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Development of Fibre-Reinforced Polymer Composites in Building Construction

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ABSTRACT

Most human civilisations have used weak composites for building purposes. Strong man-made composites first appeared after WW II. Glass reinforced polyester was used by hand 'lay-up' but the process is labour-intensive, slow and costly. Faster, more capital-intensive production methods have emerged but most relied on short fibre lengths, which limited structural capability. The invention of pultrusion allowed long fibres to be used in mass production, enabling engineering grade fibre-reinforced polymers (FRP) to appear in construction. Higher fibre content enhanced stiffness and reduced thermal movement in an inherently thermally resistant material. This combination is almost ideal for building thermally efficient and air-tight houses. The pultrusion process can make hollow sections cheaply, imparting both stiffness and extra insulation. Hollow tubes used as connecting dowels and 'snap-fit' joints allow fast, accurate assembly and minimise site time. Pultruded FRP will build 'zero carbon' modular homes by the UK government's target date of 2016.

EMERGENCE OF STRONG COMPOSITES

Composites have been used throughout the history of building construction. Mud and straw were used to make adobe bricks or mass walls. Lime plaster was traditionally reinforced with straw or animal hair. Wood is a natural Fibre-Reinforced Polymer that has been widely used in construction. Wrought iron is a composite material: the parent metal is infused with slag filaments, principally iron silicate. In the 20th century, synthetic adhesives facilitated development of plywood and 'glulam' beams, which improved the mechanical properties of timber. Natural fibre composite materials first appeared around 1930, although they never entered building construction. Henry Ford changed his mind only at the last minute to make the Model A with mild steel rather than natural fibre composite. The notorious East German Trabant had cotton fibre composite body panels. The first man-made fibres used in composites were glass fibres. Unsaturated polyester production after the war enabled Glass Reinforced Polyester (GRP) to find an immediate application in boat building. GRP moved into building construction during the 1960s, finding applications in cladding and bespoke ornament.

Processing

Cold curing resin systems and chopped strand glass-fibre mat, together with the availability of cheap moulds, enabled 'bucket and brush' techniques to provide lighter and more durable alternatives to traditional materials in a growing range of applications. The chameleon like property of GRP enabled it to copy the appearance of traditional building components competitively, making it appropriate for many kinds of decorative details. 'Bucket and brush' methods are always labour intensive, so more mechanised processes were developed for larger volume production. Matched moulds using press or resin transfer produced higher quality components with smooth faces on both sides. Faster, more repetitive production required expensive, heated tools to press bulk or sheet moulding compounds into components. The short fibre reinforcement essential for such processes reduced the mechanical properties of the end product in line with reducing cost. When better and more exacting engineering properties were demanded, e.g. to construct Formula 1 car bodies, time-consuming and labour intensive manufacturing processes were available to achieve the desired performance, but they were always expensive.

An alternative, highly mechanised production method called pultrusion was developed that pulled fibres continuously through a heated die. A thermo-setting resin was fed into the die to bind the fibres as they passed through. The components thus produced had a higher fibre content which gave vastly superior mechanical properties to rival processes. It also had the lowest labour content, which meant it could produce high performance, FRP components at more modest cost.

Pultrusion

The shapes available to pultrusion are limited to the shape of the die which produces components of a constant cross section. Standardisation led to a range of profiles becoming available that imitated rolled steel sections. However, the mechanical properties of pultruded FRP are not the same as those of steel which is isotropic. FRP is anisotropic (i.e. it is directional and not the same in every direction like steel) and it cannot be welded. Although strong both in compression and tension, FRP is not nearly as stiff as steel. Greater stiffness is achieved by making profiles thicker but this makes them uneconomic. The first building applications also imitated steel practice but did not take into account the different material and mechanical properties of FRP. Unsurprisingly, the pultruded parts could not compete with steel because, for commonplace applications, pultrusions were always more expensive.

Fig. 1. Pultruded floor grid

To off-set the price disadvantage, the first new applications focused specifically on the beneficial properties of pultrusions, such as chemical tolerance, resistance to corrosion, low thermal, electrical conductivity and most importantly, an excellent strength-to-weight ratio. Light-weight access ladders and warm-to-touch handrails sold well, as did flooring grids

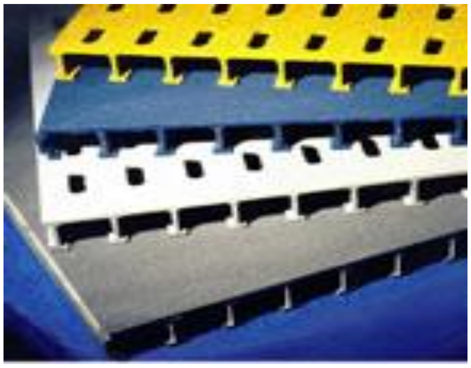

Fig. 2. Flowgrip floor panels

made of small pultrusions which interlocked at right angles and are ideal for wet areas. Whenever a solid non-slip surface was required, flat sheets with gritted surfaces were bonded to the grids.

Flooring

Redman Fisher, a traditional steel company, designed a pultruded alternative to its standard 1½" steel floor grids, called 'Flowgrip' which was more suitable for corrosive environments. A solid plate, 50cm wide, had 38mm legs to match their steel walkways and sides that interlocked to make continuous flooring. Holes were punched through the top plate where drainage was needed. Production was transferred from Fibreforce to Creative Pultrusions in America where sales boomed and 'Flowgrip' was widely copied.

Walls

Maunsell Partners, an engineering company, developed a pultruded plank to line the underside of motorway bridges. A well-engineered profile 600 x 80 mm was divided into 7 hollow sections which had thin sidewalls. Its production proved beyond the capabilities of GEC Reinforced Plastics; consequently, it was transferred to Strongwell in America. Joining planks was made difficult by the need to insert a 'dog-bone' profile from one end into recesses in the sides of adjacent planks. A sealant also had to be applied to close the joint. Nonetheless, the profile was used for a number of innovative applications from pedestrian bridges to buildings, despite the fact that it was expensive and difficult to use.

Fig. 3. Maunsell plank

Window frames

Omniglass, set up in Canada in 1984 to manufacture pultruded window frames, developed a way of making thin and complicated pultruded profiles that many had thought impossible. This clever development of the pultrusion process probably earned them more money through licensing than window frame manufacture. It demonstrated a wider potential for pultrusions. Because thin profiles pultrude faster, they could be more cost-competitive. Better thermal properties than aluminium or steel, greater strength and stiffness than PVC and more moisture-stability and durability than timber meant that pultruded window frames enjoyed great success in Canada and America. Omega pultrusions developed co-extrusion to apply a thin thermoplastic coating to their window frames that was both attractive to look at and economical to make. Recent rises in

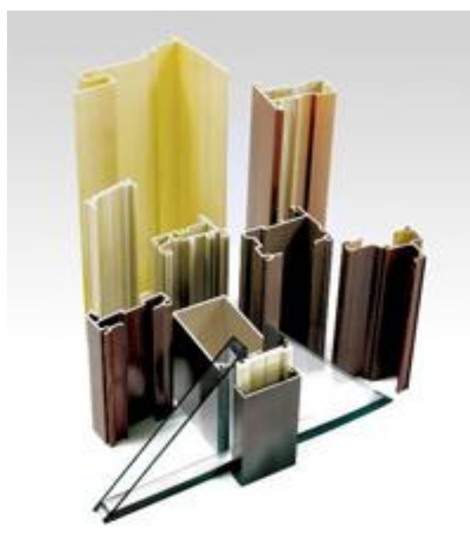

Fig. 4. Omniglass window frames

the cost of energy have made aluminium window frames more expensive than pultruded frames.

Buildings

Fig. 5. Eyecatcher building

In Switzerland, the Eyecatcher building is a five storey structure that uses pultrusions for the frame. Copying steel practice, it uses large pultruded profiles manufactured by Fiberline to demonstrate that pultrusions are a satisfactory alternative to steel frames. In Denmark, Fiberline has built for itself a new factory and headquarters. It is a 'tour de force' architecturally. One of the elements contributing to the architectural excellence is the translucent pultruded cladding applied to walls on the main facades. Matching slender window frames of the same translucent pultruded GRP are bonded to the glass. This greatly improves the thermal performance of the wall as a whole, because air infiltration at joints is virtually eliminated and there is no 'thermal bridging'. The clear polyester resin has a green tint and reveals the glass reinforcement in the pultrusions. The diaphanous property of the cladding and window frames greatly enhances the architectural effect. The architect for the factory was the Danish firm, KHR. One of its Partners, Jan Sondergaard, has designed a church in the suburbs of Copenhagen which is clad entirely in the same translucent pultrusions. The building looks from a distance as though it had been made out of clouds! This striking and unique appearance demonstrates the potential for composites to appear attractive in a way that is unsurpassed by any other building material.

BiOriginal

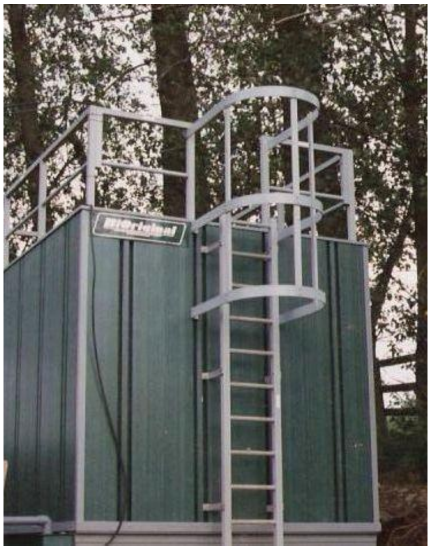

Fig. 6. Pultruded trickle filter

Development of equipment for biological treatment of waste water led naturally to the use of GRP to make treatment towers and settlement tanks. The difficult three-dimensional geometry of modular settlement tanks could only be formed by hand lay-up and the resulting system was called 'Setlink'. However, a novel application of pultrusion was used to build 'BioLink' water treatment towers. A new all-purpose pultrusion drew on the precedents set by Maunsell and 'Flowgrip'. In assembling towers, it was found that a special nut that allowed blind fixing was particularly useful. The next step was to develop four new pultruded profiles able to use 'Unistrut' (metal framing system) nuts to build better treatment towers as well as cover other applications. The system became known as 'Startlink' and a SMART award contributed to the funding of profile design and manufacture. It also helped pay for their testing at Lancaster University.

Startlink™

Despite several false starts, the system was continually refined and developed into a family of components which had broader applications. The aim in developing the system was to reduce component cost by using thin or core-filled profiles and to keep the family of components small to ensure long production runs which also reduce cost. The developed profiles were costed in America and initial evaluation of whether they could be used to build houses led to some surprising conclusions. Not only could pultrusions undercut the cost of traditional materials, but also more advantages became apparent. There followed chance meetings with an engineer enthusiastic about pultrusion and an architect with a keen interest in composite materials. Collaboration spurred the development of the profiles into a system that increasingly satisfied both engineering and architectural criteria. The next step was to publicise this discovery in order to generate interest and funding for development. Papers were written about the potential of the system to build sustainable, energy-efficient houses.

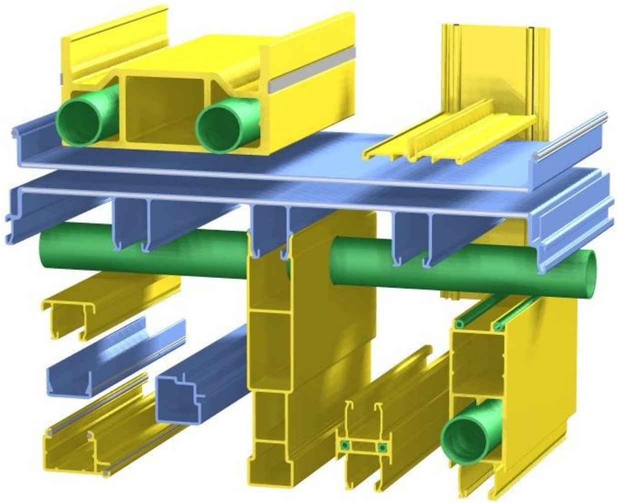

Fig. 7. Modular pultruded profiles

Making connections

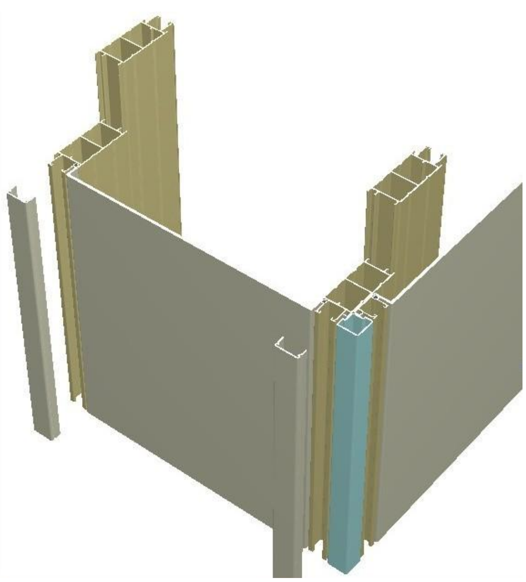

Fig. 8. Snap-fit assembly

The key to bringing pultrusions into building construction is to find a way of joining them that is as effective as welding metals. Adhesive bonding has been advanced to a state of technical excellence in composite manufacture for Formula 1 and aerospace; however, the technique requires factory conditions to be clean and environmentally controlled to laboratory standards. Time is also needed for curing. Bolted connections have limitations because bolting is problematic for pultrusions, which are not malleable like metals and the bolt head may not develop sufficient friction to secure the fastening. Bolts through pultrusions also require clearance holes to achieve alignment, which could result in loose and sloppy joints. Bolts are, nonetheless, used to join pultrusions; there are few practical alternatives. However, they require careful design and meticulous placement of washers beneath nuts and bolt heads to avoid point loads.

Instead, the ingenious and versatile 'Unistrut' (Metal framing) system has been adopted to join profiles. The realisation that thin profiles were slightly flexible led to adding the facility of 'snap-fit' with its great potential for labour-saving. The result of this fusion was a joint that combined both types of fastening and this combined jointing system has been patented. The jointing method enables components to interlock continuously along the joint line without risk of their coming apart. Furthermore, integral gasket seals make the joints both waterproof and airtight. Another key development is the use of dowels to join structural components. Hollow sections suit the pultrusion process and multiple hollow sections resist buckling in a material that is not as stiff as steel. Pultruded tubes are widely available and are used to join hollow components in a versatile, cost-effective way. Thin hollow sections, snap-fit and dowelled joints are the features that avoid reliance on steel and ensure rapid and effective assembly of pultrusions into finished buildings. Ease of assembly is one of several factors that will make pultrusions ideally suited to building construction.

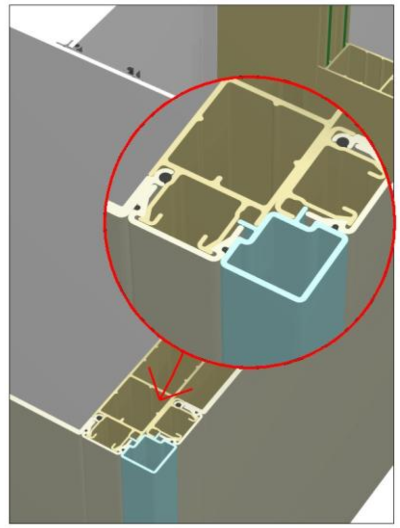

Fig. 9. Gasket seals

CLIMATE CHANGE

The Building Regulations were made tougher in relation to energy demand and thermal performance in April 2006. The UK Government took its cue from an EU Directive of 2002 that was intended to mitigate climate change. Policy is now being focused on the reduction of greenhouse gas emissions. Both Houses of Parliament have just passed the Climate Change Act 2008. By doing this, the Government has committed itself and successive governments to reducing CO_2 emissions by 80% within the next 41 years. Buildings account for approximately 40% of UK greenhouse gas emissions. 8 – 9% of total UK emissions arise from the materials manufacturing and construction phases (UN Environment Programme); therefore, construction is an obvious target for legislative measures that will reduce this total rapidly and effectively. There is now a policy drive to make Building Regulations incrementally tougher, starting with the next revision due in 2010 and continuing at three-to-four year intervals up to the middle of the next decade. Ruth Kelly in her then capacity as UK Secretary of State spoke at a conference in Germany in 2007, saying that the UK Government was targeting compliance with the German Passivhaus standard for all newly built houses by 2016. The actual UK government policy commitment is for all new homes to be 'zero-carbon' by 2016. Neither target is achievable unless house-building technology changes radically between now and 2016.

Construction challenge

One obvious change would be a decisive and permanent move away from so-called 'rationalised traditional' building construction, in which it is both difficult and expensive to achieve air-tightness and to eliminate 'thermal bridging'. The only alternative construction material that could, at a stroke, offer an effective solution to both these problems would be pultruded FRP. A set of modular, inherently versatile, pultruded components could replace the growing profusion of materials required in 'rationalised traditional' construction as it struggles to meet ever higher standards. The vagaries of the average building site would disappear. These normally cause loss of quality and lack of dimensional accuracy which conflicts with constructing energy efficient buildings. The cost-benefits of mass-production would become available and quality control could be imposed effortlessly because the lion's share of production would be factory based. Furthermore, if factory based production could replace human input with electronically controlled automation, quality would improve further whilst production costs would decline. Site assembly that required no skilled labour or reliance on water to set concrete, cement mortar or plaster would speed building delivery and eliminate use of Ordinary Portland Cement. During the manufacture of OPC, CO_2 is driven out of carbonate rock in large quantities as it is calcined.

One range of such components already exists as a well-developed design. In January 2009, a Technology Strategy Board funded project was launched that will enable this system to undergo a full range of structural modelling and production trials. A prototype two storey house will be built and tested to validate the theoretical superiority of this form of construction. By achieving Passivhaus standards, it is intended to prove that there would be much lower energy demand and that CO_2 emissions, both in manufacture and in use, would be reduced by the 80% required by the Climate Change Act.

Building the future

A design for a basic two storey, three bedroom pultruded house has been worked out in detail, thus providing an opportunity to estimate material usage. Pultrusion properties make most other materials unnecessary, leaving only a requirement for additional insulation. FRP is thermally resistant and it eliminates "cold bridging". Air-tightness is achieved by factory based bonding and the provision of sealing gaskets integral to the system. Internal linings would be made with an entirely incombustible material based on magnesium silicate, which is vapour permeable. This property would enable hydrophilic natural fibres placed as cavity insulation to absorb and release moisture, thereby using the latent heat of water to balance internal temperature and humidity. There would be no need for "thermal mass" to exert this environmental control. The linings would also be stronger with fire resistance far beyond the capabilities of plasterboard. Passivhaus standards could be achieved with 350mm of natural fibre insulation. This could give a U value as low as 0.1 $W/m^2/°K$. Such a dwelling built with about 10 tonnes of pultrusions and having insulated cavities, screw-pile foundations, modular services and standard fittings would be between 10% and 20% cheaper than a "zero-carbon" house built conventionally. Solar water heating and PV panels could be funded from money saved by fast, cost-effective assembly that did not need the site complement of skilled labour necessary to achieve the same environmental standard in traditional construction.

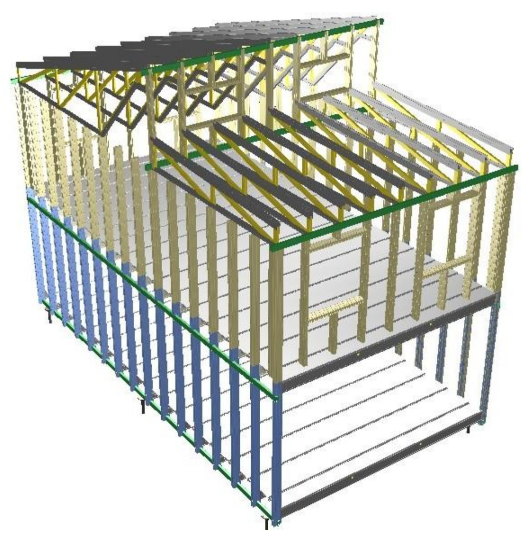

Fig. 10. Pultruded house structure

Labour saving

The biggest cost in building construction is labour. Conventional house building costs are generally reckoned to be 55% labour and 45% materials and preliminary items because building construction has always been labour intensive. More modern methods entailing mostly 'off-site' construction have, so far, achieved little more than reductions in site-time. The latest systems from continental Europe do show improved quality but this has been a long time coming. A pultruded basic house would consist of finished pultrusions delivered directly to site as one 'flat-packed' load. A four man crew with a mobile light crane could erect a house in two days. 'Second fix' would take another two days. Affordable homes could be offered to meet Sustainability Code 6 at unmatched pace. The additional cost burden for meeting Code 6, reckoned to be 25%-40% for conventional buildings, would be around 10%. This is a timely development, given UK government intentions to build 3 million new "zero carbon" homes by 2020.

Adaptability

Fig. 11. Interior wall fixings

So-called "intelligent buildings" use electronics to enable them to adapt to the way occupants use them. Traditional construction materials do not lend themselves to this adaptation. Post-construction modifications are costly. They generate a large amount of waste that is difficult to recycle. At present, 32% of landfill comes from the construction and demolition of buildings (TSB). Pultruded components can be delivered to site, cut to size and finished, producing no site waste at all. Formed into buildings, external studs could be dowelled to floor panel/beams that spanned 6m under domestic loading and each would be light enough for two people to carry. Being modular, 6m bays could be extended endlessly and additional bays added alongside. The open internal space would be divided by internal walls that were not load-bearing. Small pultruded wall plates screwed to floors and ceilings in parallel and end stops screwed to end walls would allow internal walls of any size to be configured using nothing more than snap-fit to hold them together. This unprecedented flexibility would also allow walls to be easily reconfigured at minimum cost and without making any waste.

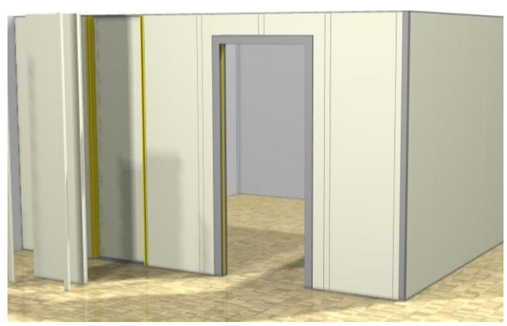

Fig. 12. Interior wall with doorway

Intelligent construction

Already, architects use computers to generate both design drawings and detail drawings. Drawings are now issued in digital form as pdf attachments or j-pegs rather than as paper copies. At planning stages, computer generated three dimensional images are usually produced and circulated to support potentially controversial applications for development consent.

If building construction were to move from its present site based activities, which are more redolent of early twentieth century practice than anything that pertains in current production of vehicles or electronic goods, building components could be generated as design elements, dimensioned to fit both the building and the site, integrated with services and their associated service routes and manipulated to produce appealing aesthetic elevations solely by computer. The digitised information could then be fed to a factory to make the components with Computer Numerically Controlled equipment on exactly the same "just-in-time" basis that now applies in the manufacture of motor cars.

Ordering, invoicing and record keeping could be managed electronically, as is the case with other areas of manufacturing. All information necessary to obtain consent under the relevant parts of the Building Regulations would be stored in the computer memory. The programmes would manipulate the information so that a Building Regulations consent application could be swiftly compiled and issued for any proposed development. Structural performance of the components would be retained in the programme. The calculations needed to demonstrate a building's structural performance and long-term stability could be done in a few seconds and sent out to all concerned parties as an email attachment.

Computer programmes could be written to create and to have fastened on any particular component RFID tags which would identify that component, its location in the building relative to other components, its structural performance and the approved means of handling and installation within the construction. The same tag could have maintenance instructions written into it. A Facilities Manager would pass a reader over the chip every four years to find out what maintenance (if any) was due. The completion of maintenance tasks would be entered in the building's digitised maintenance record. At end of life, the same tag would contain information about re-cycling options, "buy-back" possibilities or, if neither of these applied, safe and environmentally responsible disposal routes.

Under current building construction practice, it is difficult to see how this elegant, time-saving and cost reducing method could be implemented satisfactorily. Building material procurement routes are too convoluted and disjointed; also, contractual relationships are too meandering and difficult to disentangle. However, a building construction system based on one production process, a closely related family of strong, lightweight materials and straightforward procurement options for the constituent materials could lend itself very readily to rational and cost-effective use of sophisticated computer technology, as described above.

Pultrusion makes such a system possible. Adaptation of a pultruded system to this kind of computer technology would be relatively easy. Were such a system to be brought into existence with such an advantage built in, it could sweep aside over-complicated and labour intensive conventional construction methods in little more than a decade.

Aversion to risk

In recent history, new techniques introduced into construction, particularly those associated with factory-based ‘system building’, have conspicuously failed to meet expectations. Contractors, employers and building owners have been saddled with technical failures and increased costs, both in the construction phase and from defects in use. Their collective perception has often been that of unwilling guinea-pigs having to cope with the intractable problems inflicted on them by inadequately tested building prototypes. The inheritance from these experiences within the industry is an ingrained aversion to any of the perceived risks associated with innovation or with apparently untried ways of doing things. Quantity surveyors and estimators are also happier with conventional construction methods. They are much easier to price. There are no hidden price escalators or other traps for the unwary.

Design liability

Unless it is contractually assigned to another party, design liability lies with a building's architect who is responsible for any defects arising from inappropriate or incorrect detail design or specification. The liability can continue beyond a change in building ownership for as long as fifteen years after completion. The cost of rectifying serious building defects can be as large as the cost of the original construction, particularly if occupants have to be evacuated and accommodated elsewhere. In addition, the costs arising from protracted dispute resolution by legal process can be gargantuan. Building designers can defend themselves against lawsuits by specifying strict compliance with established Codes and Standards of which there are hardly any that apply to FRP for use in building construction.

The removal of detail design and specification liabilities from architects and designers is yet another compelling advantage of a pultruded building system. An architect would simply specify the entire package, bypassing responsibility for detail design and specification. This would allow the architect to concentrate on site layout, massing, elevational treatment and internal planning. Aspects such as structural stability, weather-tightness, durability and fitness for purpose would be covered by the system product warranties and guarantees. These would be supported and certified by an internationally recognised accreditation body, such as the British Board of Agrément. The other usual members of a building team would then have no liability because they would have no role. No quantity surveyor would be needed for such a project. Structural and M&E design would be bought as an integral part of the system. Instead of a building contractor, a team of riggers would assemble the components in accordance with the pre-determined erection sequence which will also be part of the system. Viewers of "Grand Designs" will recall the Teutonic diligence, precision and organisation of the team of German riggers that built the Huf Haus. Startlink™ would offer a superior system in terms of material properties. Well-trained and motivated riggers would facilitate adept and swift assembly which could be even more impressive than Huf Haus but at a more modest cost.

STRONG COMPOSITES FUTURE

The consequences of climate change are already visible in changing weather patterns. In the UK, this led to recent flooding and highlighted the danger of building on floodplains. In other parts of the world, hurricanes and natural disasters from earthquakes to tsunamis have affected buildings severely. It is becoming clear that buildings must not only resist environmental impacts caused by climate change and natural disasters but also reduce their impact on the environment by eliminating waste, CO_2 emissions and by saving energy. One building material stands out in its ability to do both yet it is little known outside the industry that produces it. Stronger than steel yet ¼ of the weight, it is the first structural building material that is unaffected by water or the termites and decay that damage natural materials. Strong man-made composites offer a timely solution towards the biggest problem the world currently faces: global warming.

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