Modern earth masonry — Structural properties & structural design

Synopsis
There has been recent increased use of earth for construction of buildings in developed countries, largely because of concerns with the environmental impact and embodied carbon from fired bricks and cement-based products. Of all forms of earth construction, the widest impact on modern construction is likely to come from commercially produced unfired earth masonry where large-scale production can significantly reduce costs.

While there are benefits to using earth masonry, structural design with earth masonry raises some specific issues that are not necessarily relevant to other forms of masonry construction. This paper summarises these issues and presents results of extensive structural testing on modern earth masonry. The structural properties required for design are compared with typical values for other masonry types in Eurocode 6, showing that commercially produced earth masonry can meet or even exceed the structural capacity of other commonly used masonry systems.

Introduction
All masonry walls are required to support load, whether just the self-weight of the wall or applied permanent or variable actions. Masonry walls must have adequate compressive strength for vertical loading and shear and flexural strength for in-plane and out of plane lateral loading respectively. In addition to the ability of masonry walls to carry vertical and horizontal loads, there are a number of different aspects that need to be considered when designing with masonry, including movement (from foundations, changes in moisture content and changes in temperature), environmental susceptibility (resistance to moisture and frost) and sustainability (including manufacture, operation and end of use). Earth masonry has many benefits over fired clay or concrete block masonry, including environmental sustainability, occupant health, building quality and cultural continuity¹. The environmental sustainability is related to
both low resource use for manufacture (no energy to fire clay bricks), easy recyclability (clay and sand are easy to recycle in situ) and low energy during occupation (providing thermal mass and buffering internal relative humidity thereby potentially reducing air changes).

The benefits related to occupant health are attributed to the ability to buffer internal humidity (reduce peaks and troughs) that can reduce dust mite and other allergen levels leading to a reduction in asthma and other chronic illness. The UK has the highest asthma rates in 13-14 year olds in the world and 'A fluctuating environment with periods of high RH to maintain water balance and low RH to minimise mould growth, may thus be the preferred environment for mite colonisation and proliferation'².

While there are undoubtedly benefits to using earth masonry, structural design with earth masonry raises some specific issues that are not necessarily relevant to other forms of masonry construction. The purpose of this paper is not to provide an overview of the use of earth masonry, but rather to outline the specific issues related to structural design of earth masonry and to provide guidance for designers. This paper is focused on the strength and stiffness of earth masonry walls. Associated aspects such as fixing capacity, creep and moisture movement are beyond the scope of this particular paper.

This paper summarises the findings of a number of different research projects on different earth masonry systems. For reasons of commercial confidentiality, the specific masonry systems are not identified by name.

**What is modern earth masonry?**

The focus of the paper is on modern earth masonry which is commercially produced to reduce costs and provide improved control over properties. This improved control can lead to thinner walls which are desirable from cost and environmental points of view, as thinner walls reduce material use and increase available space. The masonry units are manufactured in a commercial brick plant but are not fired. The manufacturing process ensures the masonry units have a high density and, in most cases, have considerably higher strength than traditional forms of earth construction such as rammed earth, cob and handmade mud or earth blocks.
It has been demonstrated that commercially produced extruded earth units have about 14% of the embodied carbon of fired clay bricks. Based on typical figures in the Inventory of Carbon and Energy, it can be shown that as an unsubjected earth masonry wall thickness increases to 225mm, 100mm commercially produced dense concrete blocks will have a similar embodied energy per unit area of wall, thereby eliminating the embodied energy benefit of earth masonry, one of its main benefits over other forms of masonry construction. It is therefore desirable to keep walls as thin as possible, to maximise environmental benefit.

In 1994 it was estimated that nearly a third of the world’s population still lived in a home built of earth. The majority of these earth dwellings were in developing countries and with the rapid urbanisation and population growth that has subsequently occurred, this proportion may have decreased but is still a significant proportion of the housing stock. Many of the traditional earth masonry structures remain in dry climates (as in wetter climates these structures do not perform as well) although there are still numerous examples of traditional earth construction in the UK and in the other, wetter areas of Europe. Forth noted that the Romans fired bricks in the UK at the same time as unfired clay bricks were used in Rome, because of the harsher climate in the UK.

This highlights one of the greatest issues facing earth masonry – that of moisture susceptibility. To ensure that thin walled earth masonry can be used in a load bearing application, it is important to consider the effect that high moisture content, due to accidental and intentional wetting, has on the strength of the material as well as the masonry. In order to protect earth masonry from erosion there are two main techniques available. The first is to limit the risk through the use of appropriate detailing, the second is to stabilise the masonry to limit the moisture susceptibility. Appropriate detailing could include; providing a plinth of a moisture resistant material (e.g. Fig. 1), the use of a moisture resistant cladding for an earth masonry building and the provision of large overhangs on roofs.

If the intention of earth masonry is to provide a reduced embodied energy or carbon, any decision on stabilisation should ensure that the embodied energy from the stabilisation does not result in a product with higher embodied energy than a concrete block or brick alternative. As before, using the data in the Inventory of Carbon and Energy it can be shown that a cement content of 5% in an earth block will increase the embodied energy to a level similar to dense concrete blocks, eliminating one of the environmental benefits. While adding 5% or less cement may reduce water susceptibility, it can also reduce compressive strength and will reduce the ability to passively control the internal environment by buffering the humidity level, both undesirable side effects.

Earth masonry units with higher cement or other mineral binder contents effectively behave as cement stabilised blocks, and design can be as for commercially produced dense concrete blocks, provided they have the required physical properties.

This paper is focused on thin walled (minimum 100mm thick) unstabilised earth masonry as this form of earth masonry provides the lowest embodied energy while providing moisture buffering and thermal mass. However, the low strength materials and thin wall section also provide the greatest challenge to the structural engineer.

**Structural properties**

The main structural properties important for earth masonry are the flexural, compressive and shear capacity. The structural capacity of fixings is beyond the scope of this particular paper but it is an aspect that requires consideration.

Throughout this paper, the strength of the earth masonry is compared with that for autoclaved aerated concrete (AAC) masonry rather than higher strength dense concrete or fired clay masonry, as earth masonry is most likely to replace this lower strength material in construction.

**Flexure**

The flexural properties are the first to consider as these are governed by the mortar and this requires innovation, as ‘conventional’ cement or lime based mortars do provide sufficient bond in earth masonry. This is demonstrated in Fig. 2 depicting the characteristic bond strength (according to BS EN 1052-5:2005) with various mortars and a particular earth masonry unit. Included are test results for the bond strength for fired clay with a cement mortar, and the Eurocode 6 (EC6) UK National Annex values for AAC flexural capacity parallel to the joint (testing similar behaviour to the bond strength test).

While some authors have indicated that clay/sand may provide sufficient capacity in earth masonry, this has rarely been tested under controlled conditions, particularly after...
the mortar has dried to a point where soil suction can no longer be relied on to provide strength. As shown in Fig. 2, the indications are that mortars without additives are unable to provide the required bond. If walls are increased to 300mm thickness with a sand/clay based mortar, the increased section width and increased self weight can be shown to provide similar flexural capacity to a 100mm thick wall with a characteristic strength of 0.2N/mm², but this will increase embodied energy to a point where 100mm thick concrete may be a preferable option (see earlier).

Although not shown in Fig. 2, lignosulphonate based mortars (a by-product of the paper industry) have been used with modern earth masonry, but these do not provide sufficient capacity with all earth masonry units, and there are concerns about their long-term performance.

On this basis, sodium silicate based mortars appear the most appropriate option for unstabilised load-bearing earth masonry. Sodium silicate based mortars are already used extensively in the construction industry as fireproof mortars, but these are very expensive because of the additional requirements for the fillers to take high temperatures. A few manufacturers are currently developing sodium silicate based mortars specifically for earth masonry and although these are likely to be slightly more expensive than cement based alternatives, they have significantly lower embodied energy. The cost and embodied energy depend on the joint thickness and thinner (3-5mm) joints are therefore preferable. This thin joint can be achieved with modern extruded earth masonry where block tolerances are small because of the lack of warping during firing.

While the bond strength does provide an indication of the flexural capacity, testing according to BS EN 1052-2:1999 provides a more accurate assessment of flexural capacity of a masonry wall both parallel and perpendicular to the bed joints. Characteristic strengths from tests on earth masonry walls with sodium silicate based mortars are presented in Fig. 3 along with the UK National Annex to EC6 values for AAC blocks, both parallel and perpendicular to the bed joints. Some manufacturers have attempted to develop earth masonry systems with dry (unmortared) perpendicular joints to aid constructability and these are shown separately from the walls with mortared perpendicular joints. These tests were undertaken after the earth masonry had been stored at a controlled 20°C and 63% relative humidity.

As shown, in all cases the earth masonry exceeded the values for AAC parallel to the bed joint, but the capacity perpendicular to the bed joints was lower for the earth masonry. This is particularly evident for the walls with dry perpendicular joints, indicating this may not be an appropriate construction technique for these relatively low strength materials. The inclusion of approximately 20% perforations for block B also results in a reduced flexural capacity. The good correlation between bond strength (Fig. 2) and flexural strength parallel to the bed joint (solid brick A on Fig. 3) should be noted.

The use of sodium silicate based mortars to achieve sufficient bond, results in a situation where the mortar and bond are generally stronger than the unit itself. If masonry unit flexural strength results were processed in the same manner as wall flexural strengths to obtain a characteristic strength, the earth ‘brick A’ would have a characteristic flexural strength of 0.37N/mm², similar to the wall strength. This is shown in Fig. 4, the failure of an earth masonry wall with sodium silicate based mortar during a flexural strength test perpendicular to bed joints. During the test the wall failed through the central section (constant bending moment) and did not follow the masonry joints.

The mortars required to give flexural capacity approaching that for AAC masonry, change the failure mode from one along joints (commonly observed with clay mortars in earth masonry) to one more typical for monolithic construction (such as rammed earth or cob). Some masonry designers are more comfortable with failure along the joints rather than failure through masonry units.

The use of monolithic earth construction is well documented and there are many examples of monolithic walls lasting thousands of years. There is also a perception amongst some researchers that a monolithic earth wall ‘provides the advantage of a longer life’ than a masonry alternative. Because of the more flexible nature of the material, earth masonry may be more resistant to cracking than conventional
masonry. This aspect does, however, require careful consideration.

Compression
The compressive strength of unstabilised modern earth masonry units has been discussed in detail elsewhere and an exponential relationship can be used to describe the relationship between moisture content and strength. Fig. 5 shows the relationship for a number of different earth masonry units.

As shown, it is difficult to declare a particular compressive strength for earth masonry. Although BS EN 771-4:2003 specifies a minimum declared strength of 1.5N/mm² for AAC units, ‘Approved Document A: Structure’ of the Building Regulations for England and Wales specifies a minimum strength of 2.9N/mm² for AAC units. Both of these are at the specified moisture content of 6% ±2% from BS EN 771-4:2003, which does cover a fairly flat portion of the graph (assuming the exponential form continues to at least 8%).

This choice of moisture content is not necessarily appropriate for earth masonry as different materials will achieve different moisture contents under the same conditions. If earth masonry is held at a particular relative humidity for an extended period of time it will achieve a certain moisture content. Data for moisture content and relative humidity for the same units as above (with the inclusion of a fired clay brick for comparison) are shown in Fig. 6.

Fig. 6 clearly demonstrates the ability of earth masonry to buffer humidity by absorbing moisture from the air at times of high relative humidity and releasing it at times of low relative humidity. Along with the storage capacity, the rate at which this moisture absorption occurs governs humidity buffering. If Fig. 6 is viewed in conjunction with Fig. 5, it also demonstrates how compressive strength changes with changes in humidity. As shown, a test moisture content of 6% ±2% for AAC is not appropriate for earth masonry and a figure of 3% would better represent a fairly high moisture content under service conditions. It is unlikely that relative humidity will be above 95% for an extended period of time without causing severe damage to a dwelling.

As shown in Fig. 5, if the test moisture content reduces to 3% the unit compressive strength will approach 2.9N/mm² for some masonry units, closer to the minimum of 2.9N/mm² in the Building Regulations. Although not shown in this paper, some earth masonry units can achieve compressive strengths in excess of 5N/mm² at a moisture content of 3%.

While the compressive strength of masonry units is important, the compressive strength of earth masonry also depends on the geometry of the wall (particularly the slenderness), the strength of the mortar and the moisture content.

The compressive strength of masonry walls was tested according to BS EN 1052-1:1999 and the measured characteristic strengths are illustrated in Fig. 7, along with the calculated values based on the EC6 calculation procedure (based on masonry unit and mortar strength). The tests were performed after the earth masonry had been stored at a controlled 20°C and 63% relative humidity. An example based on the minimum Building Regulations unit compressive strength of 2.9N/mm² for AAC is also shown.

As shown in Fig. 7, even though the earth masonry units have compressive strengths slightly below the Building Regulations minimum, the overall masonry strength exceeds the value for AAC for two of the solid units under typical environmental conditions. The excellent correlation between measured and calculated earth masonry compressive strength for the solid units demonstrates that the EC6 procedure appears applicable, but further work is needed to confirm this for perforated units. In addition to the compressive strength, the secant modulus of elasticity was measured in the tests, as this measure of stiffness plays an important part in determining global structural behaviour. The measured and calculated values according to EC6 are presented in Fig. 8.

Shear
The shear strength of masonry comprises two components. The initial shear strength is a measure of adhesion (shear strength when there is no normal stress between masonry units) while the angle of internal friction is a measure of how this increases with increasing normal stress. The results of tests for the initial shear strength (tested according to BS EN 1052-3:2002) are shown in Fig. 9, along with calculated values from EC6 (based on the masonry compressive strength).

‘Brick A’ in Fig. 9 had a 10mm mortar joint, while the other earth bricks and blocks had 3-5mm mortar joints. This could explain the increased initial shear strength as the thicker mortar joint contained more soluble sodium silicate which would have been transferred across the brick/mortar interface during drying, leading to increased interface strength and therefore adhesion (initial shear strength).

As shown, the earth masonry measured results exceed the EC6 calculated value...
for a lightweight AAC masonry commonly used in load-bearing domestic construction. The EC6 calculated values for the initial shear strength are based on the limiting values based on the masonry compressive strength, as defined in the UK national annex to EC6. As shown, the measured initial shear strength is well above the EC6 values, probably because of the mortar and bond having a higher strength than the earth masonry units, whereas the empirical correlation in EC6 would be based on conventional masonry with mortars weaker than the unit.

Rather than defining a design internal angle of friction, EC6 specifies that a value of 0.4 should be used as a characteristic coefficient of internal angle of friction (i.e. tangent of internal friction angle = 0.4). The lowest characteristic coefficient of internal friction measured for the earth masonry systems with a sodium silicate mortar was 0.50, with some values over 0.7. This indicates the EC6 value is a conservative (low) estimate of the friction provided by modern earth masonry systems.

**Structural design**

The adoption of earth masonry within mainstream construction is dependent on the ability to design with the material with confidence. The design approach used within EC6 can initially be adopted to assess the structural potential of earth masonry. Following the simplified calculation method (BS EN 1996-3:2006) it can be shown that earth masonry has an adequate strength for a two-storey domestic dwelling, which is unsurprising considering the strength and stiffness are similar to AAC masonry values.

Based on a two-storey domestic house with a maximum span of 4m, a load-bearing wall is subject to a maximum factored load of approximately 32.6kN/m. With a wall thickness of 100mm, and accounting for the slenderness, the critical design stress is 0.54N/mm². Assuming an internal relative humidity of 60% gives a mean compressive strength of 3N/mm² for all but the weakest brick. Using equation 1 (BS EN 1996-1:2005) gives a characteristic strength of the masonry wall (fk) equal to 1.65N/mm².

Taking the partial material factor to be 2.7 yields design strength of 0.61 N/mm². Earth masonry therefore has structural potential for low rise domestic applications.

\[
f_k = K_f \beta \times f_m \quad \ldots(1)
\]

Where: fk is the characteristic masonry compressive strength, fb is the unit compressive strength, fm is the mortar compressive strength and \( \alpha \) and \( \beta \) are empirical coefficients from BS EN 1996-1:2005.

The suitability of using EC6 to design earth masonry must be considered. The European standard is intended for fired clay and concrete blockwork masonry (BS EN 771-1:2003) and, as the flexure tests have shown, earth masonry performs and ultimately fails differently to conventional bricks and mortar. This clearly raises the appropriateness of Equation 1 and how the relative strengths of the brick and mortar relate to the overall wall strength and the value of constant factor appropriate to earth masonry. It may be justified that the arguably high partial material factor for fired masonry may need to be increased for earth masonry.

During the design of any structure, it is not only applied actions and minimum strengths that must be considered, but also any possible accidental actions. There are indeed specific requirements to prevent a collapse disproportionate to an accidental cause included in the Building Regulations¹¹ The Building Regulations require no additional measures for a structure that does not exceed four storeys if constructed with traditional specified masonry.

Since it has been identified that the strength of earth masonry is inherently associated with the moisture content (Fig. 5) then higher levels of moisture must be considered. The effect of accidental or intentional mechanical wetting on thin walled masonry may lead to severe erosion and eventual collapse. Unstabilised earth masonry shows severe erosion and lack of strength when fully submerged. The consequence to a plausible situation in which wetting may occur is clearly disproportionate and raises the biggest concern in terms of design for a load bearing wall. While appropriate detailing can minimise the potential for wetting, it is not possible to remove the risk completely. There is current research into reducing moisture susceptibility without compromising the beneficial aspects of earth masonry and this should limit the risk of disproportionate collapse.

An alternative to modifying the material properties could be using earth masonry with a timber frame. The structural system
can be designed based on a conventional timber frame with non-loadbearing masonry. The redundancy of the system is within the design of the timber and the lack of utilisation of the vertical load carrying capacity of the masonry. The inclusion of earth masonry may be beneficial to the structural system beyond simply taking vertical load.

The structural capacity of the earth masonry can be utilised within structural timber. The infill masonry may be used for the racking stability of the building, acting as shear walls. Alternatively the masonry may be utilised to prevent buckling of the vertical compression timber members. These methods may lead to a refined and efficient structural design while reducing the possibility of disproportionate collapse.

Earth masonry has the potential to be used structurally and its suitability should be considered as part of a good design process. There is clearly scope for earth masonry to be used within a timber frame, but its greatest potential is when the material can be fully utilised for the full structural loading regime. The inherent problem of water resilience needs to be addressed for the widespread adoption of earth masonry. The strength and stiffness of unstabilised modern earth is sufficient for two storey domestic dwellings, but water resilience is critical. Both strength and water resilience need to be improved for additional storeys.

Conclusions and recommendations
Modern earth masonry has the potential to provide reduced embodied energy and improved building performance if it is used as a replacement for concrete block masonry, but the structural behaviour needs to be quantified before it is used with confidence. As there is currently no Eurocode that includes earth masonry, the only way for designers to be confident of performance is if the structural properties of earth masonry are equivalent to another form of masonry included in Eurocode 6.

Modern earth masonry with unstabilised blocks and sodium silicate based mortars can provide similar structural capacity to lightweight autoclaved aerated concrete (AAC) masonry. It has been demonstrated that modern earth masonry systems have sufficient structural capacity for domestic two-storey construction, provided the risks of moisture susceptibility of the material can be successfully mitigated. This could be either through detailing (for example, a plinth of moisture resistant material), design (for example, the use of a timber frame) or through modifying material properties to limit moisture susceptibility (through addition of a stabiliser). For the majority of modern extruded earth masonry units, a stabiliser is only required to improve strength in situations where AAC units meeting the building regulation minimum compressive strength of 2.9N/mm² cannot be. Any decision on stabilisation should be taken with caution as stabilisation can increase the embodied energy, reduce the passive environmental control provided by the earth masonry and can actually decrease the material strength.

The inclusion of perforations (voids) in earth masonry units can lead to a reduction in both compressive and flexural capacity and this should be carefully considered before using perforated blocks in a structural manner. The use of dry (unmortared) perpendicular joints can increase construction speed but can result in a significant decrease in flexural capacity and is not recommended. Dry perpendicular joints can also have a detrimental effect on acoustic performance and air tightness.

While some simple calculations in Eurocode 6 can provide accurate predictions of performance, the moisture susceptibility is not adequately covered. Additional research, particularly focused on minimising moisture susceptibility, is required before these low-energy products can be used with the same level of confidence as other masonry systems.

Acknowledgments
The authors would like to acknowledge the support of Ibstock Brick Ltd, Kingerlee Holdings, Natural Building Technologies and the Technology Strategy Board in completing this work.

References
2. Howieson, S. G. et al.: ‘Domestic ventilation rates, indoor humidity and dust mite allergens: are our homes causing the asthma pandemic?’. Building Services Engineering Research & Technology, 24/3, August 2003, pp 137-147