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Concepts of Composite Construction - Mutatis Mutandis

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Summary

Composite construction encourages a focus on minutiae which becomes self reinforcing. Composite construction can be seen as a system concept. If one reviews it on that basis, the huge scope awaiting exploitation reveals itself.

Introduction

Construction and in particular structural design seem to stimulate the desire to extend the scope of what can be analysed holistically or in a unified manner, what we might describe as the analysable entity. In civil and structural engineering, this desire has often been focused on construction made of a notionally single material, reinforced concrete or stone or steel.

The development of our profession is illuminated by a series of distinct redefinitions of that analysable entity. Some become simply bigger or more complex, some arise from advances in technique, some are by the articulation of elements to disaggregate the difficult whole and some focus on conceptions of the technologies and processes which bring our structures into being.

Examples of the bigger or more complex include many of those bridges which are the proud record of IABSE members. But they also include structures more modest in scale, such as the shells of Candela or the membrane structures of Frei Otto or the glass structures of Tim MacFarlane.

Examples of advances in technique include the development of limit state theory, matrix methods, finite element analysis and Jacques Heyman's analyses of Gothic stone structures.

The Forth Railway Bridge and the Buckminster Fuller "tensegrity" structures both demonstrate the power of articulation into tension and compression elements. The structural behaviour, the system points and load paths, can be sensed and read off the completed structure.

In some cases the actual articulation is used to dissect the analysable entity out from its complex surroundings. A recent case is seismic design work for a Californian building making use of base isolation elements to separate the upper structure, which is then regarded as a virtual pendulum.

The intellectual restatement of the general process with which I am most familiar is what is called total architecture or total design, as formulated by Ove Arup. This conception has itself been interpreted and developed in use, with our growing understanding of the detailed implications of design. It is always characterised by the creative tensions between synthesis and analysis, between harmony and invention, between the established and the unknown and hopefully by sufficient eventual reconciliation.

We should pair the topic of the analysable entity with the framework of time which gives us the order to events that we call history. Civil engineering structures have usually been conceived as one act, however large and even if their actual construction stretches over decades.

With building structures, however, it is a surprisingly recent phenomenon, probably less than 300 years old for major buildings again to be designed as a unity and then to be completed more or less without change. Sir Christopher Wren was the first modern designer of a cathedral to see his design built. Brunelleschi's Duomo was constructed on supports which had been designed and built more than a century earlier and with little idea of how the space could be spanned. Many may argue bitterly that we have again regressed and design in parts as the construction proceeds.

Time is significant in three additional ways:

- we seek durability and longevity of predicted performance
- we add elements for changes of use and we add repairing or strengthening elements to cope with wear and ageing
- we use temporary works and falsework as a crucial element in the process or explore whether to eliminate them. The design for the Kingsgate Footbridge in Durham is an example of treating the temporary works by rotating the structures as integral to the total concept.

Composite construction

There is nothing unusually special about composite construction. The composite concept is very old.

The origins of the minerals and metals which we use in construction are in the ground in an unhelpful mix of composites. We variously recover, refine, transform and recombine these minerals into our composite materials, cements, plasters, concrete, brick, clay tiles, terra cotta, irons and steels, aluminium alloys and glasses.

The natural organic building materials (straw, reeds, timber and so on) are in themselves, composite materials. Natural structures offer us fascinating models for structural form and environmental control through their material arrangements.

One of man's earliest deliberately composite materials is probably the sun-dried, straw-bound brick. Even then, there was some understanding of the criticality of quality control, the history recording the warning about bricks without straw.

The use of iron cramps in the Acropolis stonework, of Victorian cast and wrought iron and of timber roof trusses, right through to today's use of steel/concrete and advanced polymers, all provide more recent examples of the use of the composite technique.

Today, we have started to combine materials to exploit and extend our modern understanding of composites; steel with concrete, glass and carbon with polymer and so on.

Composite construction thus describes the combination of elements or materials in ways which can be regarded as delivering a single analysable entity. These have also meant the synthesis of discrete elements, extending the spatial extent of that analysable entity. The extraordinary bridges by Maillart show us how we can extend the spatial scope of what we learn as elements into one whole bridge. The work of Fazlar Khan gave the language for a major evolution in our structural concepts of the tall building. A less obvious example is the long history of developing the structural theory of the column.

The Pegasus Paradigm

Across the axis of time we have in composite construction, a further dimension, that of definition through use and familiarity.

The creature Pegasus was formed by combining the body of a horse with the wings of a bird. Initially we comprehend the idea through the properties and qualities which the elements of composition, the horse and the bird bring to the whole. Later, ***through use*** and in language, narrative and recollection we come to treat the overall idea as a concept in itself and to realise what is distinct and gives new meaning in the unified concept.

We find this in design. A motor-cycle is more than an engine plus a bike and has become a distinct single concept. We know that e-mail is more than electrified correspondence.

So it is with composite construction. The most familiar example is reinforced concrete, which so often we can usefully regard as homogenous, as a single isotropic material. The RC paradigm has some of the original properties of the separate constituents but more importantly it has its own qualities not possessed by any one constituent.

The rediscovery today of lime putty mortars adds to our options of cement mortars, from which we see more clearly that bricks-and-mortar is a wide repertory of composite materials. This counterpoint of new and old brickwork as distinctive materials is nicely demonstrated in two buildings designed by Michael Hopkins. Glyndebourne Opera House has lime putty mortar to eliminate movement joints. The Inland Revenue Centre has cement mortar, so that the brickwork could be built in the factory and then be transported and erected on site as precast elements.

In the vista of composite construction, the most interesting issues are those made possible by the new understandings and new possibilities of the composites, those aspects which are not properties of the separate parts. These are our contribution to the Pegasus paradigm.

The Challenge of Composites

We are at the stage in the development of composite construction where we can ask some questions

- How do we systematise composite materials, composite structures and composite construction so that we will discover new possibilities of form, geometry, connection, detail and performance as the norm of our construction process?
- How do we apply composite ideology? Have these ideas transformed our thinking?
- How will doubters come to permit the use of apparently untried novelties, such as are the inevitable progeny of the composite approach? Can we evolve to a concept of controlled innovation which is customary and reliable?

We now understand established and potential construction materials in fundamentally new ways, because of innovations in knowledge, interpretation and measurement. These have led to improved knowledge and understanding of

- Materials, where investigative techniques now permit a molecular level of understanding, relating this to macroscopic engineering properties.

  In some cases, this has enabled us to rediscover some traditional materials and techniques, tailoring combinations of these materials to demand. The modern developments of ferrous castings use 19th Century craft increasingly combined with the new understandings gained through computer simulations of a casting's cooling behaviour and through fracture mechanics. These have been used in a progression of building projects: Bush Lane House, London; Centre Pompidou, Paris; Alban Gate, London; Bracken House, London; Ponds Forge International Pool, Sheffield; Menil Gallery, USA; Western Morning News, Plymouth.

  In future, we will be able to tailor materials to meet requirements, whether of the process or for the final service in place. We can regard our principal structural materials concrete, steel, masonry, timber and polymers as each referring to families of materials, creating in our minds a more continuous spectrum.

- Structure, where advanced computer methods make complex analysis freely accessible through modelling, analysis of elements and inter-action of elements. These allow a unified view of many structures which hitherto had to be analysed and hence handled in stages.
- Construction or organisation of production, where advanced manufacturing techniques like CAD-CAM can create a direct link from design simulations to production information. This will also result in higher levels of achievable and therefore demanded precision with all that follows for the quality in our product.
- The technological and industrial context, where the construction industry hovers uncomfortably at the gate still unsure whether to change radically the concept of the construction process.

We find that we are able to design composite constructions and structures which are significantly larger and more complex in space, time and material. They are a larger proportion, sometimes almost 100%, of the whole construction. We have substantially extended and redefined the scope and practical meaning of the analysable entity. Our total engineering is increasingly coterminous with total architecture.

This review is important because of changes in the context of the development of the engineer's work

- we should seek to confront with all our energy the emerging social demands of the huge mega-cities of the 21st Century, built on and in unmeasured terrain and environments, in desperately poor but irrepressibly optimistic congregations of citizens.

- we are able to contemplate greater scope of admissibility of technical solutions and methods, because of our increased ability to control their behaviour, even their meaning.

- we will soon be faced with the puzzle of how we decide structure and its form, when almost any material can be tailored to suit our process or performance requirements and almost any form can be analysed, the classic problem of rich choice.

  In particular, we now have sufficiently powerful methods and understanding to be able to consider the behaviour of an extraordinary range of different combinations of elements and structures by definition extending beyond the scope of codes of practice.

Can any engineer resist this fascinating prospect?

Meeting the challenge

One of the most pleasurable functions of the designer is to define and promote good overall ideas which the client and users had not realised were even possibilities. Solutions of this kind are typically creative adaptations of previous solutions and methods from other projects or industries. Fundamentally new solutions are extremely rare.

Recognition of what constitutes composite construction allows us to contemplate a much larger set of potential responses to existing problems, opportunities and ambitions along with an extension of the possibilities in confronting new situations altogether.

Composite materials

The construction sector is characterised by a long list of performance requirements that must all be met in some measure.

In terms of materials, it is currently possible to select a large range of materials of similar properties or performance for a particular application. Such freedom is available because of the controllable or specifiable versatility of current materials. Metals can vary their properties by alloying with different metal or fillers, concretes can vary their properties by selection of different aggregates or reinforcement whilst polymer composites may vary their properties through selection of different matrices, fillers or fibres.

The construction materials industry has produced this huge spectrum of materials on the macro scale. By altering the combination of different materials, almost the full range of properties can theoretically be obtained within a composite whole framework. It is becoming possible to create a range of advanced material solutions tailored to almost any design requirement. Many will become viable on cost as well. It is usually possible to identify the straightforward material solution; the challenge for inventive designers is to develop real benefits for their clients and users through consideration of a many new material developments or new combinations of existing materials.

Created needs are a common concept in other industries. Personal stereos (Sony Walkman) and home video games came more from the supply side of a design technology push perspective than from the demand side of consumer pull.

It maybe difficult for a bridge designer to develop new concepts without considerable support from clients and investors to reach the required confidence. Nonetheless, such an approach has been part of our history. It is an essential approach if our industry is to innovate and best make use of the opportunities that composite materials and systems provide.

For architects, this approach can be realised with relative ease since they are largely relieved of the realities of delivery carried by the engineers and builders. Richard Rogers' concept for the Centre Pompidou with Renzo Piano and the Lloyds' Building concentrated on total flexibility of use within a concept of heavily populated space and its exploitation. The buildings themselves grew systematically from this idea, adapting to the need for services, fire protection, access and the like. The central focus, of total physical re-arrangeability for users, was substantially achieved in the actual constructions.

Technically, the design of the Barcelona Communications Tower was driven by the need to deliver radio transparency. By recognising advantages of non-metallic tendons at an early stage, the designers were able to achieve sufficient confidence in the design of this new material to beneficially exploit the use of these materials in the final structure.

From specific innovative solutions, further innovation can be released to benefit subsequent projects. The confidence gained from the use of non-metallic tendons at Barcelona was a key factor in providing justification for the use of composite non-metallic prestressing in a concrete reservoir in Nottingham. Whilst the prime motivation for use differs (radio transparency or long-term corrosion resistance) the innovation continues from one application to the next. This is achieved partly by publication but more usefully through the personal confidence of the participants. Without practice innovation can rapidly cease. It is therefore strategically important to society that a culture of innovation be sanctioned.

Composite structures

Cases to illustrate possibilities in composite structures for new designs are the Commerzbank HQ structure in Frankfurt and the use of the New Austrian Tunnelling Method.

Much work in the USA, Japan and elsewhere has focused on the big issue of remedial work for old infrastructure, where the compositeness arises through the use of new composite materials per se and their use in being added to existing materials or structures. A USA survey identified the following priorities

- corrosion mitigation, by replacing or protecting metallics with composite elements.
- strengthening degraded bridge components, where composites can replace metallic or concrete elements which are subject to characterised stress or degradation.

- seismic retrofit, by jacketing under-designed elements.
- transforming into very low-cost erection or low-cost maintenance structures, such as pedestrian bridges, maintenance walkways.

This potential for enhancing existing structures demonstrates the further extension of composite, the combination of the old and its repair, a time-dependent case of the composite analysable entity.

Organisational and production issues

In some projects, we have seen the power of a production perspective in developing structural design.

Peter Rice exploited the potential from resolving a structural form into repetitive elements which would rationalise and economise production as well as expressing a powerful overall design theme. He sometimes combined this with an attempt to develop composite structures in which the constituents' weaknesses were deliberately confronted and resolved in the Pegasus mode. Examples include the IBM travelling pavilion and the Seville pavilion. His critical emphasis was the pursuit of regularity, repetition and modularity, of standardisation in the best sense, thereby bringing dreams across to reality.

Industrial issues

Specifiers tend to utilise only tried and tested materials and systems in construction for very human reasons. Despite many benefits from materials such as polymer composites, their exploitation to date has been limited to applications where their higher initial materials cost may be offset against unique benefits and the investment in empirical testing for future applications.

The extensive knowledge that we now possess about materials and systems has created new standards of admissibility for materials and systems. It allows us to begin to think more clearly about controlled innovation in the manner of all advanced industries.

At the moment in the UK there are major research initiatives to see how far construction can learn from manufacturing and other areas of advanced production engineering. One programme is by the Engineering and Physical Sciences Research Council as its Innovative Manufacturing Initiative. This has a specific programme for construction, called Construction as a Manufacturing Process. The Royal Academy of Engineering published the results of its study on the subject in 1995 in a report called "A Statement on the Construction Industry".

Remember that construction is not a backward form of manufacturing, which should look uncritically to say the car industry as a model for emulation. Consider some distinctive features of our sector:

- since construction is mostly fixed to the ground, it needs a mobile industry to reach each site and this imposes various hazards and uncertainties which make the process as unique as the delivered product.

- because they enclose activities constructions are bulky in their nature and are likely to remain so.

- in the building sector, we use thousands of different products and components, often only a few of each on any given project. This leads to an extraordinary range of production and assembly methods and consequent complexity of the process and of the product in contrast to the brilliant simplicity of many of the components. In civil engineering, we tend to use a smaller range of materials and components, but in larger quantities which present their own logistical problems. It often pays to study them in analytically more demanding ways

- since elements have to be long-lasting, durability is tricky as are the associated forms of finance and procurement. Society does not wish to wait a full life cycle before it claims the benefit of some new composite material.

- in a long-industrialised and urbanised country such as the UK, over half of construction is work to existing buildings/structures.

- construction is made from relatively cheap heavy materials compared to many other manufactured products. Construction materials cost about £0.2/kg and finished construction around £0.8/kg, compared with cars, where materials typically cost around £6/kg and the finished product around £12/kg. The methods of recovery, conversion, manufacturing, handling and transport are consequently distinctive.

  The comparison shifts when we consider the cost per cubic metre of created volume in the products of different industries, like houses, factories, reservoirs, cars, ships, trains or planes.

Construction is different and distinct from manufacturing, but we can still learn a lot from these other forms of advanced production, mostly in rethinking ***the whole project process*** and systematically incorporating controlled innovation.

We are now faced with a new synthesis of product and process with the developments in CAD-CAM, modelling and simulation of supply chain processes, the use of virtual reality and the use of single project databases as the unifying common information of the design team. These methods already exist in the aero-space, automotive and process plant industries. We should relish their impact upon our own sector. They will be crucial as we exploit the full potential of composite design in construction.

Simultaneously we see a renewed interest in the use of pre-assembly and standardisation, as we recognise their role in industrial change.

Composite design as a reconciliation of contradictions

The constituents of a composite solution must be compatible and the benefits of the composite approach should outweigh any disadvantages. Fortunately, steel and concrete have similar thermal expansion coefficients and for a period compatible surface chemistries. Polymer composite reinforcements and concrete move differently for thermal change. This extra effect must be overcome in effective design, a typical problem when mixing untried materials or systems.

An effective solution is not always achieved. Clinker as an aggregate for 19th Century concrete was cheap and readily available. It can however support combustion with difficulties for compartment floors and walls and create incompatibility problems when wet for embedded iron or steelwork, due to its content of sulphur.

For today's polymer composites, considerable unknowns remain regarding aspects like creep, fire performance and methods of joining to other components.

The construction industry must attempt to clarify such unknowns if only by appropriate safety factors to allow for problems in use. Use will then be more extensive and we will find worthwhile challenge in the unresolved contradictions.

The concept of controlled innovation has served in other industries. It is available for us in the construction sector to embrace more overtly. It would affect the industry in its organisation as well as in the components of construction.

The argument would deliver a virtuous circle driven by modern technological and industrial methods in which

- we increase our understanding of materials
- we develop our analytical techniques
- we develop our computational subtlety
- we redefine a larger and more complex proportion of the designed product as the analysable entity, inevitably more composite
- we add new materials to old constructions, to enhance their life and performance
- we understand and exploit the significance of greater precision of manufacture and new organisation of production
- we better define and then simulate both the product and the production processes
- we see prospects for changing the overall project process
- we can invent new composite structures and constructions
- we feel free to examine more materials, more performance attributes, more structural combinations

In this formulation, the concept of composite construction is the temporarily stable means by which we can get on with aspects of our work, including the resolution of inherent performance contradictions of materials or structural forms. The very stability sows the seeds of further change, through redefinition of the design task and eventually through its demands for ever more precise and controlled production.

The engine of the creative resolution of these current issues will be the new ideas from our designers.

Even with all these more powerful techniques, tools and understandings we have not eliminated the need for good engineers. It is like using a Stradivarius violin. If you give me one, I shall probably be concerned with not dropping it. If you give one to an orchestra musician, her performance will sound a bit better. But if you want to hear the difference it makes to use high class instruments, you need a world-class musician. So it is with engineering: to get the best out of the new tools, we need excellent engineering designers. Even then the designer is not to be set merely equal to the world class musician, whose art is a reproductive or at least an interpretive one. The designer has a clean sheet each time, and is limited only by his own mind and the other minds he can access.

I thank my colleagues at Arups for their help in developing this proposition.