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Advanced Composites for Earthquake Resistant Structures

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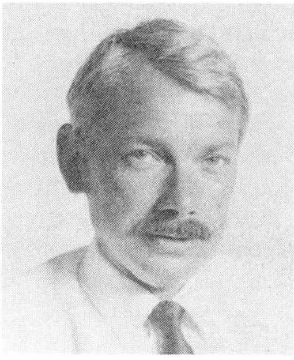

Peter Head has played a key role in research and design development leading to the introduction of advanced composites in civil and structural engineering. Notable successes are the world's first all composite footbridge, first advanced composite road bridge and one of the first all composite multi-storey buildings. He was awarded the Royal Academy of Engineering's Silver Medal in 1995 for an outstanding personal contribution to British Industry.

Summary

Lightweight high-strength advanced composite materials are now being used to retrofit and strengthen many earthquake-prone structures in Japan and USA. Little attention has been paid to the role these materials could play in the design of a new generation of building and bridge structures which have much greater resistance to earthquakes. The high strength to weight ratio of fibre reinforced polymers makes them ideally suited to this role and development work in new forms of composite structure carried out over the last ten years points the way forward. The paper examines this work in detail and shows the new forms of structure that could be adopted in the future to provide more cost effective and reliable solutions.

1. Introduction

Advanced composite fibre reinforced polymer materials are now being introduced into a wide range of civil and structural engineering applications. In Japan these include concrete reinforcement and prestressing using carbon fibres, ground anchors using carbon and aramid fibres and rock bolts using glass fibres. Perhaps the largest application area is the retrofit strengthening of existing reinforced concrete structures to improve their resistance to earthquake damage. The high strength and stiffness characteristics of the fibres, when bonded to and wrapped around concrete columns and beams has been found to greatly increase the ductability of the reinforced concrete in the rapidly changing stress cycles experienced during earthquakes.

The stresses generated in earthquakes are a direct function of the mass and dynamic frequency response of the structure. Considerable design development has taken place in the last thirty years to refine the way in which steel and concrete are used in tall buildings and bridges to improve earthquake resistance and further developments are reported at this Conference.

However most findings are reported with no recognition of the important role that advanced composite materials could play in this design area in the future. Research work carried out in the United Kingdom over the last 15 years has demonstrated new structural forms that can be used to build lightweight advanced composite bridges and building structures.

The paper presents detailed information on these systems and then indicates using some design studies how they might be applied in the future to achieve reliable but effective solutions for major structures in earthquake prone areas. The paper concludes by suggesting areas of research for the future.

2. Advanced Composite Materials and Building Systems

Advanced composite materials are fibre reinforced polymer structural sections in which the continuous fibres have high strength and stiffness and are orientated in the direction of maximum stress (Fig.1). Most sections currently used in construction are pultruded and typical properties for different fibre types are shown in Table 1. Important physical characteristics are the high strength to weight ratio compared with steel and concrete which makes the materials more attractive as the structure span and height increases. Designs, particularly when using glass reinforcement, are governed by stiffness rather than strength, because of the high strength to stiffness ratio. Hence in actual designs we find that the low structural weight reduces cyclical dynamic earthquake forces in these structures and there is also a large reserve of strength and strain capability before rupture. Although the materials are inherently brittle in tensile tests, well designed structures exhibit much improved earthquake resistance. The method of construction and form of connection are, however, critical.

Fibre Reinforcement		Glass	Carbon	Aramid	High Tensile Steel Wire
Fibre Fraction	%wt	80	72	67	-
Relative Density	ρ	2.31	1.57	1.36	7.86
Tensile Strength τ	GPa	0.95	1.61	1.59	1.82
Tensile Modulus ε	GPa	50	136	64.3	200
Specific Strength	τ/ρ	44	105	119	24
Specific Modulus	ε/ρ	21.6	86.6	47.3	25.4

Table 1: Properties of composites with high proportions of unidirectional fibre reinforcement

Fig. 1 Pultruded section showing glass reinforcement

The Advanced Composite Construction System (ACCS) was conceived and developed by Maunsell to try to meet the growing demand for a lightweight modular system for constructing buildings and bridges which would reduce the labour costs for assembly and would provide lower capital and operating costs. Other systems may come along in the future but this proven one enables new forms of bridge and building to be illustrated. The system that was conceived and patented in 1982 is a cellular system of components (Fig 2) which can be formed around an insulating core.

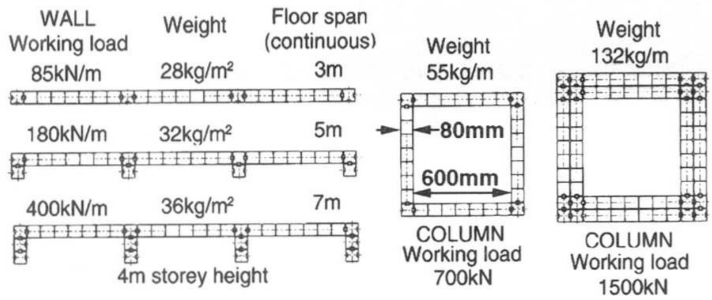

Fig. 2 ACCS components

Walls, columns, beams, bridge girders, floors and roofs can be built using just three primary components pultruded from glass fibres and a suitable thermoset resin and insulating core materials. Structures can be designed using a fully developed limit state design method which is consistent with British and European building codes (1) (Fig 3).

The unique method of connection allows any two components to be brought together, side by side, with epoxy adhesive applied to one face, and by sliding the toggle connector into the groove which holds the components together in accurate alignment while the adhesive cures. In site applications, heaters can be used to achieve controlled and rapid cure.

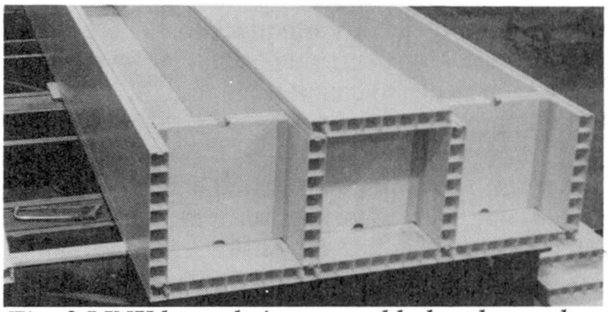

Fig. 3 LINK beam being assembled at the works

The first Research Programme undertaken on structures built from this System was a LINK programme carried out at the University of Surrey between 1991-93 in which two major beams, each 18 metres long, were built (Fig 3) and subjected to a wide range of long and short term static and dynamic load tests (2), including full flexural tests to destruction. Small components were also subjected to a full range of accelerated weathering, fatigue, fire and strain aging tests.

3. Bridge Decks

ACCS has been used to build a variety of different bridge decks. The beam shown in Fig 3 has been used for the design of footbridges with spans up to 17 metres (Fig 4) and road bridges with spans up to 12 metres (to be constructed in 1999). The weight of the beams is 40% of an all steel design and less than 15% of a steel composite solution with a concrete deck. Hence in addition to offering excellent durability, the lightweight structures offer much reduced vertical and horizontal earthquake forces generated in support structures.

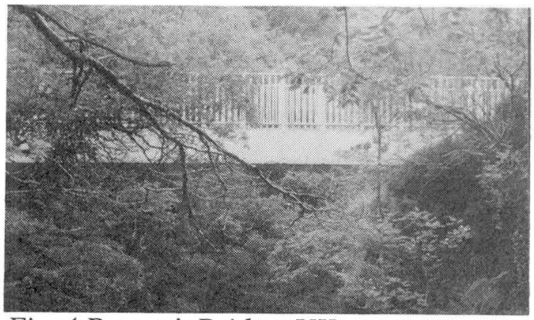

Fig. 4 Parson's Bridge, UK

Designs are also being progressed in which the advanced composite materials are used to form an aerodynamic enclosure and torsional box connected to a lightweight steel space frame truss (Fig 5). This system is called *SPACES* and offers construction (3) and earthquake resistant advantages also. The weight can be significantly less than a traditional truss bridge deck.

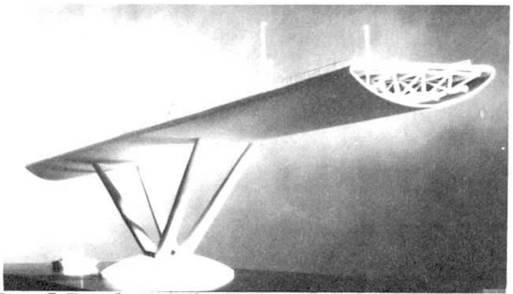

Fig. 5 Poole Harbour bridge design, UK

4. Building Structures

4.1 Beam, Column, Floor, Wall and Roof Sections

Figures 2 and 6 show typical configurations of ACCS used in beam and slab floors, load bearing walls and columns. Table 2 shows some comparative weights of typical steel, concrete, composite and brick structures which provide similar load carrying and other functional characteristics. It can be seen that very substantial weight reductions can be achieved using advanced composite materials and these can have major advantages in reducing foundation costs and improving earthquake resistance in tall buildings. Earthquake resistance also derives from the high strength to weight ratio and lower elastic stiffness. A two storey office building was built in Bristol in 1992 using this System and no other materials. It has been used successfully ever since (Fig 7).

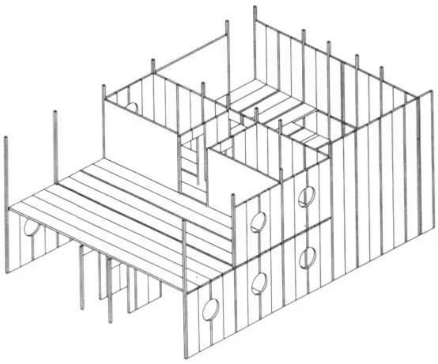

Fig. 6 Typical configeration of ACCS uses in buildings

Fig. 7 Second Severn Crossing site office

Typical Walls	ACCS Wall Brick Cavity Wall Reinforced Concrete Wall	= 0.3 Kn/m^2 = 2.0 Kn/m^2 = 2.2 Kn/m^2
Typical Floors (5 metre span)	ACCS Floor Reinforced concrete floor Lightweight concrete/metal deck floor	= 0.35 Kn/m^2 = 3.3 Kn/m^2 = 2.2 Kn/m^2

Table 2: Comparative weights of different materials

4.2 Thermal Insulation

ACCS sections 80mm thick with a polyurethane foam core have a thermal insulation value of U = 0.35 W/m^{2}K. This meets UK requirements for domestic buildings and offices. Buildings can be fitted with double glazed windows with pultruded GRP window frames and this then provides a largely integral glass structure with excellent thermal insulation and uniform temperature expansion characteristics. The GRP sections overcome the cold-bridge effect and buildings have been found to be comfortable and have low running costs. Window seals maintain their integrity because of the lack of differential expansion.

4.3 Fire Performance

ACCS sections manufactured from glass fibre and isopthalic polyester resins, with a polyurethane foam core, have been tested in a whole range of fire tests (Fig 8). The high glass content in each pultruded section means that heat is not conducted away from the fire source, or through the panel thickness. Also glass has a relatively high melting temperature and the cellular configuration of the panels maintains load carrying integrity for long periods of time. Panels meet BS 476 Part 7 Class 1 surface spread of flame test requirements and can provide up to 60 minutes fire resistance as a wall or floor section in a BS 476 Part 21 Test. Surface coatings can be used to achieve Class 0 spread of flame performance and to further inhibit smoke emission. If smoke is a design criterion, alternative resins are available for pultrusion such as phenolics and methacrylates.

Fig. 8 ACCS wall panel test to BS 476 Part 21

4.4 Durability and Long Term Performance

Well designed Advanced Composite building structures such as ACCS can be expected to have low maintenance costs because of the inherent excellent durability of the materials. They are resistant to UV deterioration, moisture ingress and chemical attack because of the high glass content, careful manufacture and choice of resin. The technological advances made by those developing ACCS over the last ten years has led to a quality of manufacture and accuracy of fit that has previously been unavailable in the building industry. This enables water tightness and integrity to be achieved consistently with new modular forms of construction.

4.5 Environmental Considerations

There is a worldwide realisation of the damage that a rapidly rising energy-consuming population can do to the ecology and environmental balance of the planet. There is general agreement that future technology developments will need to meet criteria such as biological sustainability, minimum use of energy and raw materials that will probably be set internationally.

Advanced composite materials are being seen to have benefits compared with traditional materials in many of these areas, particularly in their low energy consumption during manufacture, construction and subsequent building operation (4). Although there are environmental problems associated with material manufacture, particularly resins, a number of far sighted manufacturers are already improving this aspect significantly. Glass reinforced plastics require relatively low energy during manufacture compared with metal structures, have much lower thermal conductivity and are more durable.

4.6 Electrical Properties and Service Integration

Electrical 'field free' properties are inherent in an ACCS building structure which is a major advantage in an age when buildings are becoming a support framework for large complex computer networks, whether it be the office or home. The cellular structure also enables services to be channelled out of sight. There is an inherent labyrinth of service channels in the panels of a building. If a water service leaks in an unseen location there is no danger of corrosion and structural deterioration.

4.7 Acoustic Insulation

Tests have shown that attenuation of airborne noise through a standard ACCS panel is much better than simple calculations based on the weight would suggest and is typically 25dB Leq. Structural borne noise is a significant design matter because of the lightweight structure. Special floor tiles with a foam underlay, or suspended floor structures are needed where stringent noise transmission requirements are present.

4.8 Blast and Dynamic Load Resistance

The integrity and flexibility of bonded monocoque advanced composite building structures makes them uniquely resistant to bomb and other dynamic loading such as gas explosions. This has been proven in tests carried out for the use of the materials in blast walls for offshore structures (5). Advanced composites have become important materials in offshore construction over the last five years to reduce topside weights and to improve accidental blast and fire resistance. This points the way for the use of the materials in tall buildings.

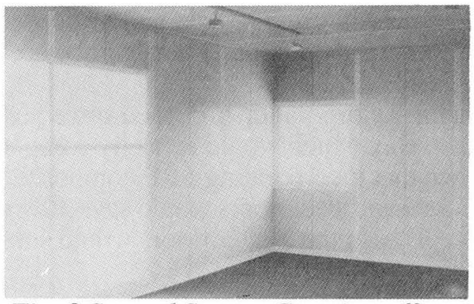

Fig. 9 Second Severn Crossing office conference room

5. Forms of Structure and Connections

A new form of building structure has been developed using ACCS in which the walls and floors are bonded together to form an integral monocoque structure (Fig 6). Vertical ACCS panels in the walls, with suitable openings for doors and windows, form the vertical box carrying members and floors span between them and act as stiffening diaphragms to the vertical box structure. Floors can be ribbed slabs or a beam and slab form if the spans are large.

Wall and floor components can be delivered flat packed and are light enough to be handled by small cranes or robots. Connections are made by bonding as described earlier and load continuity between ends of sections is achieved by bonded lapping sections, rather like bolted splice plates where bolts are replaced with adhesive. Connection integrity can be further enhanced with local *in situ* carbon fibre wrapping.

There is no reason why very tall multi-storey buildings cannot be built this way in the future. Such structures will have major advantages in earthquake prone areas and will enable a completely new approach to building safety to be achieved in these situations. Fig 9 shows the inside of an ACCS office building.

Design work carried out to date has shown that buildings up to ten storeys high can be built using the form of structure shown in Fig 6, and excellent resistance to even extreme earthquakes can be achieved. Also foundation loads are much lower and so construction on poor ground can become more attractive and cracking caused by differential settlement is eliminated.

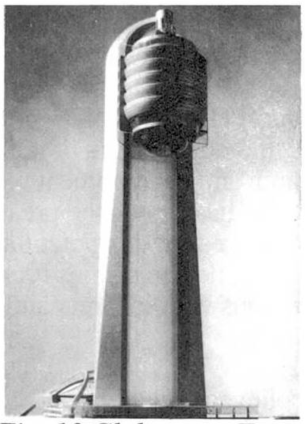

Fig. 10 Globorama Tower

The architectural possibilities of this form of building structure are only just beginning to be investigated. The combination of ACCS pultrusions, curved mouldings and glass provide exciting opportunities for new structural forms.

Fig 10 shows a proposed tower structure called Globorama in which the top viewing platforms and entertainment centre are constructed using bonded advanced composite materials. The lightweight materials enable such new forms of structure to be considered, whereas previously with traditional materials dynamic oscillation would have been a near insoluble problem. A small mass damper is all that is needed to ensure the comfort of users at the top of the 190m high tower.

6. Extending The Limits of Tall Buildings

An important question that needs to be addressed is cost. Advanced composite materials are generally more expensive materials than steel and concrete but can form cost effective complete structures when advantages of lightness and ease of construction are fully utilised. When incorporated in taller buildings the advantages of weight reduction become greater and greater. Since even two storey buildings can be attractive from a cost point of view, when mass produced, it is certain that their use in tall buildings of the future will grow rapidly and most particularly in earthquake prone areas. Here both vertical and horizontal acceleration effects will be accommodated more easily.

Obayashi Corporation proposed some years ago a building structure called Aeropolis 2001 (Fig 11) in Tokyo Bay which would be a city complex rising 2000m into the sky. A desk study by the author has shown that incorporating FRP composite floor systems into the 500 storeys instead of the lightweight concrete and steel floors would save 30% of the main column steel weight, a staggering 270,000 tonnes of steel. Also the lighter floors would substantially reduce the design problems under earthquake loading.

Lightweight materials can also be used to build extra storeys on top of existing buildings, thereby gaining significant additional revenue from a developer's existing land.

Building designers can also consider putting an increasing proportion of advanced composites into a building at a greater height from the ground. A building could therefore start with traditional heavy steel and concrete at ground level and move to the use of lighter advanced composite floors at the middle levels and then change to an all advanced composite bonded monocoque form at the top. This change in material could also be reflected in the architecture to bring more curved aerodynamic shapes at the higher levels, where wind speeds are greater.

Fig. 11 Aeropolis 2001

7. Conclusions

Sophisticated design solutions are now being adopted in steel and concrete to produce cost effective tall buildings and bridges in earthquake prone areas. These include large dynamic dampers and the introduction of plastic hinges in steel beams.

More cost effective solutions may lie in the incorporation of advanced composite materials into bridge decks, the upper floors of tall buildings and in the complete structures of buildings up to ten storeys. Research and development work in the United Kingdom and the construction of a number of prototype structures has shown the great potential of these materials. Areas of research and development that are needed to realise this potential in other countries are testing for earthquake resistance and fire resistance; design studies for overall costing; national testing for compliance with Building Standards; discussions with Insurers and Statutory Authorities and production of building and construction standards.

It is believed that advanced composite materials will gain significant applications in building construction in earthquake prone areas of the world within the next 10 years.

References:

1. Head P.R., Templeman R.B. *The Application of Limit State Design Principles to Fibre Reinforced Plastics*, British Plastics Federation RP Group Congress 1986.
2. Lee J., Holloway L., Thorne A. and Head P.R. *Long term static testing of an FRP prototype highway structure*. Composite Structures 28 pp441-448. 1994.
3. Cadei J.M.C., Churchman A.E. *The Design Approach for a Raw Composite Space Frame Bridge System*, IABSE Composite Construction Conventional & Innovative Conference, Innsbruck 1997
4. Dawson D.G. *How Green is Reinforced Plastic in Construction*. British Plastics Federation RP Group Congress 1992 BPF.
5. Churchman A.E., Cadei J.M.C. *The Development and Implementation of a Predictive Capability for Advanced Composite Materials*. Composite Materials for Offshore Use, MIMechE. London 1994