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Built Environment Infrastructure Design: Some Lessons from the Past

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Abstract—**Some valuable lessons for the designer have been drawn from the author's experiences as a professionally qualified civil and structural engineer. Ten main lessons have been identified from a brief review of vernacular construction; other industries; feedback from asset managers; site experience; strength assessment, repair and strengthening; multi-disciplinary design challenges; feedback from construction and maintenance specialists and the author's interaction with various client organizations. The challenge faced by construction professionals engaged in infrastructure design is to ensure that these lessons are not forgotten and that appropriate action is taken to improve the service provided to their clients and to Society, in general.**

Index Terms—**Design, inspection, maintenance, vernacular construction.**

I. Introduction

A. Principal Aim and Methodology

As many communities depend on infrastructure networks to support, maintain or improve their quality of life, one of the principal design requirements is the reliability of the infrastructure to perform well over an extended period of time. This is largely a function of the durability of the construction and the constituent materials.

The main aim of this paper is to identify ways in which construction professionals engaged in design can improve the quality and reliability of the built environment. The improvements are identified via a process of reflection to identify lessons gained from the past. They are drawn from the author's experiences as a chartered civil and structural engineer gained from the planning, design, construction, operation, maintenance, repair and strengthening of built environment infrastructure during a period of just over 35 years.

B. Author's Practical Background

During the 35 year review period the author has worked for the following organizations:

1). A major international firm of multi-disciplinary consulting engineers. Experience was gained in feasibility studies and detailed design of various parts of the largest oil terminal facility in Europe. The terminal is in an environmentally sensitive location where there is a very strong sense of local community spirit. Further experience was gained in the design of a series of bridges for a major industrial facility in Saudi Arabia. The bridges were subjected to large temperature variations coupled with exposure to very high levels of soluble salts in the groundwater.

2). A large UK public sector highway authority. In this case the author was involved in the planning, design, supervision of construction and contract management of a range of highway structures including rehabilitation works. Experience was also gained in the condition and structural assessment of a range of existing bridges and associated structures.

3). A small engineering consultancy. Although the practice was based in the UK, experience was also gained working in Australia, Hong Kong, Malaysia and Singapore. Almost all of this work involved the condition assessment, repair and strengthening of a variety of existing structures including buildings, bridges, tunnel linings and viaducts. Client organizations ranged from small private sector companies to larger consulting engineering practices and public authorities. Some of the author's design work was also carried out for design and build contractors.

C. Author's Academic and Professional Body Background

Throughout the 35 year period referred to previously, the author has also been engaged in research and teaching at three UK universities. His teaching specialism, developed over many years, is integrated built environment design using a project-based learning approach. He also served as the head of a department of civil and environmental engineering and as the leader of undergraduate and taught Masters programs in civil, structural and architectural engineering. The author has gained knowledge and experience of many different universities running civil engineering (and related) degree programs. This has been extended through his work with the UK Engineering Council, external examining duties for undergraduate and taught Master's programs and program accreditation activities with the UK's Joint Board of Moderators (JBM) and the Hong Kong Institution of Engineers (HKIE). The JBM makes recommendations to the UK Engineering Council on the accreditation of undergraduate and Master's level civil engineering (and related) degree programs via its four member bodies, namely the Institution of Civil Engineers (ICE); the Chartered Institution of Highways and Transportation (CIHT); the Institute of Highway Engineers (IHE) and the Institution of Structural Engineers (IStructE). Although the JBM tends to focus on UK degree qualifications, it also undertakes accreditation visits to universities in Egypt, Indonesia, Malaysia, Russia, Singapore, Sri Lanka and The West Indies.

The author's work with the UK Engineering Council involved the development of the generic output standards for

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accredited engineering programs [1]. Additional time has been spent engaged in the qualifications-related activities of the Institution of Structural Engineers, in particular, the various routes to Incorporated and Chartered Engineer status.

D. Key Areas of Consideration

The lessons from the past are described in section II of this paper under a series of principal headings. These headings are used for convenience; many of the factors described are inter-related. It is also important to appreciate that the list of lessons referred to in this paper is, by no means, exhaustive. One of the aims of this paper is to demonstrate the potential benefits of reflecting on the past with a view to identifying where improvements could be introduced in the future.

II. The Lessons

A. Vernacular Construction

Architectural forms that have been developed intuitively and handed down from generation to generation over many centuries deserve, at the very least, due consideration by the modern designer. In many cases such vernacular forms of construction may provide guidance towards achieving designs that are not only successful technically, but also reflect local cultural and societal needs. A good example of this can be found in the work of the late Egyptian architect Hassan Fathy [2] whose scientific examination of traditional Middle Eastern forms of construction demonstrated that the use of courtyards, wind towers and other features were, in fact, highly energy efficient as well as being understood by local people in terms of construction, maintenance and repair. In particular, the vernacular forms that can be found in many parts of the Middle Eastern region are much more in tune with the hot and arid climatic conditions than many recent high initial cost, glass-clad buildings that need to be cooled using even more high cost, low energy efficient mechanical forms of cooling instead of relying on natural processes for heat retention and cooling.

Similar parallels can be drawn from a study of construction in some of the seismically active zones of the World. Langenbach [3] studied the performance of vernacular timber frame buildings with masonry infill in Pakistan, Turkey, India and Haiti. He found that many of these buildings exhibited a capability for resilience under seismic conditions that was not replicated with more modern reinforced concrete frames.

Necessity being the mother of invention has led to many communities developing appropriate technology solutions to the seismic retrofitting of their non-engineered, low cost houses, over a prolonged period. A good example of this can be found in Iran, a country in which there are many adobe (sun-dried mud brick) houses that have been ravaged by frequent and severe seismic events. Several methods of seismic retro-fitting have been developed to suit the different types of damage that have occurred. One such method consists of wrapping adobe buildings with strips of tree bark that are subsequently encapsulated in a mud bonding "mortar" to encourage composite behavior between the bark and the adobe substrate [4]. A modern version of this, making use of stronger, more reliable materials such as steel wire mesh or polypropylene mesh, has been used in Peru [5] and Nepal [6], respectively. Another form of rehabilitation used in Iran consists of the use of adobe bricks laid in a "herring-bone" pattern to fill in the extensively damaged parts of walls. In this case, the layout of the bricks provides maximum resistance to the diagonal principal tensile stresses generated by seismic activity. It is likely that this approach was developed from the intuitive understanding of the effects of seismic activity gained by the local people from the damage they witnessed. Such simple methods are often used by the local indigenous population instead of the recommendations provided by governmental building authorities to move into new, modern forms of accommodation. In summary, it seems that modern design can gain a great deal from the study of tried and tested ideas developed in the past.

B. Learning from Other Industries

Consumers throughout the developed World have become accustomed to manufacturers of a variety of goods providing guidance on how their products should be maintained for maximum satisfaction. A simple example can be found with some items of clothing which contain brief guidance on matters such as wash temperatures, ironing temperatures and whether or not the garment can be dry-cleaned. With more expensive products such as motor vehicles it has become commonplace for most manufacturers to provide a transferable warranty of up to 7 years, provided that the owner follows regular maintenance schedules provided in an owner's manual or similar.

So, if the manufacturers of comparatively low cost items such as clothing and vehicles provide guidance on ownership, why can't the construction industry do the same? The simple answer to this question is that ownership manuals ARE provided in SOME sectors of the construction industry. One of the earliest design projects completed by the author in the 1970s was the accidentally contaminated drainage system for the Sullom Voe terminal in Shetland, Scotland. Sullom Voe is still the largest oil terminal in Europe; it was designed to receive and store much of the UK's crude oil from the North Sea oil fields which lie to the north and east of the British Isles. The accidentally contaminated drainage systems included the drainage of water from the concrete lined spillage containment areas for the terminal's many crude oil storage tanks. Any crude oil spillages were designed to be drained directly into the accidentally contaminated drainage system via a series of valves located in reinforced concrete chambers in the spillage containment areas. Oil-contaminated water collected in this way was cleaned using a series of treatment processes before being released into the sea. On completion of the design the author was required to write a client's operations manual for the drainage system; apparently this was standard practice in the petro-chemical industry in the 1970s. The manual not only explained what to do in the event of a spillage or similar accident but also provided guidance on routine inspection processes and preventative maintenance. The client was given clear advice on the extent and frequency of inspections and any items that needed replacing or servicing on a frequent basis such as joint sealants and valve motors. In doing so the design team was giving a clear message to the client, namely, "*The asset that you have paid a great deal of money for is not maintenance-free. It needs to be looked after and this is how we, the expert designers you have hired to best advise you, recommend you should do it*".

Although the provision and use of ownership manuals is growing, notably for building services plant and bridges, many client organizations are still not provided with advice on the best way to operate and manage their expensive assets. The soft landings framework for building projects [7] is a step in the right direction. It is an excellent initiative involving the client, designer, contractors and facility managers at the outset of the design process. The primary focus of the framework is the improvement of building performance and post-occupancy experience with particular reference to how the building operates and the need to make adjustments in performance to improve energy efficiency and to best meet the client's needs. Although this approach tends to involve the building services engineering aspects of design more than others, the framework could prove to be a useful model for other construction projects with the possibility of being extended beyond the first three years of ownership to cover a broader range of performance. Something needs to be done.

C. Learning from Asset Managers

Asset managers are responsible for keeping processes or facilities doing what they were intended to do, when first designed. Typically this involves carrying out inspections of the parts of buildings or other structures that are essential to maintain the required level of in-service performance and safety. If the inspection reveals the early signs of deterioration, then it is common practice to recommend that maintenance should be carried out to prevent an initial minor problem from developing into one that may become a health and safety hazard or require a much more costly and disruptive solution at a later date. The following lessons have been gained from the author's experience of inspection and maintenance:

1). Many designers do not build the need for future inspection, maintenance or, if necessary, replacement into their designs.

2). Many designers tend to assume that the products and construction details that they have used in the past have performed well and continue to specify them in the future. This is because they do not usually have an opportunity to review the performance of what they have designed and any feedback from contractors or maintenance staff tends not to reach those responsible for design.

3). Many client organizations do not insist on the creation of a structural inventory or similar in which as-built details (including repair and strengthening work); borehole logs; materials test records; etc. are kept. In the author's experience the information contained within an inventory can be of tremendous use when assessing the strength of structures or when planning repair or strengthening work. The increasing use (and client insistence on the use) of Building Information Modeling (BIM) software should help to address this shortcoming.

4). Client organizations are not always given due warning of the costs of inspection and routine preventative maintenance or that such work is required. As a result those subsequently given the responsibility to carry out such work often do not have adequate financial support to carry out such work.

D. Learning from Site Experience

1). A great deal can (and does) go wrong on site. The pressures to maximize profit, the need to complete construction activities in minimal time to reduce overheads and the need to meet specified quality standards all create a challenging environment for materials suppliers and contractors. Most construction processes require a great deal of care as well as quite a detailed knowledge of the behavior of materials. Taking reinforced concrete construction as an example, it is evident from the literature [8, 9] that there is scope for a great deal to go wrong on site. This is, perhaps, not surprising once it is realized that at least one chemical reaction (hydration) has to be understood and controlled on site to minimize the permeability of the cement paste and to reduce the likelihood of plastic and early-age cracking of the concrete. With the increasing use of specialist admixtures and partial cement replacements such as ground granulated blast furnace slag, pulverized fuel ash and silica fume, there is even greater scope for more to go wrong. Many of the resulting problems such as corrosion-induced cracking only tend to be revealed several years after completion of construction but well before a structure reaches its first period of anticipated maintenance. Such problems tend to be difficult, costly and disruptive to rectify and few client organizations plan for such remedial work. This tends to result in deferred work and an exacerbation of the problems by the time client organizations understand the extent of the problems and obtain the funding required to implement any repair or strengthening work.

2). Independent checking is important. Given the range of problems that can occur during construction and the commercial pressures facing contractors and materials suppliers, there seems to be a need for independent checking of work on site, as construction proceeds. The author's first experience of working on site was gained in 1975 as a student on a summer placement in the UK with a large firm of civil engineering contractors. (The firm went out of business many years ago). The contractor was engaged on a design-and-build basis to construct a new reinforced concrete floor for a major structural steel fabricator. There was no independent supervision of construction on site and, as a result, there was little evidence of any commitment from the contractor to achieve high quality construction. On completion of the contract, the only time that the client's representatives inspected the construction, the floor DID have a high quality surface finish. What was not in evidence during the client's inspection was: a). the complete lack of reinforcement in parts of the floor slab; b). the fact that, where reinforcement HAD been provided, most of it was not in the position shown on the drawings; c). that additional cement had been added, by the contractor, to the concrete cube samples to give a false indication of the compressive strength of the concrete actually used in the construction; d).

that the thickness of sub-base layer installed below the floor slabs was 50% less than the amount shown on the drawings.

This was the author's introduction to the real world of construction. The site experience subsequently gained involved work that was supervised by a resident engineer's staff engaged, at least in part, to ensure that the work was constructed in compliance with the contract specification. Even when supervisory staff were present on site to carry out independent checking, many potential problems were revealed during the checking process. The author's concern is that a lack of independent checking in design and build contracts could, potentially, lead to major defects and the need to carry out repair or strengthening work in the future that is expensive, disruptive and unplanned. Some client organizations consider that the cost of independent checking on site is an unnecessary expense. The author's counter-argument is that "if you don't pay for independent checking initially, you will, many times over, in the future".

c). All designers should have some site experience. An understanding of how things are built; what can go wrong (and how to avoid things going wrong); construction tolerances; what is realistically achievable; temporary instability risks; the space required for temporary works; sequences of construction; details that are buildable; the provision of access for future interventions; etc., all help the designer to detail different forms of construction that work well and will, hopefully, minimize the risk of construction defects and future maintenance liabilities. In the author's opinion, the responsibility for design should not be given to anyone who has not gained some knowledge and experience of the challenges of construction through a period of site experience. The importance of the provision of good quality site experience should not be forgotten by organizations employing architectural or engineering graduate trainees; it will be a very cost-effective investment for the future.

E. Learning from Assessment, Repair and Strengthening

Inspection of existing forms of construction that are in need of repair or strengthening is often very revealing. When inspecting reinforced concrete construction it is common to find that the cause of structural disruption is the expansive corrosion of embedded carbon steel, notably steel reinforcing bars. During the ensuing repair or strengthening work it can often be seen that the original reinforcement had moved during the placement of the wet concrete resulting in a significant reduction in cover and increased susceptibility to carbonation-induced corrosion. Other common construction defects that are revealed during repair work include poor compaction of the concrete and the occurrence of plastic and early-age thermal or shrinkage cracking. Although contractors are often blamed for such defects, designers have a responsibility to avoid congested reinforcement details, detail the reinforcement so that it can be properly supported during the placing of the wet concrete and to design and detail sufficient secondary reinforcement to control early-age cracking. In some cases, scarcity of locally available high quality aggregate for structural concrete has led contractors to make use of fine aggregate (sand) from local beaches. Invariably these materials are not washed and so introduce chloride ions into the concrete and, with it, the very high risk of chloride-induced corrosion of the steel reinforcement. Even worse, in some parts of the World, some contractors working in hot climates in coastal regions use seawater in the concrete (or for curing) thereby building a significant maintenance liability into the new construction.

Many engineers and architects making decisions about new construction do not always realize that it is much more cost-effective to invest more time and money to create high quality construction at the outset. Perhaps more importantly, construction professionals usually do not succeed in getting this message across to their clients. The extent and frequency of any maintenance, repair or strengthening work both have a large impact on the whole life cost of a structure. The financial problems resulting from the compounding effects of deferred maintenance were encapsulated by De Sitter [10] in his "Law of Fives": If maintenance is not performed, then repairs costing approximately 5 times the maintenance costs are required. If the repairs are not carried out then the subsequent renewal costs will be in the order of 5 times the repair costs.

These problems are further emphasized once it is realized that it is extremely challenging to carry out durable and reliable repair or strengthening work. Often, because the nature and causes of deterioration are complex, it is not always easy to correctly diagnose its true cause. As a result, it is not uncommon to apply an inappropriate form of repair. Even if the initial diagnosis has been correct, being able to achieve a high standard of workmanship is often very difficult. Contractors are working under pressure to re-open the facilities that they are repairing and are sometimes rewarded financially for early completion. As a result, the care required to remove damaged material from the existing construction and to prepare the existing surfaces to receive the new repair or strengthening materials can be severely compromised. The selection of repair materials that are incompatible with the existing materials, e.g. with different thermal expansion and stiffness characteristics, can also contribute to premature failure and the need to re-repair. The need to protect the existing infrastructure from dust and water used in the repair operations; to provide safe access for site workers and to provide protection to the environment all add to the disruption caused by repair activities as well as the cost. In many cases client organizations are not made aware of these consequences until it is too late. In summary it is essential to advise client organizations of the possible implications of future repair or strengthening work and a lack of initial investment in good quality materials and independent supervision of construction. It is also worth questioning the principle of rewarding repair contractors for completing work ahead of schedule and awarding contracts on the basis of lowest tendered bid without carrying out some form of quality audit.

F. Design – the Need for an Integrated Approach?

In the early published guidance on building and civil engineering design provided over 2000 years ago by Vitruvius [11] and others, it is evident that the different professional disciplines of architect and engineer did not exist for many years. Indeed, for many years after the time of Vitruvius and his successors, the design and construction of major works such as military fortifications and religious buildings was carried out by the armies and master craftsmen of Europe and other parts of the World. By the nineteenth century, many nations were experiencing the full effects of industrial revolution which saw the development of new materials, processes and entrepreneurial attitudes; architectural freedoms beyond neo-classical and gothic revival styles with their echoes from the past; the rise of technology-fuelled wealth as well as social and political reform. Such developments saw the birth of new professions such as the civilian (or civil) engineer; the mechanical engineer and the architect, each with its own learned society which later also served as the regulatory body for the award of professional qualifications. In the UK this took the form of the Institution of Civil Engineers, the Royal Institution of British Architects and the Institution of Mechanical Engineers founded in 1818, 1834 and 1847, respectively.

These professions tended to become stronger and more separate with the continued development and application of new technologies even though they shared the same foundations of mathematics and science. By the late twentieth century, many of the World's universities had moved away from offering general programs of study to those that are more specialist and discipline-focused. This was accompanied by an increase in the number of specialist engineering institutions to such an extent that the UK Engineering Council now represents a total of 35 specialist engineering bodies. This is at a time when building design, in particular, is more in need of a multi-disciplinary approach than ever before, particularly if low or zero carbon/energy targets and low operating cost designs are to be achieved. Experience shows that the greatest success is achieved when design teams tend to bring architectural and engineering specialists together at the earliest stages of a project. This integrated approach has become common practice with many of the large multi-disciplinary consultants that operate on a World-wide basis in the 21st century.

In 2011, the UK-based architect Richard Rogers [12] recommended that UK universities should provide a general first degree in which architecture, planning, transport, civil engineering and landscape architecture are all taught together for a few years before specializing. To some extent such a model has been in existence in the UK for many years although not with the same breadth of study as that envisaged by Rogers. The author's own university (Leeds in the UK) has been running an integrated program in Architectural Engineering (AE) for over 40 years and a small number of other UK universities has followed suit. AE may be summarized as an integrated approach to building design. Students study a number of individual subjects (modules) that are core to civil engineering (namely geotechnics, materials and structures) but also architecture, building physics and building services engineering. Integration of these disciplines is achieved through a continuous thread of design projects of increasing challenge as the students progress from their 1st to final (4th) year of study.

The Leeds program took its lead from the AE degree programs first run in the USA in the 1930s. Indeed the AE program run by the University of Leeds initially included a compulsory study abroad year hosted by Pennsylvania State University, one of the first universities in the World to offer an AE degree program. Now, Leeds students have an option to complete their third year of study out of four at a number of American universities running Accreditation Board of Engineering and Technology (ABET) approved AE programs. The Leeds AE programs are all fully accredited to CEng status by the Institution of Civil Engineers and the Institution of Structural Engineers. In addition, the degree award is accepted by the Chartered Institution of Building Services Engineers (CIBSE) for progression to chartered engineer status and some AE graduates from Leeds have gained part 1 registration from the UK's Architects Registration Board (ARB). It might be of value to note that many AE graduates from Leeds are employed not only by many of the aforementioned multi-disciplinary consultants but also by structural engineering practices, building services engineering consultants and contractors, particularly those engaged in building construction.

G. Learning from Maintenance Specialists and Contractors

When working for a large public sector highway authority in the late 1970s and early 1980s, the author became aware of the benefits of an in-house design and maintenance organizational structure. The maintenance team was responsible for inspecting and maintaining the authority's highway structures and, in this role, gained a great deal of knowledge of forms of construction, construction details and products that were either successful or maintenance liabilities. This information was fed back to the teams of engineers responsible for new design who could not only design to avoid future maintenance liabilities but also to design for ease of inspection, maintenance and replacement. In addition, the same highway authority introduced post-construction audits with the main contractors (and any major sub-contractors) to identify details and forms of construction that were considered to be good and poor practice. These lessons were then fed back to the design teams along with those obtained from the staff responsible for maintenance. Both these approaches were considered at the time to be very useful ways of closing quality assurance loops but they do not seem to have been carried forward to current practice. In summary, designers can learn a great deal from those responsible for construction and maintenance. This can be achieved through post-construction audits and liaison with maintenance practitioners. Similarly, engaging these specialists at the early stages of the design process for new works would seem to be very worthwhile.

H. Designing for Re-Use rather than Recycling or Waste

The principle of re-using materials or parts of existing construction is, by no means, new. There is a great deal of guidance available on designing for re-use [13, 14] rather than re-cycling or worse still, creating waste. There are also potential financial savings to be made. It seems that we need to make greater use of this advice in the future if we are serious about improving the sustainability of our new designs.

III. Conclusions

A good designer should always be seeking to improve and should recognize that lessons can be learned from others engaged in the planning, design, construction, operation, maintenance and demolition or reconstruction of our infrastructure. From the brief overview presented in this paper it is evident that:

1). Current design challenges such as energy efficiency, designing for re-use and some of the broad principles of sustainability are not new. Good design ideas that are appropriate for the modern World may well be based on ideas that have evolved over many centuries.

2). Designers ought to do more to provide guidance on how infrastructure managers or owners should care for their assets.

3). "You get what you pay for". Lowest price does not usually equal best value and rarely yields the most durable, reliable infrastructure. Cutting costs by avoiding independent supervision of construction is a false economy.

4). Construction professionals need to do more to explain the longer-term consequences of lack of initial investment in achieving high quality forms of construction. Deferred maintenance work is not only disruptive and very costly but it can threaten the health and safety of the users of the infrastructure.

5). Designers should ensure that what they design can be readily inspected and maintained. They should also make provision for the eventual replacement of the most vulnerable parts of their designs.

6). Designers should seek advice from construction and maintenance specialists as part of the design process to increase their chances of developing buildable, low maintenance designs.

7). A "good" designer is someone who has a broad knowledge of construction practice.

8). It is unrealistic to expect repair and strengthening work to be maintenance-free in the future given the challenging conditions under which such work is usually carried out.

9). Repair and maintenance work can be very costly and disruptive, particularly when the need to provide access; a safe working environment and environmental controls are taken into account. It is far better to get the design right at the outset rather than have to rely on future repairs.

10). Understanding the holistic nature of infrastructure design has many benefits. Perhaps we focus too much on developing specialist knowledge at an early age? It may be useful to explore programs of learning and subsequent training that better reflect the multi-disciplinary nature of design.

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Starting as a graduate trainee with consulting engineers Sir Alexander Gibb and Partners in 1977, he gained design experience working on the Sullom Voe Terminal, Shetland and the Sea Water Cooling Project for the Jubail Industrial City in Saudi Arabia. He obtained further design and site supervision experience as a bridge engineer with Greater Manchester County Council before starting his academic career at the University of Bolton (then Bolton Institute of Higher Education) in 1984. Moving to the Department of Civil and Environmental Engineering at the University of Bradford in 1990, he served as the Head of Department from 1997 to 2002. He left in 2002 to establish his own consulting practice, Garrity Associates, but continued his link with the University of Bradford as a Visiting Professor in Civil Engineering Design. He accepted the post of Hoffman Wood Professor of Architectural Engineering at the University of Leeds in 2009. His principal research interest is structural masonry.

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