings and tail sections. In the construction industry they are commonly use for injection of concrete cracks and external strengthening of structures.

STRUCTURAL ADHESIVES

Structural adhesives are distinguished from other adhesives by being high strength materials that are designed to support loads. Such adhesives are often subjected to cycling high and low temperatures and aggressive environments, fluids or the weather. They are generally used for the bonding of rigid structures, although a degree of flexibility is required in the adhesive to counter the effects of movement, impact or vibration. Materials most commonly bonded with structural adhesives are metals, glass, ceramics, concrete, plastics and composites. Structural adhesives include anaerobics, epoxies, reactive acrylics, polyurethanes, reactive hot melt polyurethanes, and special formulations of cyanoacrylates. As structural adhesives, epoxies are the most widely accepted and used; therefore primarily structural bonding with epoxies will be discussed in this paper. Epoxies typically contain several components, the most important being the resin. In a broad sense, the term epoxy refers to a chemical group consisting of an oxygen atom bonded with two carbon atoms already united in some way. Epoxy resins are a group of polymers with extremely different chemical, thermal and mechanical properties. The resins are obtained through refining of petroleum. The mixing of epoxy resin with a hardener results in an epoxy adhesive. The properties of epoxy plastics are mainly dependent on the hardener used. Epoxy adhesives were first used in 1930 in Germany, USA and Switzerland.

During the 1950's epoxies began to be used commercially in the construction industry. Tremper (1960) describes the use of epoxies in repairing concrete highways and Gaul and Apton (1959) for repair on runways and roads. Wakeman et. al. (1962) describes resin injection of cracked pile caps and beams.

CONSIDERATIONS FOR SELECTING THE RIGHT ADHESIVE

The successful performance of a bonded product is dependent upon adequate adhesion between two or more constituents. The strength of bonded joints depends not only on the cohesive strength of the adhesive, but also on the degree of adhesion to the bonding surface. One of the disadvantages of adhesive bonding as a method of fastening is that the surfaces need to be clean and whatever their chemical nature, coherent if a satisfactory degree of contact, and therefore adhesion, is to be obtained. This is explained schematically in figure 1. If the surface tension value of the liquid is greater than the surface-free energy value of the substrate the liquid molecules stay bound together (a); conversely, when the surface free energy value of the substrate is higher than that of the liquid it allows the liquid to uniformly wet the surface (b). The purpose of surface preparation is to remove contamination and weak surface layers, to change the substrate surface geometry, and/or introduce new chemical groups to provide, at least in the case of metals, an oxide layer more receptive to the adhesive. Different materials need different surface treatment, for example when bonding to concrete the surface is often sandblasted, properly cleaned and often a primer for the bond system is used to enhance the bond.

Figure 1 The importance to wet the surface to be bonded

Figure 2 Different forces acting on a bonded joint

In addition, the design of the bond joint may dictate the adhesive to use. Depending on the joint design varying forces will be applied to the bond, i.e.: peel versus shear, cleavage and compression, as shown schematically in figure 2. Also bond thickness and bond area will affect the ability to transfer the load. A bonded joint is preferably loaded in shear. It is also important when choosing the right adhesive to investigate the environment where the adhesive is going to be used. The ability of an adhesive to maintain adhesion while exposed to harsh environments varies as does their chemical resistance. Before we move into the use of adhesives in the construction industry a brief presentation of adhesives in the aerospace, automotive and marine industries is provided.

AEROSPACE

The earliest structural adhesive applications were made during the First World War for bonding the wooden frames of Mosquito aircraft; strength was adequate but, by today's standards, moisture resistance was poor. The motivation in the aerospace industry to replace mechanical fasteners with adhesives stems from the desire to prolong aircraft life and to reduce costly maintenance. Since aerospace structures need to be reasonable light the use of adhesives reduces the weight of the structure at same time improving the stiffness and strengths of connections. In addition, the use of adhesives prevents corrosion processes when different materials have to be combined (galvanic corrosion). Finally, due to uniform, plane load transfer through the adhesive, layer notch sensitivity is reduced.

The use of bonding also provides high potential for variation in styling due to the possibility of combining different materials. In modern military aircrafts, as much as 50 % of the airframe may be carbon fibre reinforced polymers (CFRP), with adhesives being used for primary structural bonding. An example, the Swedish military aircraft JAS Gripen, is shown in figure 3. A large part of this military plane is built of composite materials. To fasten the different composite parts together adhesive has been used. In this particular case, epoxy as well as cyan ester has been used. It can also be seen in figure 4 that the epoxies used for aerospace applications are considerably stiff.

Figure 3 The Swedish Military Aircraft Jas Gripen,
a) Composite Parts, b) Bonded Parts (SICOMP Workshop, 2004)

AUTOMOTIVE

Adhesives have been employed in the automotive industry since its beginnings, with the use of natural resins to bond wood and fabric bodies Mays and Hutchinson, (1992). Recent developments in synthetic resin technology have resulted in a very wide range of adhesive materials available to the design engineer. In figure 4, a shear strength versus strain diagram for various adhesive types used in the automotive industry is shown. From this diagram it is clear that bonding is widely used in the automotive industry both for structural- and non-structural parts.

Figure 4 Shear versus strain for different bonded parts in the automotive industry

The drivers for the automotive industry are lightweight structures, use of mixed materials, long term performance, crash performance and also styling and design. Since the adhesive can improve the stiffness and strength of a joint the weight can be reduced. Adhesive bonding can furthermore allow the realisation of combining different structural materials such as FRP, metals, glasses and ceramics. In figure 5 an example of different bonded parts and materials for the Mercedes CL-coupe is shown.

It is quite clear that many parts of different materials have to be brought together through bonding, sometimes together with rivets. In many situations this is preferred to welding. Similar to aerospace bonding, galvanic processes can be delayed or prevented when adhesives are used, in particular when different materials are joined together. Improvement of crash performance is possible by the use of substrates and adhesives with a high potential of energy absorption. Finally, diversity of styling and design are possible due the possibility of combining different materials and components and joining them together by bonding. Adhesives for automotive and industrial bonding are modified acrylics/methacrylates which provide high strength and elongation properties and also bond to thermoplastics. Other adhesives are polyurethanes, which are tough and have a high abrasion resistance and good adhesion at low temperatures. Silicones are also used for bonding to glass, plastics or other rubbers

Figure 5 Different adhesively bonded automotive parts for the Mercedes CL-Coupe (Journal-Entwicklung, July, 1999)

MARINE AND OFF-SHORE

Casein and then formaldehyde resin compositions have been used as adhesives and gap fillers in wooden boat construction for many years (Mays and Hutchinson, 1992). Many GFRP-hulled boats, both naval and civilian, now rely significantly on resins for laminating, stiffening, the fabrication of sandwich panels, and for bonding attachments. Traditionally the shipbuilding industry uses welding as the primary process for joining the different structural parts in a ship. It is well known however that this process results in induced stresses during the fabrication stage which in turn lead to distortion in the shape of structural components and indeed, the ship itself. Considerable effort has thus to be expended to mitigate these weld-induced distortions leading to increased production costs. One additional problem, in the case of aluminum, is the significant reduction in the fatigue load capacity in welded structures (Kecsmar, 2003). As a consequence, either the structural topology has to be designed to cope with increased stress levels or the scantlings of the structure have to be enhanced. In either case, there is an increase in the weight of the structure. Since structural weight needs to be minimised, especially in high speed, high performance ships, there is a need to investigate alternative joining techniques for aluminum structures; adhesive bonding is one of them (Clark, 1996 and Cantrill, 2004).

Adhesive bonding offers the opportunity to replace welding of steel structures, to reduce distortion, effectively eliminate residual stress and to improve fatigue performance when compared to welded connections. Avoidance of hot-work leads to safer construction practices in hazardous environments. Adhesive bonding of composites provides well-distributed loading and maximises the utilisation of the adherent materials. Typical adhesives in the marine industry are polyesters which are less expensive than epoxy and are widely used in other industrial applications. Polyester, however, is chemically weaker than epoxies and experiences a high degree of shrinkage. Vinyl ester, which provides higher strength, modulus of elasticity, and elongation than polyesters is still less expensive than epoxy are often preferable to polyesters. For bonding to metallic parts epoxies are typically used.

BUILDING AND CIVIL ENGINEERING

General

A wide range of adhesives have been used for many decades in the construction industry. Historically, many of the adhesives used were based on natural products and were highly effective as adhesives in essentially non-structural applications (Shaw, 1990). It has been shown that structural adhesive bonding has been employed in the aerospace and other industries for many years and for many purposes, whereas its use in civil engineering is relatively recent. However, the application of adhesive bonded structures has increased dramatically over the past few years. After the successes achieved in the aviation, automotive and transport industries, the advantages and opportunities of structural adhesive bonding are now acknowledged in the building and construction industry. The applications include adhesive bonded reinforcements, sandwich panels, adhesive bonded anchors, composite aluminum profiles and glass constructions. The use of adhesives in the construction industry may be divided into a) repair and strengthening; and b) new-built; both these areas are discussed in more detail below.

Repair and strengthening

Repair and strengthening of existing structures using bonding techniques is mainly associated with concrete structures. During the 1950's and 1960's an enormous amount of new constructions were built and, as these structures age, many faults have become evident. In addition, the deterioration of concrete structures due to many different factors has decreased useable remaining life. A variety of concrete repair methods have been developed many of which rely on adhesion between a repair material and the concrete substrate (Mays and Hutchinson, 1992). When repairing or strengthening an existing concrete structure the bond between the old structure and the new substrate is essential for proper force transfer; this is often dependent on the substrate. There are many different methods to improve the bond, but they all have in common that at least the weak laitance layer is removed. This is preferably carried out by water or sandblasting. The repair substrate may be ordinary concrete or polymer concrete, with or without reinforcement. The concrete may be put in place by traditional formworks or by spraying. If increased structural capacity is needed then external plate bonding can be an alternative. During the 1970's and up to the end of the 1990's, steel plate bonding was not unusual, however in the last decade, the use of advanced composites for external strengthening has become quite common (see for example Täljsten, 2004 and Teng et. al., 2003). Also a great number of models for debonding have been presented (including Vilnay, 1988; Roberts, 1989; Täljsten, 1994 and 1997; Chen and Teng, 2001; and Gunes, 2005).

In the UK a very large number of cast-iron-framed, brick jack-arch structures were built as public buildings, textile mills and warehouses. Many of these still stand, and careful refurbishment allows these structures to be adapted for alternative modern uses (Cadei et. al., 2004). In addition to this, in the UK 10-15 % of all bridges are believed to be metallic and many of these need to be strengthened. A similar situation also exists in the US where 52 000 structurally deficient steel bridges exist. Many of these structures can be strengthened by externally bonded CFRP systems. However, the demand for strengthening metallic structures with external plate bonding is not as great as for concrete structures.

Timber structures sometimes also need to be repaired or strengthened. Strengthening of timber beams by means of flexural reinforcement of glass or carbon fibres is a system that enhances wooden beams in several ways. First of all, a flexural capacity increase of 40-60% may be achieved (Buell and Saadatmanesh, 2005 and Svecova and Eden, 2004). Furthermore, a stiffness increase of 5-25% may also be achieved (Buell and Saadatmanesh, 2005). The most important performance increase relates to the change of failure mode from a brittle failure on the tension side of the beam to a ductile failure in compression inflicting crushing of wood. In terms of increased safety of the structure, the change in failure mode is important. For in situ upgrading of bridges, for example, simple and rational installation of the reinforcement is needed. In the case of an existing structure it may not be possible to install reinforcement bars or sheets along the entire length of a beam; therefore, the establishment of the anchoring length for the reinforcement is crucial in order to give recommendations on installation (Johansson and Stenberg, 2004). Shear reinforcement of timber beams (stirrups) might be necessary to prevent the occurrence of plug shear and splitting. Such reinforcement should be placed at locations of maximum moment, not at locations of maximum shear force. For timber members with a low span-to-depth ratio, reinforcement to sustain the shear force at the support might be needed (Svecova and Eden, 2004). The increase in bending stiffness is also tempting to use for members loaded both in bending and compression e.g. in large bridges or in rafters. Even heavily loaded columns may be an application. Work is currently underway in this area. Apart from the possible occurrence of brittle failure modes, the most pressing question for future research is the long term reliability and strength of a reinforcement system. However small, the reinforcement will always induce stresses in the surrounding wood and the impact of these stresses is not known when it comes to shrinking and swelling of wood, creep and durability of materials.

Reinforced concrete structures are designed so that the inevitable cracking of the concrete is restricted so that no cracks at the surface should exceed 0.1 mm in width. For many reasons, cracking in excess of acceptable design limits occur rather too often either during construction or during the service life of the structure. If cracks are not sealed or structurally bonded deterioration may occur. It is possible to restore the structure to its original uncracked strength by injection with low viscosity epoxy resins specially developed for repairing cracks, providing the bonding surfaces of the concrete at the crack interface are clean and sound.

There are of course many other situations related to repair and strengthening which may require a bonded joint, for example, different types of concrete overlays, although the principle remains the same – the weakest part fails. In concrete structures this is normally the old concrete substrate, in metallic structures the weak link is normally in the adhesive and for timber structures, in the case of strengthening a combined failure is likely. The

failure also depends on the type of strengthening and an over-strengthened structure may lead to a changed failure mode; i.e over-strengthening a structure in flexure, may result in a shear or compressive failure.

New-Built

If we discount glulam beams, structural bonding is not very common in new-built structures. Adhesive is often used for filling voids or gaps and to fasten secondary, non-load carrying elements. Adhesives are also used to fasten bridge bearing and expansion joint nosing. On steel decks, skid resistant surfacing materials in the form of small gravel-filled epoxy or polyester resins are often used. There are also examples where epoxy resin systems have been used to bond precast concrete slab units directly to a steel girder surface for a steel-concrete composite bridge, (German Bonded Bridge, 1979).

Applications of resins as true adhesives in new constructions have been relatively scarce although increasing use is being made of epoxies in the joints between segmental precast, prestressed bridge construction where the adhesive is being employed as a stress distributing bonding/sealing layer between the precast elements. This concept was pioneered in major structures in France in the construction of the Choisy-le Roi bridge over the River Seine near Paris in 1962 (Muller, 1964). This bridge was made up of precast concrete box units 2.5 m long. The units were “match cast” off-site in continuous lengths; one unit being cast against the next with a thin plastic film separator to ensure perfect fit and that the thickness of the epoxy layer was kept to a minimum. In comparison to mechanical or welded joints, however, structural bonded joints are few. This might change, however, with increased use of new-built FRP structures for building and civil purposes. By way of example, a brief description of a FRP bridge structure built in the UK 2002 having all structural joints made by epoxy is presented. The ASSET bridge project, founded by the European Commission, began in 1998 and was completed in the autumn of 2002. The project mainly covered design, manufacture and prototype construction of a fully polymer composite road bridge. This prototype bridge replaced an existing bridge, the West Mill bridge, in Oxfordshire. The project is described in greater detail in (Luke et. al., 2002). The prototype bridge is 7 m wide by 10 m long and consists of four rectangular longitudinal polymer composite main girders manufactured of Glass Fibre Reinforced Polymer (GFRP) stiffened with carbon fibre flanges and a fully composite bridge deck manufactured of GFRP. The bridge deck is built up of pultruded framework sections bonded together. The deck subassemblies, consisting of 5 or 6 pultruded profiles, are then bonded to the longitudinal composite girders. The mid-span cross-section of the bridge is shown in figure 6.

Figure 6 Mid-span cross-section of West Mill Bridge (sketch by Mouchel, 2002)

A significant outcome of the ASSET project has been the ability to develop a complete bridge system, whereby the advanced composites deck profiles can be connected to conventional or other advanced composite materials forming the main longitudinal beams and other relevant bridge appurtenances by bonding to form a complete bridge. From the construction work it was concluded that the bonding procedure chosen was time consuming, but also that this could be improved in future applications by a better choice of equipment for handling the composite deck during bonding. The final installation of the bridge was easy to carry out. For future applications, it would be possible to build a bridge (depending on size) off site and transport and lift it into position at site.

FUTURE BONDING POSSIBILITIES

The extraordinary climbing skills of gecko lizards, shown in figure 7, have been under investigation for a long time. (Sun et. al., 2005) have measured the adhesion force produced by an individual gecko setae. As the gecko force was influenced by the surface hydrophobicity as well as the presence of water they concluded that the dominant component of the adhesion force is the capillary force. This finding epitomizes one of many intriguing natural phenomena that can possibly be adopted to improve the technological know-how of bond without chemical components. The future will show if this can be transferred to structural applications.

Figure 7 Images of a flat-tailed house gecko and its seta. Top is a photograph of the gecko on a glass covered mirror used in the study. At the bottom are scanning electron microscope (SEM) images of gecko setae showing the tree-like structure with a magnification of (a) 900 times and (b) 8500 times (Sun W. et. al., 2005)

Another very interesting finding regarding bonding comes also from the nature. Researchers at Purdue University in the USA have discovered that iron in seawater is the key binding agent in the super-strong glues of the common blue mussel, *Mytilus edulis* (Ninan et al., 2003). The knowledge will be used to develop safer alternatives for surgical and household glues, among others. Furthermore the discovery could lead to the creation of unusual new materials with designed plasticity, strength and adhesion for structural uses. Figure 8 shows a common blue mussel “hanging tough” after a night adhering to otherwise “non-stick” Teflon.

Figure 8 Blue mussel bonding to Teflon (Ninan et al., 2003)

SUMMARY AND CONCLUSIONS

In this paper it is shown that structural bonding today is used in many different industries and appears to be becoming more and more important in the future. The aerospace and automotive industries are ahead of other industries, probably due to the need for weight savings and the for joining many different materials together. In the construction industry mechanical joints are most common and will probably continue to be so in the future. However, structural bonding in construction is not uncommon. It has been frequently used in repair and strengthening of existing structures by the use external plate bonding, sprayed concrete, concrete overlays and so on. The increase of FRP structures in the building and civil industry probably will also lead to increased use of structural bonding. However, if structural bonding is to become more widely accepted in the construction industry, it is essential that the long term behaviour of bonded joints can be guaranteed – civil structures are expected to last 50-100 years and other factors make them very different from products in the automotive and

aerospace industries. Finally, our design culture is based on codes and standards and until structural bonding is accepted in our codes the use of structural bonding will still be limited.

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