

CLAY BRICKWORK AND ITS POTENTIAL CONTRIBUTION TO SUSTAINABLE INFRASTRUCTURE

Stephen Garrity
University of Leeds, United Kingdom
E-mail: s.w.garrity@leeds.ac.uk

Abstract

As we strive to achieve more sustainable forms of construction, factors such as the thermal mass of a material; its local availability; maintenance demands; ease of maintenance; opportunity for re-use; the amounts of embodied energy and embodied carbon, to name a few, all gain greater significance. Many of these aforementioned factors are inter-dependent and are influenced by durability.

Experience shows that well-fired clay brickwork can be extremely durable. This point is illustrated from a brief review of the performance of two distinctly different structures, both built in the UK, subjected to very severe exposure conditions and a lack of planned maintenance over a prolonged period of time. The first of these is a Saxon church built, in 664, from the remains of an earlier Roman fort. The second is a multi-span railway viaduct built between 1882 and 1884. In both cases the brickwork has remained in excellent condition and, where repair work has been necessary, it has been much easier to implement than is the case with other more commonly used construction materials. The longevity of clay brick construction and the scope to re-use bricks both result in a material that has a very low level of embodied energy per unit of time.

In spite of these potential benefits, clay brickwork now tends to be used in the UK as a non-structural cladding material for buildings. It is rarely used for engineering structures. This is due, primarily, to the long construction periods when compared with steel and reinforced concrete construction. The principal purposes of this paper are to identify the potential of clay brickwork to contribute to sustainable design solutions; to encourage those engaged in building and civil engineering structure design to consider clay brickwork as a structural material for new build and to summarise the main challenges facing designers.

Keywords: Bricks, Durability, Low maintenance, Masonry, Sustainability

1. Introduction

1.1 Durability and infrastructure

Construction professionals now place greater focus on achieving more sustainable infrastructure designs than ever before. As a result, greater consideration is given to factors such as the embodied energy; operational energy; carbon emissions; thermal mass; buildability; water usage in construction and operation; the option to re-use materials and construction components; environmental control; localisation of skills and the sourcing and scarcity of materials than in the past.

The infrastructure for transportation; energy; communications; education; health; security; food and water systems usually relies on some form of building construction or other structural system. The design requirements for buildings and other structures are numerous and often inter-related. 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.

Durability is not a recent design requirement. Among some of the earliest known guides relating to infrastructure design are Vitruvius's "Ten Books on Architecture" (*De Architectura libri decem*) published over 2000 years ago. The first book refers to "firmness or durability" (*firmitas*) with "commodity or convenience" (*utilitas*) and "delight or beauty" (*venustas*) as being the three requirements of public and private construction works (Morgan 1914). In 2006, the UK Commission for Architecture in the Built Environment (CABE) referred to these as the principal qualities for well-designed buildings. The importance of durability in design is also emphasised in the Eurocode (BSI 2010) which states that "*A structure shall be designed and executed in such a way that it will, during its intended life, with appropriate degrees of reliability and in an economical way, sustain all actions and influences likely to occur during execution and use, and shall be designed to have adequate structural resistance, serviceability and durability*". In the case of highway infrastructure design in the UK, durability is judged to be sufficiently important by the Highways Agency to warrant its own design guidance (DMRB 2001).

The extent and frequency of any maintenance, repair or strengthening work has a large impact on the whole life cost of a structure. Engineers responsible for the management of assets such as highway and railway networks have been familiar with the financial problems resulting from the compounding effects of deferred maintenance for many years. These were encapsulated by De Sitter (1983) 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.* When the additional effects of deferred maintenance such as loss of income or service from the structure;

increased carbon emissions (particularly with highway bridge repairs arising from traffic diversions and vehicle queuing) and the disruption of support to local and regional businesses and communities are taken into account, the need for more reliable, durable, minimal maintenance forms of infrastructure becomes even more important. This paper considers the potential of clay brick to contribute to sustainable infrastructure.

1.2 Clay brickwork: the current situation

Clay brickwork, consisting of fired clay bricks laid in a cementitious or lime mortar, has been used extensively in the past as a structural material for a variety of buildings and other structures. In modern construction, however, brickwork tends to be used as a non-structural cladding for buildings. It is rarely used as a structural material in its own right. Even its use as a non-structural cladding material appears to be under threat. Key (2011) comments that brickwork and other forms of masonry construction are judged, by some, to be unsustainable because of the relatively high levels of energy used in the manufacture of the masonry units. Consideration of the embodied energy values for different construction materials does not provide an accurate picture. Many specifiers use the Inventory for Carbon and Energy (ICE) developed by Hammond and Jones and published in the form of a guide (2011). This resource is a database of the embodied energy and embodied carbon of many commonly used materials. It is based on a “cradle to gate” approach. The guide advises that a robust assessment of carbon and energy should include whole life considerations such as the operation and the end of life of the structure, i.e. a “cradle to grave” analysis. Although the UK brick industry has made considerable progress to improve energy efficiency in the production processes (BDA 2011), the principal advantages of clay brickwork are likely to be seen in the “gate to grave” period, principally in the potential to use clay bricks for a period that extends well beyond the design life of the structure in which they are used and the low maintenance requirements. With this in mind two markedly different structures are now considered as case studies. Both structures contain some clay bricks within their construction and have survived until today after prolonged periods of exposure to very severe environmental conditions with little or no maintenance.

2. St. Peter’s-on-the-Wall chapel, Bradwell, Essex, UK

This stone and fired clay brick masonry structure is located in the county of Essex in south east England. It can be found approximately 3 miles to the east of the village of Bradwell-on-Sea on the north east coast of the Dengie peninsula some 20 miles from Chelmsford, the county town. The peninsula is bounded by the River Blackwater to the north, the North Sea to the east and the River Crouch to the south. The chapel is one of the oldest religious buildings in the UK that is still used as a place of worship. It is generally accepted that the present chapel was built on the site of a former Roman “Saxon Shore” fort known as Othona (Rigold 1977, Rodwell 1980, Allen and Fulford 1999). Othona was built during the Roman occupation of the British Isles, as a defence against attack from tribes from mainland Europe. Cotterill (1993) suggests that the fort was probably constructed between *circa* 275 and 285 AD. When the Romans left the

British Isles *circa* 410 AD, the masonry fort remained unused and fell into ruin. As christianity started to become established within the then Saxon community in the region, the site of the former fort was chosen for the first church which was completed *circa* 664 AD. It was built into one of the walls of the former Roman fort and extensive use was made of the fired clay bricks (usually referred to as “tiles”) and limestone blocks used in the original fort construction (Allen and Fulford 1999, Potter 2001). The clay bricks were used primarily to form the arched windows and the arched openings separating the nave and the chancel; see Figures 1 and 2. Triple courses of clay bricks have also been seen in what is thought to be the remains of the original Roman walls surrounding the fort. Re-use of masonry materials was very common in the 7th century in the British Isles because the Saxons did not then have any significant masonry construction skills or experience.



Figure 1. The chapel showing an exposed original clay brick column and the remains of an arch (the roof and gable walls are not original construction).

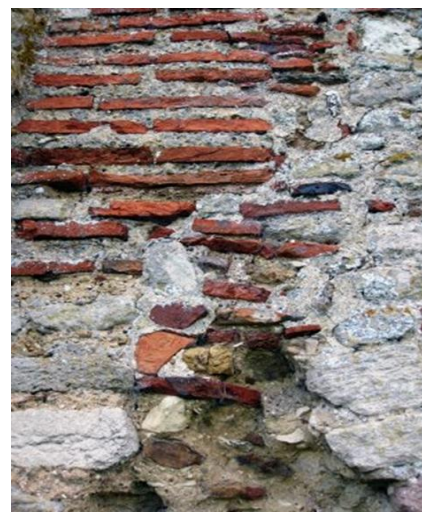


Figure 2. Typical Roman clay brick (or tile) construction.

Historical records indicate that the Dengie peninsula has been prone to flooding from the salt waters of the North Sea for well over a millennium. In particular, severe flooding was recorded to have occurred in 1098 and 1099 (Ingram 1823). As the church was located very close to the seashore it is thought that the severe flood events prompted the local community to establish a new church (the church of St. Thomas) further inland. It seems likely that the original church was used as a subsidiary chapel throughout the Middle Ages, eventually falling into disrepair. Thereafter it was used as an agricultural storage building. The curved apse and tower of the original church fell into ruin; it is likely that the stones and bricks were used for construction elsewhere. Sometime during the 1920s, the original purpose of the building was recognised. Subsequent to this discovery, the building was restored to its original use and was re-consecrated as a chapel in 1985.

The principal point to be made is that the clay and stone masonry used to construct much of this building seems to date from the 3rd century yet much of it remains intact today. It is very likely that no major maintenance or repair work was carried out on the masonry walls of the building

for many centuries and it was exposed to extremely severe conditions including flooding, severe winds, a wide range of thermal variations including many thousand freeze-thaw cycles and a salt-rich coastal environment. Rising water levels mean that, today, the edge of the building is now within a few metres of the North Sea. In spite of these very challenging conditions, the fired clay bricks reclaimed from the original Roman fort which are in the order of 1700 years old still appear to be in very good condition. Hence, the embodied energy or carbon associated with the manufacture of the original materials averaged out per year of service life will be close to being negligible. In addition, it seems that the cost of ownership and operating energy associated with the in-service life (or “gate to grave” period) of the building are similarly small.

3. Larpool viaduct, Whitby, North Yorkshire, UK

Larpool viaduct was originally constructed to carry the Scarborough and Whitby railway across the River Esk in Whitby, North Yorkshire, England; see Figure 3, below. The railway was built to link the two thriving coastal holiday resorts of Whitby and Scarborough. Construction of the railway started on 3rd June 1872 and the completed line was officially opened to rail traffic on 16th July 1885; the total cost of construction was £649,813 (Fox 1885-86).



Figure 3. Larpool viaduct.

The viaduct is of clay brick construction. It is approximately 279m long and consists of thirteen clay brick segmental arches each spanning just over 18m with a rise of approximately 8.4m. The arches are supported on solid clay brickwork piers of tapered construction. Typically the cross-sectional (or plan) dimensions at foundation level are 8.0m x 2.8m reducing to 5.18m x

1.68m at springing level. The tallest pier measures 25.3m high between the top of the foundation and arch springing level.

The viaduct was designed by Sir Charles Fox and Sons, a firm of consulting engineers based in Westminster, London, UK. Clay brickwork was selected as the principal construction material instead of the then more commonly used iron or steel because the near-coastal location was thought to present an unacceptable risk of corrosion. The viaduct was constructed by John Waddell and Sons of Edinburgh under the supervision of resident engineer Charles Arthur Rowlandson, of Sir Charles Fox and Sons. Construction of the foundations started in October 1882 and all thirteen arches were constructed between May and September 1884. The first train crossed the viaduct on 24th October 1884. It is estimated that approximately 5 million bricks were used in the construction; the total cost of the viaduct was then approximately £40,000.

A detailed description of the construction of the viaduct is given by Fox (1885-86). Of particular note were the problems encountered when constructing the foundations in the River Esk and the centring used for the construction of the arches. The near-surface ground conditions consist of alluvial deposits of sand, mud, silt and silty clay. The foundations were constructed on a thick layer of shale which is part of the sedimentary formations of the Middle Jurassic period. For each of the piers constructed within the tidal range of the River Esk, three brickwork caissons of cellular construction were sunk down to the shale. The voids in the caissons were subsequently filled with mass concrete and the three caissons were connected by two multi-ring arches on which the piers were subsequently built, as shown in Figure 4.



Figure 4. Solid brickwork piers of Larpool viaduct.

The centring for the main arches each consisted of four timber frames supported on diagonal struts which were supported on steel rails built into the piers below. Lateral stability was increased by the use of tensioned steel ropes connected to temporary anchor piles. Each arch

barrel consisted of seven rings of clay bricks laid in a 1:4 (OPC : sand) mortar giving a total ring thickness of approximately 0.84m. The extrados (upper surface) of each arch ring was coated with two 20mm thick layers of asphalt and then backfilled with a drainage layer of clean ashes up to ballast level.

The Scarborough and Whitby railway was closed to rail traffic on 6th March 1965 as a result of an extensive review of Britain's entire railway network. The viaduct remained under the ownership of Rail Property Limited then British Railways Board (Residuary) Limited until it was purchased by its current owner, Railway Paths Limited (RPL), for a nominal sum. In 2000, most of the former railway line, including Larpool Viaduct, was opened to public access and it has since become a popular tourist attraction particularly for walkers and cyclists. It is also part of a national cycle network. Little maintenance work was required whilst the viaduct was part of an operational railway. It is unlikely that any significant maintenance work was carried out after the closure of the line in 1965.

By 2006, visual inspections had revealed that numerous pieces of clay brickwork had spalled from three of the piers of the viaduct. These posed a threat to the health and safety of the occupants of a number of new houses constructed on one of the banks of the River Esk, beneath the viaduct; see Figure 3. As a result, the viaduct owner let a contract to repair the three piers. The author was appointed by the owner to provide specialist advice on the proposed repairs and the methods employed by the repair contractor (Garrity 2010). As part of these responsibilities, the author carried out an initial inspection of the viaduct early in 2007 which revealed the following:

- a). There was considerable evidence of surface dampness and moisture on many of the external faces of the existing piers particularly close to the arch springings at the tops of the piers. There was also evidence of leakage of rainwater through the arch barrels spanning between the piers. Hence, it is highly likely that the brickwork has been subjected to saturated conditions for a prolonged period of time (i.e. many years).
- b). There was considerable evidence of damage to the external surfaces of much of the clay brickwork. This was more marked on the upper sections of the piers, where there was the greatest evidence of dampness. The damage seemed to be worst on the eastern (upstream) elevation of the viaduct. It is assumed that this is because the prevailing winds have tended to blow up the river valley from the North Sea estuary onto the eastern elevation. This damage was found to be in the form of spalling (sometimes fairly extensive) of the brick faces; this is typical of frost damage. There was no evidence of chemical attack, salt crystallisation damage or other similar forms of deterioration.

Once the repair contractor had started to remove the damaged surface brickwork, it was evident that the rest of the existing construction was in very good condition, i.e. the damage was only surface deep. As a result it was decided that a half-brick thick surface layer of frost-resistant

brickwork, bonded into the original construction using stainless steel ties embedded in a cementitious mortar, was all that was needed to repair the viaduct.

Larpool viaduct is an example of a large clay brickwork structure that has withstood the test of time extremely well. Its river estuary location and resulting exposure to extreme and varying environmental conditions; the fact that much of the viaduct has been in a saturated condition thereby making parts of it very prone to the damaging effects of freeze-thaw action and a lack of systematic planned maintenance, indicate a high level of durability and low operating costs. As with the previous case study, the embodied energy and carbon associated with the manufacture of the original materials will be very small when averaged out over the service life of the structure using a “cradle to grave” approach.

4. Discussion

The two case studies illustrate the durability of fired clay bricks even after prolonged exposure to very severe environmental conditions. The durability and low maintenance liabilities of well-fired, frost resistant clay brickwork construction are well known. This prompted the UK Highways Agency to issue a design guide for new masonry arch bridges (DMRB 2004) stating that: *“Experience has shown that arch bridges are very durable structures requiring little maintenance in comparison to other bridge forms.”* Although the relatively high embodied energy of fired clay bricks is seen, by some, to be unsustainable, “cradle to grave” considerations indicate that the energy per year of service is likely to be very small when compared with other structural materials such as structural steelwork and reinforced concrete. Exposed structural steelwork construction requires repainting on a fairly regular basis to maintain an acceptable level of protection against corrosion. This requires the existing paint to be removed, careful surface preparation and new layers of paint to be applied. When carrying out such work it is often necessary to make use of fairly extensive environmental protection and worker safety measures. These tend to be more costly and disruptive than with masonry rehabilitation. With reinforced concrete construction, carbonation or chloride induced corrosion of the carbon steel reinforcement tends to be the main cause of deterioration. The works required to remove damaged or chloride contaminated concrete; clean or replace the steel reinforcement; prepare the existing substrate and to install patch repair material or additional protective measures are more complex than with masonry repair and are not always as reliable. Hence, even if masonry structures are in need of rehabilitation in the future, such work tends to be less costly, simpler and less disruptive than with more modern materials such as structural steelwork and reinforced concrete.

So why has clay brickwork been relegated to the role of a non-structural cladding material? Also, why, in spite of the publication of design guidance for masonry arch bridges by the UK Highways Agency, have very few masonry arch bridges been constructed in the UK since the beginning of the 20th century? The possible reasons are summarised below with, where appropriate, some brief suggestions for improvement.

a). *Lack of Awareness.* There is very limited awareness of the potential benefits of masonry construction particularly with regard to its durability, ease of repair and potential contributions to a low carbon economy by virtue of its low “cradle to grave” carbon emissions. (See also *Lack of Knowledge*, below). In many ways it seems that masonry is the construction industry’s “best kept secret”.

b). *Inappropriate Procurement.* Many client organisations continue to place a great deal of reliance on procurement decisions and methods that are based on lowest initial cost. Although some public sector organisations have understood and embraced the benefits of low maintenance and reliability, few client organisations seem to take into account the financial benefits of low carbon designs and embed these in their procurement strategies. The challenge of achieving resilient, sustainable low carbon futures could be met through the procurement of public sector construction projects with sustainable design and performance targets featuring as essential requirements of the client’s brief. Several steps in the right direction have been made in the UK through revisions to the Building Regulations, the provision of a voluntary Code for Sustainable Homes and the Climate Change Act, 2008.

c). *Lack of Knowledge.* There is a general lack of knowledge, understanding and experience of masonry materials, design, specification and construction. This stems from the education of the people entering the construction professions. Few colleges and universities in the UK and elsewhere, providing programmes of learning in architecture, building or civil engineering, include masonry within the curriculum. Of those that do, few identify the reliability of masonry materials and the impact of this on achieving sustainable low carbon design targets. Furthermore, few universities have programmes of research that relate to the development of new forms of masonry construction. These observations are based, in part, on the author’s experience of accreditation visits to UK universities by the Joint Board of Moderators. The lack of inclusion of masonry in the curriculum of many engineering degree programmes may be due to the gradual broadening of the curriculum of many engineering degree programmes to meet the demands of the modern construction industry (Joint Board of Moderators 2009). Learned societies such as the International Masonry Society and The Masonry Society (US) could, perhaps, work more closely with university departments to provide teaching and learning materials and training for academic staff. Thereafter, a united industry-focused voice (or similar) needs to help raise awareness and to provide sources of knowledge to the range of construction professionals who are in a position to specify masonry construction. (See *Lack of Industry Cohesion*, below)

d). *Slow and Expensive Construction.* Many construction professionals shy away from specifying masonry because it is often labour extensive, time consuming and expensive to construct. This could be addressed through the design and specification of pre-built elements of construction. Once it is realised that the use of small amounts of stainless steel reinforcement can be incorporated into pre-fabricated masonry construction to accommodate lifting stresses, more use could be made of pre-fabrication. Indeed, in the author’s opinion this creates a business opportunity for the pre-cast concrete industry which could readily diversify its operations to include the construction of pre-fabricated elements of brick or block masonry

construction. Alternatively, to keep transportation costs (and associated carbon emissions) to a minimum, pre-fabrication of brickwork could be carried out at ground level on-site thereby avoiding costly and time consuming falsework or centring. By pre-fabricating elements of masonry instead of using on-site construction, it ought to be possible to increase structural efficiency. Pre-fabricated construction, with its potential for improved quality control, may permit designers to use lower partial safety factors than is currently the case. The use of pre-fabricated elements of masonry construction is not new and, despite numerous attempts, it has not been embraced by industry. Nevertheless, some masonry manufacturers have taken the lead in developing pre-fabricated masonry construction as part of sustainable building systems (Hanson Building Products 2007).

e). *Lack of Industry Cohesion.* In the UK, the “masonry industry” has been diverse and fragmented due, in part, to the range of different masonry units, e.g. clay bricks, concrete bricks, concrete blocks, and quarried stone. This also seems to be the case in many other countries. As a result, until recently, masonry has not had the benefits of a single unified industry voice to inform people of its virtues as a reliable, durable, low maintenance, sustainable material. This is in sharp contrast to the structural steel and concrete industries. In the UK, the relatively recent formation of the Masonry Industry Alliance and masonryfirst.com may help to address this problem.

f). *Lack of focus on brick reclamation and reuse.* It is estimated that in the 1990s, in the order of 5% of the 2.5 billion bricks available from demolished buildings in the UK were salvaged and reused (Coventry et al 1999) with the remainder being either crushed for fill or transported to landfill. Although there are some concerns relating to the lack of information about the properties of the reclaimed brick and difficulties with surface preparation, there is a great deal of scope to explore ways in which bricks can be more easily reclaimed and reused. The reclamation and reuse of masonry materials is not new, as indicated with the first case study described earlier in this paper. By developing brickwork construction in which the bricks can be reclaimed and reused in new construction, the embodied energy and carbon per unit of time can be reduced considerably making masonry an even more attractive proposition from an environmental perspective.

5. Conclusions

Fired clay bricks have a huge part to play in delivering sustainable infrastructure. They can be extremely durable and remain serviceable over long periods of time in severe exposure conditions. Cradle to grave analysis reveals that the total embodied energy and carbon involved with fired clay brickwork construction can be very low. This can be reduced even further if bricks can be reclaimed and reused in new applications.

Brick manufacturers; suppliers; designers (architects and engineers); educators; researchers and learned societies need to work together to develop faster methods of masonry construction and to raise the awareness of the benefits that clay brick construction can bring to the construction

industry. If we don't address these challenges we will continue to fail to make the most of one of our greatest resources.

Acknowledgement

Thanks are due to Miss S. C. Garrity who provided guidance on the archaeological and historical background of St. Peter's-on-the-Wall chapel.

References

Allen J R L and Fulford M G (1999) 'Fort building and military supply along Britain's eastern channel and North Sea coasts: the later second and third centuries', *Britannia*, Society for the Promotion of Roman Studies, **30**: 163-184.

BDA (2011) *Brick: building a sustainable resource for the future*, London, Brick Development Association.

BSI (2010) *BS EN 1990 Eurocode - Basis of structural design (incorporating corrigenda December 2008 and April 2010)*, London, British Standards Institution.

CABE (2006) *Design review. How CABE evaluates quality in architecture and urban design*, London, Commission for Architecture in the Built Environment.

Cotterill J (1993) "Saxon raiding and the role of the late Roman coastal forts of Britain", *Britannia*, Society for the Promotion of Roman Studies, **24**: 227-239.

Coventry S, Woolveridge C and Hillier S (1999) "The reclaimed and recycled construction materials handbook" Report C513, London, Construction Information and Research Association.

De Sitter W R (1983) "Costs for Service Life Optimization: The 'Law of Fives'", *Durability of Concrete Structures, CEB-RILEM International Workshop Report*, Ed. Steen Rostam, 18-20 May, Copenhagen, Denmark, 131-134. (published as Comité Euro-International du Béton Bulletin d'Information No. 152).

DMRB (2001) *BD 57/01 Design for Durability*, Design Manual for Roads and Bridges, Vol.1, Section 3, Part 7, London, The Highways Agency.

DMRB (2004) *BD 91/04 Unreinforced Masonry Arch Bridges*, Design Manual for Roads and Bridges, Vol.2, Section 2, Part 14, London, The Highways Agency.

Fox F (1885-86) "Viaduct over the River Esk at Whitby, and the Embankments and Culverts in the Ravines". Paper No. 2117. *Minutes of the Proceedings of the Institution of Civil Engineers*, **86 (4)**: 301-311.

Garrity S W (2010) "The rehabilitation of a Victorian clay brick railway viaduct", *Proceedings of 8th International Conference on Short and Medium Span Bridges*, 3 – 6 August 2010, Canadian Society for Civil Engineering, Niagara Falls, Ontario, Canada.

Hammond G and Jones C (2011) *Embodied Carbon. The Inventory of Carbon and Energy (ICE)*, BSRIA guide, Lowrie F and Tse P (Eds), Bracknell, UK, BSRIA.

Hanson Building Products (2007) *Hanson Eco-HouseTM*, Bedford, UK.

Ingram J (1823) *The Anglo-Saxon Chronicles*, with contributions by J A Giles (1847), London, Everyman Press (pub. 1912, edited and revised by D B Killings in 1996).

Joint Board of Moderators (2009) *Guidelines for accredited MEng degree programmes leading to Chartered Engineer*, London (available online <http://www.jbm.org.uk/downloads.aspx> [accessed on 31/08/2012]).

Key M (2009) *Sustainable masonry construction*, Watford, UK, HIS BRE Press.

Morgan M H (1914) *Vitruvius. The Ten Books of Architecture*, (1960 re-publication), New York, Dover Publications Inc.

Potter J F (2001) "The occurrence of Roman brick and tile in churches of the London basin", *Britannia*, Society for the Promotion of Roman Studies, **32**: 119-142.

Rigold S E (1977) "Litus Romanum – the Shore forts as mission stations", in Johnston, D E (ed) *The Saxon Shore, CBA Research Report 18*, London: The Council for British Archaeology: 70-75.

Rodwell W (1980) "Ecclesiastical sites and structures in Essex" in Buckley, D G (ed) *Archaeology in Essex to AD 1500, CBA Research Report 34*, London: The Council for British Archaeology: 118-122.