THINK BRICK AUSTRALIA

Manual 7

Design of Clay Masonry for Serviceability

This publication updates and supersedes the publication of the same name published by the Clay Brick and Paver Institute in October 2001.

Cover: Melbourne Grammar School's Nigel Peck Centre for Learning and Leadership creates a new campus entry as well as consolidating library facilities and providing lecture theatre and seminar spaces. The elaborate brick patterning of the book stack pavilion continues above the 'fold,' with a single shaped brick allowing a seamless transition. Book-like vertical bricks project at the upper level. Bricks by Daniel Robertson Australia, design by John Wardle Architects, construction by Probuild Constructions, bricklaying by Deca Constructions. Photograph by Roger du Buisson.

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1. Introduction

This manual provides guidance for the serviceability design of clay masonry in buildings. The guidance is of a general nature and represents industry recommendations for good practice. Alternative methods, where they exist, might be preferred in some situations for architectural, geographical or other reasons.

In conjunction with this manual, appropriate reference should be made to the Building Code of Australia (BCA)[1] and the various relevant Australian standards, including Masonry Structures (AS 3700)[2] with its Commentary[3], Masonry in Small Buildings: Design (AS 4773.1)[4] and Masonry in Small Buildings – Construction (AS 4773.2)[5]. (Both standards are pending publication.)

For structures to remain serviceable, their deflections and any tendency to crack must be controlled. Little guidance is given in the standards on appropriate deflection limits, but the robustness provisions in AS 3700 for individual walls and piers are designed to restrict the sizes of members to ensure that serviceability will be satisfactory. There is also a range of semi-empirical procedures to minimise cracking from external effects and these are discussed in this manual.

Appropriate load factors and the design provisions of AS 3700 should be used to check serviceability limit states for particular load conditions imposed on the structure, such as serviceability wind loading.

The following movements should be considered in design for serviceability:

- Expansion or shrinkage of the masonry caused by moisture
- Thermal expansion or contraction
- Deflection, creep and other movements in associated materials
- Foundation movements
- Deformations during the construction process

Calculation of deflections in masonry structures must be in accordance with accepted engineering principles and the relevant properties of the materials. The code AS 3700 gives values for elastic modulus that can be used for serviceability design.

The primary means of controlling cracking in masonry structures are the use of footings with adequate stiffness and the inclusion of control joints, the design of which is discussed in this manual. While some minor cracks can often be tolerated, crack widths should be kept to a minimum for aesthetic reasons and to avoid jeopardising durability, especially in reinforced masonry.

2. The Use of Clay Masonry in Structures

2.1 General

Clay masonry is a versatile medium that is used for a wide variety of structures. Design for serviceability is important for all types of structure, although different aspects of design will assume primary importance for different structural types. The following summarises the various types of construction where clay masonry is used and the various structural elements that are employed.

2.2 Houses

The most common form of domestic construction in Australia is the single-occupancy house. The vast majority of these are clad with clay masonry, with brick-veneer the most popular form of construction in the eastern states. Full-brick cavity construction is popular in Western Australia and single-leaf construction using hollow units is popular in north Queensland. Because the walls of houses generally support only a light roof load or no load at all, the critical design condition is usually lateral load from wind or earthquake.

In a veneer-wall house, the frame (timber or steel) is relied upon to resist the main forces, including vertical (gravity) forces and lateral shear from wind and earthquake. On the other hand, in a cavity-wall house and single-leaf construction, the masonry walls must provide the resistance to all lateral forces, usually by in-plane shear. The latter can be the governing action where earthquake forces are high.

The most common serviceability problems with masonry houses are cracking (caused by foundation movements) and durability failures. Means of preventing these are discussed later in this manual.

2.3 Multiple-occupancy domestic units

Loadbearing masonry structures greater than four storeys in height are common in other parts of the world (for example Europe) and have been built in Australia in the past. However, because of the increased emphasis on earthquake loading, the vast majority of multiple-occupancy units in Australia are less than five storeys in height.

Multiple-occupancy domestic units of loadbearing masonry (commonly called three or four-storey walk-ups) are common in Australia and two-storey semi-detached townhouses are becoming increasingly popular. In these buildings, the masonry walls usually support concrete floor slabs and the roof structure, and the wall sizes are determined accordingly. However, wall designs can be governed by resistance to out-of-plane forces, especially in the upper storeys.

In these structures, the masonry walls must also provide the resistance to lateral in-plane (shear) forces from wind or earthquake, with the floor and roof acting as diaphragms to distribute forces to the walls. This requires a cellular form of structure.

When serviceability problems occur with these structures they tend to be related to differential movement (dimensional changes) or durability; these are discussed later in this manual.

2.4 Low-rise commercial and industrial buildings

Where masonry panels are used as cladding for commercial and industrial buildings their structural design is usually governed by resistance to wind and earthquake forces. Economy in design is vital for these walls. The design flexibility, aesthetics and excellent fire resistance of masonry make it an ideal material for these applications.

In these buildings, the frame of concrete or steel provides the overall resistance to lateral forces and the walls must have sufficient flexural resistance to span between frame members and other supports. Deflection compatibility between frames and walls is an important consideration and, if not treated properly, is the main cause of serviceability problems for these structures.

2.5 Multi-storey framed structures

Masonry cladding is popular for multi-storey structures where the frame is made of reinforced concrete or steel. In these cases, the walls provide the envelope to protect the interior against the weather and are only required to resist lateral out-of-plane wind and earthquake forces, which are then transferred by the connections to the supporting frame. Often, the inner leaf is an infill wall tied to the frame. The external leaf is usually a veneer, supported by angles or nibs on the floor slabs. Masonry is also extensively used for internal partition walls in these buildings.

The walls in the upper storeys of multi-storey buildings can be subjected to high wind loads because of their height above the ground and this will usually govern their design.

The main sources of serviceability problems for masonry in these structures are improper treatment of joints, inadequate tying between the masonry and the structural frame and insufficient provision for differential movement, especially relating to long-term moisture expansion of clay masonry.

2.6 Types of masonry elements

2.6.1 General

Various types of masonry elements are used to make up a typical masonry structure. These include walls (which might be of veneer, cavity, solid or diaphragm construction), piers and freestanding elements such as parapets and chimneys. These various types of elements behave in different ways and their design must take into account their particular characteristics.

The types are briefly described in this section as background to the later discussion of serviceability design.

2.6.2 Loadbearing walls

Loadbearing walls rely on their compressive load resistance to support other parts of the structure. Buckling and crushing effects, which depend on the wall slenderness and interaction with the slab or roof above, determine the compressive capacity of a wall. Compressive strength is influenced by the shape of the units, particularly the presence and size of hollow cores. External loadbearing walls will usually be of cavity construction (see Section 2.6.4) to ensure adequate water penetration resistance, but single-skin walls are used in some areas.

2.6.3 Veneer walls

Unreinforced masonry is widely used as a veneer in residential, light commercial and multi-storey framed construction. Veneer walls consist of a single skin of masonry attached to a timber or steel frame by wall ties. Clay brick is by far the most common choice of masonry for veneer walls.

As the name suggests, the veneer is non-structural, so that the backing frame must be designed to resist the total applied load. Although they are non-structural, veneers are nevertheless subject to wind and earthquake loading. In particular, the seismic performance of veneers is important because of their widespread use and the high cost of repair if their performance proves to be inadequate. Any lateral loads on the veneer must be transferred to the structural frame by the wall ties, which therefore play an essential role. The ties must have adequate strength and stiffness, and be located at an appropriate spacing to transfer the load effectively. Attention must also be given to the durability of the tie material.

A veneer wall relies on flashing and damp-proof courses, in conjunction with weep-holes, to act as an effective barrier to moisture entering the building. The presence of flashing and a damp-proof course will influence behaviour under lateral load.

It is important to note that although veneer walls are non-structural, they still have the potential to crack from the causes described in Section 4, and must be detailed and constructed accordingly.

2.6.4 Cavity walls

Cavity wall construction is a traditional form of building, which is still common in some parts of Australia. It provides a wall having good thermal and strength properties, without the need to maintain an external coating. Cavity walls are constructed of two leaves of masonry separated by a cavity, which is typically 50mm in width and is intended primarily to prevent water penetration into the building. The two leaves are connected by wall ties. Usually only one of the leaves is loadbearing (normally the inner leaf). The two leaves can be of different materials and thicknesses. As for the case of veneer walls, the non–loadbearing leaf must be adequately supported by wall ties so that lateral loads are effectively transmitted to the loadbearing leaf.

In resisting applied loads normal to the face, cavity walls rely on the interaction between the two leaves through the ties. Behaviour of the whole system is complex and a detailed structural analysis would be required in order to predict accurately the forces in individual components. This is usually impractical and simplified rules are employed to design the masonry leaves and the ties. Essentially, the ties act as springs to transmit axial forces only.

Proper detailing of flashings, damp-proof courses and weep-holes is essential to ensure that a cavity wall remains an effective waterproof barrier. As for the case of veneer walls, the presence of flashing and a damp-proof course will affect behaviour under lateral load.

Cavity walls must be suitably detailed to avoid distress and cracking in the masonry from the causes described in Section 4.

2.6.5 Single-skin walls

This form of construction has been used in recent years, particularly in northern Australia, utilizing hollow clay units similar to traditional hollow concrete units. A single loadbearing leaf of masonry is used for the external walls and water penetration is prevented by the use of suitable coatings or render on the surface of the masonry, often combined with a roof system incorporating overhanging eaves. In cyclonic areas, hollow clay units can be used to permit partial or full wall reinforcement by incorporating reinforcing steel in the cores of the hollow units. Hollow units also accommodate the roof tie–downs that extend from the roof to the footing system.

Single-skin walls rely on the external coating to provide moisture penetration and durability protection but they must be correctly detailed to avoid cracking from the causes outlined in Section 4.

2.6.6 Masonry infill panels

Unreinforced masonry infill panels have the potential to add considerably to the strength and rigidity of a framed structure if they are designed and detailed for composite action. The extent of composite action will depend on the level of lateral load, the degree of bond or anchorage at the interfaces, the geometry, and the stiffness characteristics of the frame and infill masonry. The possibility of mobilising the infill, especially to resist seismic loads, can be considered in design. However, this is not usually done in Australia and it is generally considered good practice to leave gaps at the vertical edges and top of infill panels to allow for long-term movements in the masonry. The infill panels are secured to the frame by ties, which permit the desired relative movements, and flexible sealant fills the gaps. In these cases, composite action will not occur until large frame deflections have taken place.

If not designed for composite action, infill wall panels must be correctly detailed to avoid serviceability problems from unintended structural interactions.

2.6.7 Piers

Masonry piers can either be isolated (supporting a slab) or engaged (providing enhanced load resistance to a wall). Isolated piers are designed for compressive load capacity in the same way as loadbearing walls. The effect of engaged piers is taken into account by the use of an effective thickness for the wall/pier combination.

2.6.8 Freestanding elements

Parapets and other freestanding elements are commonly used in unreinforced masonry structures. Because of the low flexural strength of the masonry, these elements have little resistance to lateral load and must rely on gravity for stability. The presence of a flashing or damp-proof course at the base exacerbates the situation. In addition, these elements are usually located at or near the top of the structure where the wind loading is highest and the effects of seismic ground motion are magnified by the dynamic response of the building.

It is desirable to avoid the use of freestanding elements, or, if they must be used, for them to be supported or locally reinforced to provide flexural strength.

2.6.9 Other wall types

There are various other structural forms for walls, including diaphragm walls, zigzag or chevron walls, fin walls, and walls with staggered engaged piers in a cavity space. These forms are usually used when it is necessary to achieve a high resistance to lateral out-of-plane load.

3. Masonry Properties

3.1 General

This section summarises the important properties of masonry and its constituents, particularly as they affect its serviceability performance. Masonry units, mortar, assembled masonry, wall ties and connectors, and damp-proof courses and flashings are each considered separately. This subject is discussed in greater detail in TBA Manual 2, The Properties of Clay Masonry Units[6].

3.2 Masonry units

3.2.1 Category and type

Whereas the terms brick and block have been traditionally used to describe masonry units, recent trends towards highly perforated clay units have made precise definition of these terms increasingly difficult. Consequently, AS 3700 does not use the terms and refers only to masonry units. To distinguish between units of different behaviour (and treatment in design) they are categorised as solid, cored, and hollow.

Solid units can contain recesses (frogs) up to 10% of their volume, whereas cored units have holes that are intended to be oriented vertically in the wall. Both solid and cored units are laid with full mortar bedding. There is no limitation on the area of cores in a cored unit; the category depends on the manufacturer's intention as to how the units are laid, and the units must be tested in that orientation.

Hollow units also have holes that are intended to be oriented vertically in the wall. These units are laid with mortar strips covering the face shells only, not the cross webs, a practice known as face-shell bedding. The manufacturer's tests to establish a strength rating and the designer's calculations are both based upon face-shell bedding and this ensures that the correct design capacities are obtained for the masonry members.

Horizontally cored masonry units are becoming increasingly popular. These units have holes that are intended to be oriented horizontally in the wall. They are laid with full bed joints.

The type of a masonry unit refers to the material of manufacture. The types included in AS 3700 are clay, concrete, calcium silicate, autoclaved aerated concrete and natural stone.

3.2.2 Dimensions

Masonry unit dimensions can vary within a range according to the masonry unit standard AS/NZS 4455.1[7]. All design calculations are based on the work size dimensions nominated by the manufacturer and used to determine strength ratings. The work size dimensions are the length, width and height, as well as the face-shell width for hollow units.

3.2.3 Compressive strength

In masonry design, the most commonly used property is the compressive strength of the masonry units. The symbol used for the characteristic unconfined compressive strength of units is f'_{uc}. For clay units, values of this property can range from about 12 MPa to 40 MPa or more.

Like other materials, masonry units expand laterally when subjected to vertical compression forces. Because of the wide difference between the tensile strength and the true compressive strength of the material, failure occurs by tensile splitting caused by this lateral expansion.

The compressive strength used for units is called an unconfined strength because the effects of platen restraint have been eliminated by introducing a factor based on the height-to-width ratio of the unit. The correction factor is called the aspect ratio factor and is tabulated in AS 3700 Appendix C. For hollow units the aspect ratio factor is based on the height-to-thickness ratio of the face shell and is usually 1.0.

The dimensions used for finding the aspect ratio factor are the work size dimensions of the unit. It is important to use the right dimension for hollow units, where the face shells might be tapered but the manufacturer nominates a single work size dimension.

3.2.4 Lateral modulus of rupture

When a wall is loaded in out-of-plane flexure caused by wind or earthquake, the masonry units are subjected to tensile stresses at the surface of the wall. The strength in this mode of bending is referred to as the lateral modulus of rupture. Values of this property can vary from less than 1 MPa to over 2 MPa, depending on the shape, core pattern, and material of the unit. A value of 0.8 MPa is permitted by AS 3700 in the absence of test data.

3.2.5 Salt attack resistance grade

The resistance of masonry units to salt attack is measured by a standard salt cycling test and the requirement for a particular job should always be stipulated by the designer and given on the documents. The available grades are protected, general-purpose, and exposure. Requirements for various exposure conditions are given in AS 3700. The mechanism of salt attack and measures to prevent degradation are discussed in Section 7.2.

3.2.6 Coefficient of expansion

Clay masonry units expand after manufacture because of an irreversible time-dependent dimensional change in the material caused by absorbing moisture into the structure of the brick. Moisture in the atmosphere is usually sufficient for this mechanism. The magnitude of expansion depends on the particular clays and manufacturing process and is assessed by a standard test to measure coefficient of expansion.

The movements are accommodated by the use of control joints, which can be placed at nominal spacing or designed based on the material properties. If the spacing of control joints is calculated from a coefficient of expansion, the value should be given on the documents to ensure that the units used for construction are appropriate. Design of control joints for clay masonry expansion is discussed in TBA Manual 9 Detailing of Clay Masonry[8].

3.3 Mortar properties

Mortar has traditionally been specified in a prescriptive way by giving the proportions of cement, lime and sand. Properties such as compressive strength and workability, while having some value in a research environment, have proved to be of little value for typical design and construction and would only be specified in exceptional circumstances. Tensile bond strength is strongly affected by mortar type, is usually enhanced by the presence of lime, and may be reduced by workability admixtures.

AS 3700 is entirely based on a mortar classification of M1, M2, M3 and M4; it gives typical mixes deemed to achieve these classes. The masonry designer should choose an appropriate class for the mortar and specify it on the documents. In many cases, the actual composition of the mortar mix can be decided on site to suit the required classification and the available cement and sand types. Design for durability of mortar is discussed in Section 7.3.

3.4 Masonry properties

3.4.1 Compressive strength

The compressive strength of masonry is a function of the masonry units, the mortar composition and the slenderness of the member. Even without slenderness effects, the compressive strength of masonry is usually less than that of the units alone.

Although mortar is substantially weaker than are masonry units, failure of masonry in compression does not occur in the mortar. This is because the mortar joints usually have a lower elastic modulus than the units, and therefore a higher Poisson's Ratio. The tendency of the mortar joints to expand laterally under load to a greater degree than the units induces tensile stresses in the units, causing them to split.

This effect is provided for in AS 3700 by relating compressive strength of masonry to the strength of the units and the type of mortar, resulting in a masonry compressive strength f'_{mb}. The value f'_{mb} is adjusted by a factor that expresses the effect of the mortar joint thickness relative to the masonry unit height. This factor is 1.0 for traditional brick sized units of 76 mm height with mortar joints of 10 mm thickness. For units with a greater height, where a smaller number of joints will be used in a given wall height, the strength is enhanced. Similarly, for units of lower height the strength will be reduced because of the greater number of joints. The resulting characteristic compressive strength of the masonry is referred to by the symbol f'_m.

For most cases, the values for f'_{mb} given in AS 3700 will be adequate. These values are based on the characteristic unconfined compressive strength of the unit, the material of manufacture, and the class of the mortar, and have been established from a lower bound fit to a wide range of tests carried out in Australia.

3.4.2 Tensile strength of masonry

Tensile strength of masonry can only be relied upon when the action is flexure caused by transient loads such as wind and earthquake. In all other cases, the tensile strength should be assumed as zero.

When a masonry unit contacts a mortar bed, moisture is drawn from the mortar into the unit by its suction. This movement of moisture carries with it some of the fine particles of cement, lime and sand, which enter the pores on the surface of the unit. As hardening of the mortar occurs by hydration of the cement and other chemical reactions, the products lock into the pores in the units and provide the tensile bond strength. This clearly requires a fine balance between the mortar properties, such as water content and presence of fine material, and the unit properties, such as short-term and long-term suction.

Because of this complex mechanism of bond formation, the flexural tensile strength of masonry is influenced by many factors, including the unit suction and surface characteristics, the sand grading, mortar composition and water content, as well as the conditions at the time of laying. Even under closely controlled conditions, there is still a high level of random variation in strength from joint to joint. It is important to remember that flexural tensile strength is a property of the masonry, not just the mortar. Flexural tensile strength is usually measured by the bond wrench, as specified in AS 3700 Appendix D.

The characteristic flexural tensile strength is referred to as f'_{mt}. Values up to 0.2 MPa are permitted to be used in design without on-site quality control testing. However, the designer should be satisfied that the strength chosen can be achieved with the available materials under the site conditions prevailing. Higher values of strength, up to 1.0 MPa, can be used provided site tests are carried out during construction. The masonry is then classified as *Special Masonry* for tensile strength.

At interfaces between masonry and other materials, the tensile strength is usually taken as zero, but it is possible to derive a value from the results of tests with the actual materials to be used in the construction.

3.4.3 Shear strength of masonry

Similar to the case for tensile strength, shear strength is related to the bond at the unit/mortar interface. It is usually taken as a direct proportion of the flexural tensile strength and is identified by the symbol f'_{ms}. For bed joints in masonry built with clay units, the shear strength f'_{ms} is taken as 1.25 f'_{mt} . For the default value of f'_{mt} equal to 0.2 MPa, shear strength f'_{ms} will therefore be 0.25 MPa.

At interfaces between masonry and other materials and at damp-proof courses and flashings, the shear strength of the interface is taken as zero unless it is based on the results of tests with the actual materials to be used in the construction.

The other contribution to the overall shear strength on a horizontal plane is through the shear (or friction) factor. The value of shear factor for mortar bed joints in clay masonry is 0.3. Factors are also tabulated in AS 3700 for various interfaces and damp-proof courses. These values have been derived from tests carried out in Australia. This shear factor is combined with the vertical compressive force across the bed joint to calculate the frictional component in the overall shear strength.

3.4.4 Elastic modulus

Values for elastic modulus are required for calculation of deflections and relative movements in a structure. If the masonry is assumed to behave in a linear-elastic way, that is, at working stress levels, and if test data are not available, tabulated values in AS 3700 can be used. For unreinforced masonry these are related to the compressive strength of the masonry f'_{m}. Different values are given for short-term and long-term loading.

3.4.5 Density

Where the density of masonry is required and in the absence of more accurate data, the values given in Appendix A of AS/NZS 1170.1[9] can be used as a guide. For example, in the case of solid burnt-clay brick masonry the mass can be taken as 0.19 kN/m^2 for each 10 mm thickness.

3.4.6 Bedding

The other important parameter assumed in design is the bedding of the units (with either full bed joints or face shells only). It is important that the bedding assumed in the design is consistent with the manufacturer's intention and with the actual construction. The testing on which the manufacturer has based the nominated unit strength will have been carried out consistent with the intended form of construction. For a given type of unit, testing by full bedding and face-shell bedding will give quite different strengths.

Solid and cored units are intended to be laid with full bedding; hollow units are intended to be laid with face-shell bedding. Any raking of the joints must also be allowed for in design as a reduction in the bedded area.

3.5 Wall ties and connectors

Wall ties are the most common accessories built into masonry walls. They are of two basic types:

- Cavity ties, which connect two leaves of a cavity wall to ensure that the out-of-plane lateral force is shared between the leaves.
- Veneer ties, which connect a leaf of masonry to a backup frame of timber or steel studs and ensure that the out-of-plane lateral force is transferred from the masonry to the structural framework.

Other types of connectors are used to tie masonry walls to columns and beams of structural frames, and to tie across control joints. These are designed to transfer forces in the principal direction, while allowing freedom of movement in the other two orthogonal directions. Ties and connectors cannot generally be relied on to transfer shear forces across a cavity.

The properties of wall ties and connectors are controlled by the manufacturing standard AS/NZS 2699[10]. A test procedure is applied, leading to the establishment of a strength rating for the ties based on their performance under tensile and compressive load. This rating is determined from tests for a particular cavity width and can be used for any smaller cavity. The ratings are *Light Duty, Medium Duty, and Heavy Duty.*

The grade of tie required in a particular application is a function of the type of wall, the loading and the tie spacing. For most common applications medium duty ties are adequate. AS 3700 includes tables giving characteristic strengths of veneer ties and cavity ties that can be used for design, as well as tables showing the required ratings for domestic construction.

For other types of connector, such as ties connecting masonry walls to columns and beams, the strengths should be obtained from the manufacturer. A wide range of such connectors is available.

Designing for durability of wall ties and connectors is discussed in Section 7.3.

3.6 Damp-proof courses and flashings

The documents for a job should indicate the type of materials used for damp-proof courses and flashings, their locations and the requirement that the materials must comply with the relevant standard AS/NZS 2904[11]. Recommended locations for damp-proof courses and flashings are given in TBA Manual 9, Detailing of Clay Masonry Walls.

4. Causes of masonry cracking

4.1 Introduction

Minor cracking of masonry is relatively common in domestic construction. It is difficult to generalise on the significance of cracking because, provided the cracking does not have structural implications, the assessment of the impact of a crack is subjective and influenced by aesthetic and other factors. For example, a 1 mm crack in a rendered and painted wall will be much more obvious than a crack of similar size in the joints of a face-brick wall.

Some guidance on the significance of crack size is given in the Residential Slabs and Footings Code (AS 2870)[12] and is summarised for masonry walls in Table 1. These limits provide a basis for an objective assessment of damage, although crack width is not the only factor that should be considered. Where the cracking occurs in plasterboard or similar, the limits can be 50 percent higher.

Table 1. Masonry wall damage classification

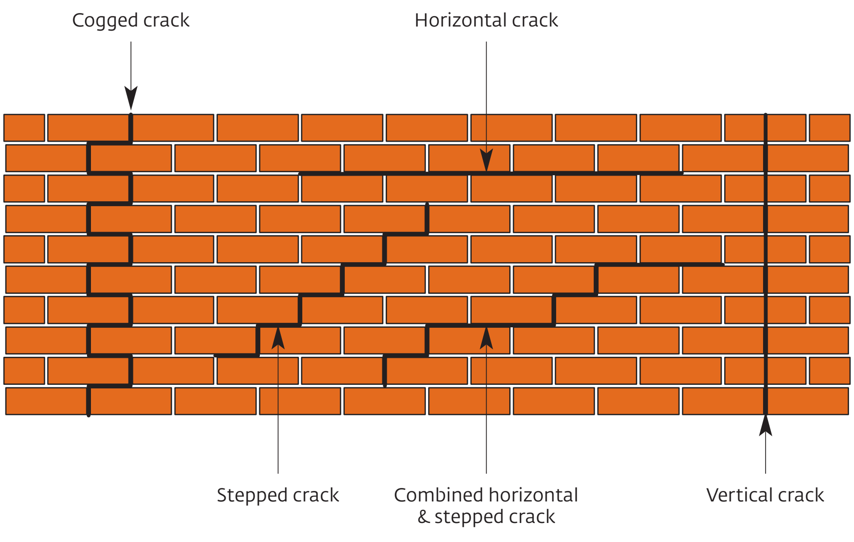
Damage	Category	Typical damage and consequences	Approximate crack width limit
Negligible	0	Cracks are hairline only.	<0.1 mm
Very slight	1	Fine cracks that do not need repair.	< 1 mm
Slight	2	Cracks are noticeable but easily filled. Slight sticking of doors and windows.	< 5 mm
Moderate	3	Cracks can be repaired and minor replacement of wall is needed. Sticking of doors and windows. Possible disruption of service pipes. Impairment of weather tightness.	5 mm to 15 mm (or a group of several cracks 3 mm or more)
Severe	4	Extensive repair work and replacement of wall sections. Distortion of window and doorframes. Noticeable distortion of walls Loss of bearing in beams. Disruption of service pipes.	15 mm to 25 mm

This is a summary based on information given in AS 2870.
For the requirements of the standard, reference should be made to that document.

An extensive study on cracking in brick and block masonry was published by Sorensen and Tasker in 1976[13]. Crack types were identified as:

- **Vertical** – extending through perpends and masonry units.
- **Horizontal** – along a bed joint.
- **Stepped** – through bed and perpend joints.
- **Cogged** – following bed and perpend joints in a vertical direction.
- **Combined** – any combination of these.

Figure 1. Crack types in masonry



These crack types are shown diagrammatically in Figure 1. The cracking pattern is influenced by many factors, including the relative strength of the joints and the masonry units, the presence of openings or other points of weakness, the degree of wall restraint, and the cause of the cracking itself. A more detailed description of the causes and effects follows.

4.2 Cracking due to external effects

4.2.1 General

Cracking in this category can be caused by excessive movement of foundations resulting from external ground movements. If the extent of these ground movements can be predicted, the footing can be made stiff enough to accommodate the expected movements and thus avoid subjecting the masonry to excessive deformations. This is the philosophy adopted in AS 2870.

Similarly, the Concrete Structures Code (AS 3600)[14] limits the deflection of beams and slabs supporting masonry walls to span/500 where provision is made to minimise the effects of movement, or otherwise span/1000. The Steel Structures Code (AS 4100)[15] recommends the same limits, and the standard AS/NZS 1170.0 Structural Design Actions: General Principles[16], recommends a limit of span/500 for floors supporting masonry walls.

Alternatively, the masonry itself can be designed to act as a deep beam and span across the displaced area. The danger in this latter approach is that if the masonry does crack, the crack is likely to be large. If the masonry walls are articulated and thus able to tolerate some foundation movement, the stiffness of the footings can be reduced. The main causes of ground movements are outlined in the following sections.

4.2.2 Moisture movement in reactive soils

Reactive (or plastic) soils comprise clays and very fine silts that swell and shrink as their moisture content increases or decreases. These movements can be quite large. Sorensen and Tasker[13] indicate that movements of 50 mm are common, and in extreme cases movements as high as 100 mm have been recorded. The soil moisture content near the surface is influenced by seasonal changes in rainfall, watering of gardens, leakage from water pipes, the presence of trees and shrubs, and solar radiation.

The moisture content of the soil beneath a building will not be uniform. In particular, the moisture content around the edges of a building will vary considerably with time due to the effects described above, while the moisture content under the interior of the building will be more stable. If the soil is reactive, large relative movements can be expected in the soil, producing either a 'dishing' or ' doming' of the soil profile under the building.

Doming will occur when the soil around the outside of the building shrinks on loss of moisture, in comparison with the soil beneath the building. Dishing will occur when the soil around the edges expands with moisture. If the footing is too flexible, distress can be expected in the masonry as a result of these movements.

Cracking related to this distress can be vertical or stepped depending on the wall geometry and the presence of openings. Because the segments of masonry between cracks will rotate as rigid elements with the footing, the varying width of the crack will be consistent with this rotation (that is, larger at the top or bottom depending whether doming or dishing has occurred). Typical cracking patterns are shown in Figure 2 and Figure 3.

The presence of a horizontal damp-proof course near the base of the wall has an important influence on this mechanism, as it acts as a plane of weakness. Recent tests at the University of Newcastle[17] on typical domestic masonry walling systems have shown that with increasing beam curvature the masonry cracks and separates along the plane of the damp-proof course, with the courses below this plane deflecting with the foundation beam. If the masonry is capable of spanning across the void created by the beam deflections, no further distress occurs. Otherwise, the wall will crack and follow the curvature of the beam.

To eliminate the effects of soil reactivity, either the moisture variation must be stabilised, or the foundations must be supported by underpinning (or both). Variations in moisture content can be reduced by the removal of offending trees, suitable drainage, and the placement of an impermeable ground moisture barrier around the building. If desired, a vertical barrier can also be installed to a depth at which the soil moisture content is constant.

Figure 2. Typical cracking from a doming foundation

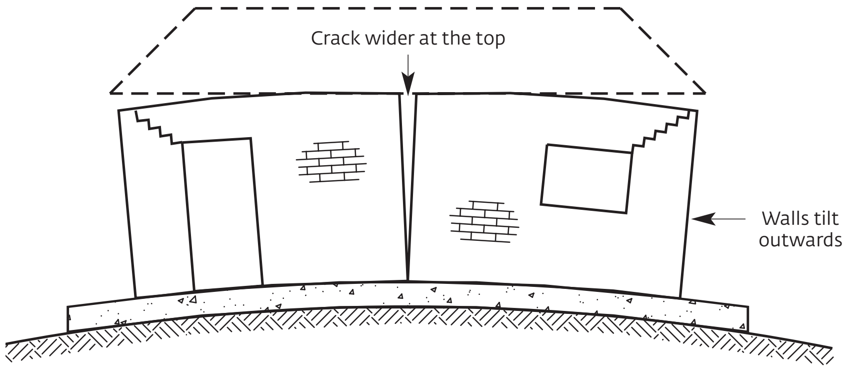
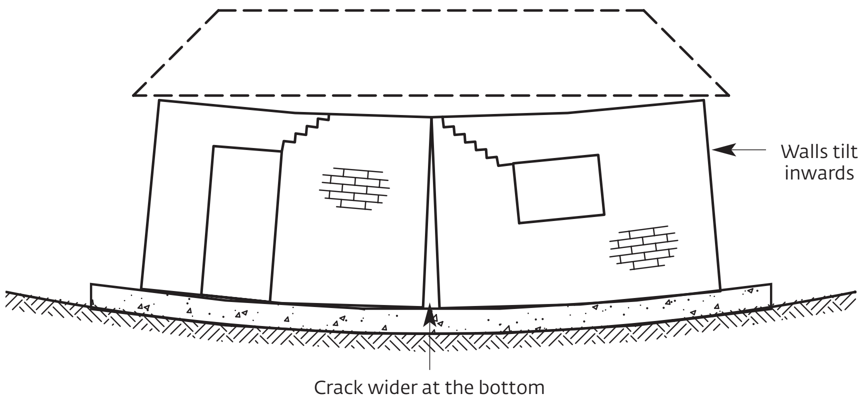


Figure 3. Typical cracking from a dishing foundation



4.2.3 Differential settlement of foundations

Differential settlement of foundations can result from a variety of causes, including non–uniform consolidation, construction of the building over variable ground conditions, and local shear failure of part of the foundation.

Cracks resulting from uneven settlement can take several forms, but are usually a combination of stepped and vertical cracks. They are similar in many respects to the mechanisms described in Section 4.2.2, although the extent of the distress will depend upon the location and nature of the differential settlement.

4.2.4 Mine subsidence

Several areas of Australia have, or can expect to have, coal mining under residential areas. The traditional method of coal removal has been by the 'bord and pillar' system, where initially only 30% to 40% of the coal is mined, with substantial pillars of coal left to support the strata above. These pillars may then be removed later as part of the secondary extraction process. Subsidence of the surface will occur shortly after this secondary extraction is complete.

A more recently developed alternative process is 'retreat longwall mining' in which the complete coal seam is removed progressively, with the strata above the removed section of the seam temporarily supported by a moveable propping system. This temporary propping system advances with the longwall and surface subsidence occurs progressively[18].

Mine subsidence can subject houses and their footing systems to severe movements. The ground movements include lateral strains, settlement, curvature and tilt. A typical sequence of events as a house is undermined by the longwall process is for upward curvature (doming) to be followed by tilting, downward curvature (dishing), and finally a return to level at some distance below the original ground profile, as the subsidence wave moves beyond the dwelling.

Cracking in masonry walls resulting from mine subsidence will often have a form similar to that resulting from soil shrink-swell, as upward and downward foundation curvatures are involved. In this case, the influence of tensile ground strains can also be significant, particularly if the footing system is not isolated from the effects of these strains. The effects of ground strains can be minimised by keeping the footings as shallow as possible to avoid keying into the ground, and incorporating slip layers to isolate the footing from the ground movements[19,20]. In order to reduce the effects of curvature, the same philosophy of footing design should be adopted as that used for footings subjected to soil shrink-swell. That is, the stiffness and strength of the footing are designed to accommodate the expected curvatures so that distress to masonry walls above the footing system is kept within acceptable limits[12].

4.2.5 Extreme loading

An additional potential source of cracking in masonry housing is from severe loads caused by an unusual event such as a severe storm or an earthquake. Although the likelihood of these events in the life of the structure might be small, the consequences can be large. For example, the total cost of damage from the 1989 Newcastle earthquake exceeded $1 billion, with the bulk of the damage being to masonry[21].

Although it might not be economical to design domestic structures to emerge unscathed from this level of loading, the extent of damage can be minimised by good design, detailing and construction practices. This was illustrated by the Newcastle experience, where a significant proportion of the damage to masonry in housing was the result of lack of tying of walls, bad workmanship, poor detailing and general building deterioration[22].

4.3 Cracking from dimensional changes in masonry

4.3.1 General

Masonry will undergo changes in dimensions due to variation in temperature, cycles of wetting and drying, and long-term changes associated with moisture. If the wall detailing is such that these dimensional changes are restrained, then cracking can result. The main sources of movement are briefly described below. Further details are given in the Australian Masonry Manual[23]. This subject is also discussed in TBA Manual 2, The Properties of Clay Masonry Units.

4.3.2 Thermal changes

The thermal expansion coefficient of masonry units depends upon the material, the method of manufacture and the colour, and is likely to be in the range of 0.008 to 0.01 mm/m/°C. Cracking from thermal effects can result from the differential thermal movements caused by temperature fluctuations between the external and internal components of the building. Temperature gradients through the wall thickness may also produce flexural cracking.

4.3.3 Wetting and drying changes

All masonry units expand on wetting and contract on drying. The magnitude of these movements is less for clay than for concrete and calcium silicate products. This is a reversible process, which normally does not require consideration in common design of masonry.

4.3.4 Long-term permanent expansion in clay products (brick growth)

All clay products undergo a permanent long-term expansion, which for practical purposes is irreversible. The change is the result of chemical reactions between water and certain minerals in the clay. This moisture expansion, or growth, occurs at a higher rate initially and gradually diminishes, with approximately 50% of the total growth occurring in the first 6 months. The vast majority of the growth will have occurred within a period of 15 years. Growth occurs in both the horizontal and vertical directions.

Cracking patterns from brick growth are usually quite distinctive and reflect three mechanisms: differential movement between walls, the restraining effects of surrounding elements, and relative movements between sections of the same wall. Expansion occurs both horizontally and vertically, so that the effects of restraint in the vertical direction can be just as important as restraint in the horizontal direction. The rate of growth in restrained walls is less than in unrestrained walls such as parapets.

Cracking patterns characteristic of brick growth include:

- Vertical cracks or distress close to the corners of long walls.
- Over-sailing of upper portions of walls over lower parts.
- Bowing and arching of parapets or walls where expansion is restrained.
- Distortion of window frames and doorframes.
- Diagonal cracking adjacent to openings, caused by differential movements within different sections of the wall.

Some examples of problems that can occur if expansion is not properly accommodated are shown in Figure 4, Figure 5 and Figure 6.

Figure 4. Cracking at offsets and corners caused by expansion

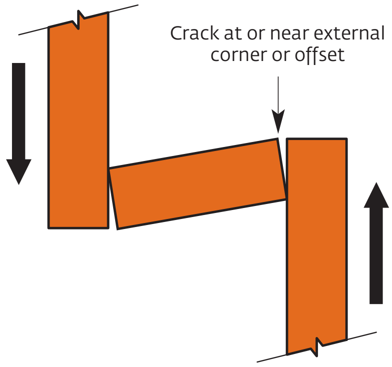


Figure 5. Oversailing of DPC caused by expansion

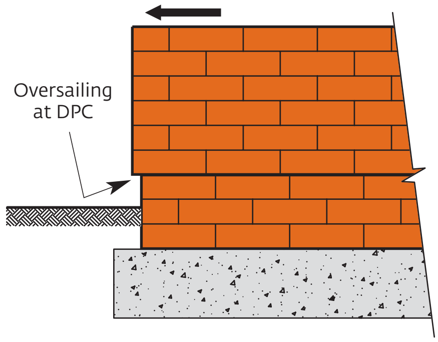
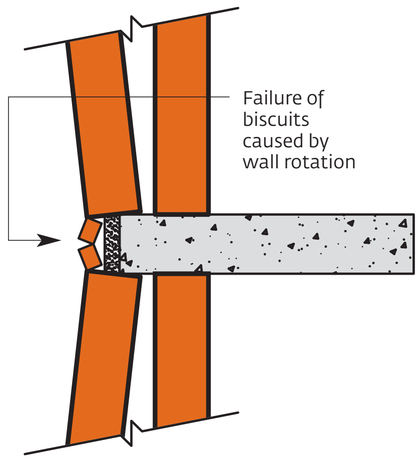


Figure 6. Failure of biscuit bricks caused by bowing and restrained expansion



In recent years, a more complete understanding of the mechanism of brick growth has been obtained and AS 3700 requires that appropriate control joints be placed in masonry to prevent possible adverse effects. A 4-hour accelerated test can be performed to predict the 15-year characteristic unrestrained expansion value for brick units (e_m) and manufacturers can provide these values when required. This coefficient of expansion can range from less than 0.6 mm/m for a low expansion unit, up to 1.8 mm/m in some extreme cases.

Once the coefficient of expansion is known, the spacing, size and location of suitable control joints can be determined to ensure that the expansion of the brickwork can occur without distress. These procedures are described in TBA Manual 9, Detailing of Clay Masonry.

4.3.5 The Influence of render

Cement-based render is a commonly used finish in domestic masonry construction, and the choice of an appropriate render is important if it is to perform adequately in service. Failure of render can occur either by loss of bond with the backing wall (drumminess) or by cracking. It is also possible for render shrinkage to cause distress in the masonry backing. Whether or not failure occurs by loss of bond or cracking will depend upon the degree of shrinkage of the render, the quality of the bond, and the movement of the backing. Where the adhesion of the render is good, the restraint of the wall will absorb a proportion of the shrinkage stresses, with the remainder of the stresses dissipated by cracking. A good review of render properties has been given by Jones[24].

Rendering is a wet process with a high content of water to provide workability. Drying after placement causes shrinkage in the render, which creates tensile stresses that may cause the render to crack. The potential degree of cracking depends upon:

- The amount of water in the mix – the higher the water content, the greater the potential for cracking.
- The rate of water loss from the mix – the faster the drying rate, the greater the likelihood of cracking.
- The cement content of the mix – shrinkage tends to increase with higher cement content, higher temperatures and more finely ground cements.
- The sand grading – this significantly affects the mix water demand and the plastic properties of the mix. The water demand influences the subsequent behaviour of the render, particularly its shrinkage characteristics.
- The standards of workmanship, the accuracy of batching of the materials and the possible abuse of plasticising and other additives.

In addition to these shrinkage effects, cracking of cement renders can result from:

- Structural movements.
- Restraints provided by intersecting walls, door and window openings.
- Joints in the background material.
- Interaction with the background masonry (particularly if the render undergoes dimensional variation at a different rate from that of the masonry).

4.4 Cracking from interaction with other structural elements

Cracking in masonry is sometimes caused by interaction with other structural elements rather than by the properties of the masonry itself. In most cases, the potential for cracking can be eliminated by appropriate detailing.

External effects that might lead to cracking include the following:

- **Shrinkage of concrete slabs**
  Concrete slabs supported by or supporting masonry walls will undergo drying shrinkage and, if they are bonded to the masonry, this will lead to undesirable stresses in the walls. This distress will act to exacerbate the effects of simultaneous moisture expansion of clay masonry. Cracking of this type can be avoided by incorporating a suitable slip joint between the slab and the wall. In the case of a wall supported on a slab or beam, the inclusion of a slip joint acts as a bond breaker, which will prevent unintended composite action that can crack the wall (see Section 5.5).
- **Thermal movements of associated elements**
  If steel trusses or beams are attached to masonry walls with no provision for relative movements, the expansion and contraction of the members can cause distress in the masonry similar to that described above.
- **Spreading of pitched roofs**
  Pitched roofs, particularly if tiled, have a tendency to spread and cause flexural stresses in the supporting masonry walls, which could lead to cracking. Strutting should be provided to avoid this problem.
- **Corrosion of embedded steel**
  Steel fitments in the form of lintels, arch bars and bolts are commonly embedded in masonry. If corrosion occurs, the rusting process increases the volume of the steel, causing local displacement and cracking of the masonry in its vicinity. The resulting cracking is usually horizontal or stepped, and generally originates from the point of embedment. Cracking of this type can be avoided by using steel fitments having the appropriate corrosion resistance rating. This can be determined from the provisions of AS 3700, which specifies the required corrosion resistance rating as a function of geographical location and proximity to the sea or sources of industrial pollution.

5. Design to Avoid Cracking

5.1 General

If the causes and mechanisms of cracking are understood, masonry can be constructed to perform satisfactorily and remain essentially free of cracks for its design life. Many of the problems described in Section 4 can be avoided by good design and detailing, combined with reasonable standards of workmanship.

5.2 Foundation design

Provided it is possible to define the external effects to which a house is to be subjected, a foundation system with the required stiffness and strength can be designed using the principles and details given in AS 2870.

For these procedures to be effective, it is imperative that the degree of soil reactivity be established with a reasonable degree of certainty. A consistent set of assumptions must be made with regard to the degree of soil reactivity, the footing system (for example strip footings or slab on ground), the structural system, and the form of masonry construction (articulated or non–articulated).

The deflection that can be tolerated in the footing (and hence its stiffness) will depend upon the materials and construction of internal and external walls, the surface finish of the walls, the number and location of articulation joints, and the length and plan layout of walls. The required beam stiffness increases with increasing soil reactivity and decreasing structural ductility. In most cases the deemed-to-comply provisions of AS 2870 can be applied.

Alternatively, if a first-principles soil-structure interaction analysis is to be performed, the approach set out in AS 2870 can be utilised. Table 2 summarises the appropriate differential movement limits for footings and rafts supporting houses with various forms of construction.

Appropriate design and construction of a footing does not necessarily guarantee a trouble-free life for the structure. It is essential that the foundation be maintained and guidance is available on means to accomplish this[25].

Provided the influence of ground strains can be eliminated by suitable detailing[19], the design of a foundation system for a house to be subjected to mine subsidence would follow procedures similar to those described above. Differential settlement effects (if they can be predicted) could also be considered in a similar manner.

Table 2. Relative differential movement limits for footings and rafts supporting houses

Construction	Deflection limit as a proportion of span	Maximum sagging or hogging movement (mm)
Clad frame	1/300	40
Articulated masonry veneer	1/400	30
Masonry veneer	1/600	20
Articulated full masonry	1/800	15
Full masonry	1/2000	10

This is a summary based on information given in AS 2870. For the requirements of the standard, reference should be made to that document.

5.3 Masonry quality

5.3.1 General

Cracking results from tensile and/or shear stresses induced in the masonry. The causes of cracking have been described in Section 4. The ability of the masonry to resist cracking under a given set of circumstances is directly related to its tensile strength. For typical clay masonry, the tensile bond strength of the joints is significantly lower than the compressive strength of the masonry units. The achievement of good bond between the mortar and the masonry units is therefore essential, if cracking is to be minimised.

5.3.2 Bond strength

The bond strength between mortar and masonry units is influenced by many factors, of which the main ones are:

- Initial rate of absorption (suction) of the masonry units.
- Water retention properties of the mortar.
- Composition of the mortar and the presence of additives.
- Standards of workmanship.

Values of bond strength can vary widely because of these effects (particularly workmanship) but characteristic flexural tensile bond strengths will usually lie in the range of 0.2 MPa to 0.5 MPa. However, if workmanship is poor, and the mix is overdosed with plasticiser, there is no guarantee that this level of bond will be achieved. The various factors are discussed in what follows; further guidance on bond strength is given in TBA Manual 10, Construction Guidelines for Clay Masonry[26] and the Cement and Concrete Association Technical Note 65[27].

Unit suction and mortar water retention

An effective match of the suction properties of the unit and the water retention properties of the mortar is essential if good bond is to be achieved. The bonding mechanism is critically dependent on the chemical and mechanical processes that take place at the microscopic scale at the interface of mortar and brick. In most cases, units should be laid dry and high water demand should be balanced by adding extra water to the mortar, or by including lime in the mix. In a few cases, the units may have to be wetted before laying. A methyl-cellulose water-thickening additive can also be used to offset the effects of high suction units.

Mortar composition

A mortar must have adequate workability during laying and adequate strength and durability in service. With the exception of proprietary thin-bed mortars, mortar should be mixed from cement, lime and sand, with the proportion of cement increasing as the durability requirements increase. Any materials used in addition to these ingredients should be used with care and strictly in accordance with the manufacturer's instructions. Overdosing with plasticising additives can seriously reduce the masonry bond strength and affect the mortar durability. Clear evidence of this was given in the examination of damaged buildings after the Newcastle earthquake[22].

Workmanship

Poor workmanship practices can drastically affect masonry bond strength. Mortar ingredients should be accurately volume batched using a box or bucket (not a shovel) or by adding a fixed volume of cement (for example a 20 kg bag) to a mixer of known volume. The mixing process should be controlled, particularly the use of additives. Bonding surfaces should be clean, both bed and perpend joints should be completely filled, and freshly laid units should not be disturbed after initial placement.

Tying and support of masonry

Masonry is a brittle material with relatively low tensile strength. It must therefore be adequately supported to ensure that any applied loads can be resisted satisfactorily and that cracking does not result. Masonry veneer walls, which are non–structural, must be adequately supported by ties that will transfer the loads to the supporting structure. It is essential that these ties have adequate strength and stiffness, and be spaced and installed correctly. Ties for domestic construction are usually either light or medium duty as categorised by AS/NZS 2699.1. Deemed–to–comply details for tie placement are given in AS 3700 and further guidance is given in TBA Manual 4, Design of Clay Masonry for Wind and Earthquake[28]. The durability requirements for wall ties are particularly important if the structure is located near the coast or industry, because ties with inadequate protection can be destroyed by corrosion. Design for durability is discussed in Section 7.4.

5.4 Masonry detailing

5.4.1 General

Apart from effective tying and support, masonry must also be detailed correctly if cracking is to be avoided. Provided the masonry is of sufficient quality, masonry cracking can be avoided by the provision of various forms of control joints and adequate detailing. The nature, location and spacing of the joints will depend upon the movements for which they are inserted, and in many cases can compensate for several types of movement at once. For example, articulation joints inserted to cater for foundation movements will also function as expansion joints for clay masonry. This section gives a brief overview of suitable jointing and detailing techniques. Further guidance can be found in TBA Manual 9, Detailing of Clay Masonry.

5.4.2 Locations of articulation joints

Articulation joints are used in conjunction with a foundation to control the effects of ground movements. The joints articulate the masonry components of the building into separate elements, which undergo rigid body rotations as the footing deflects, without causing distress in the masonry. The more flexible the footing, or the more susceptible the surface finish is to cracking, the closer the required spacing of the joints will be. Articulation not only limits cracking of walls, but also avoids the potential jamming of windows and doors caused by foundation movement.

The effects of articulation are shown diagrammatically in Figures 7 and 8. A comprehensive guidance document on articulated walling techniques has been published by Cement, Concrete and Aggregates Australia (Technical Note 61)[29]. Table 3 gives a simple summary of recommended maximum spacing of articulation joints for walls up to 2.7m high, for various levels of soil reactivity. For further details, refer to Technical Note 61[29] and AS 4773[4,5].

The location of articulation joints will be governed by the maximum spacing dictated by the conditions. Joints should also be included at positions where potential concentrations or variations in the wall stresses might occur, for example at changes in wall height or thickness, at window and door openings, and at the intersection of dissimilar materials.

Figure 7. Effect of foundation movement on articulated walls (doming foundation)

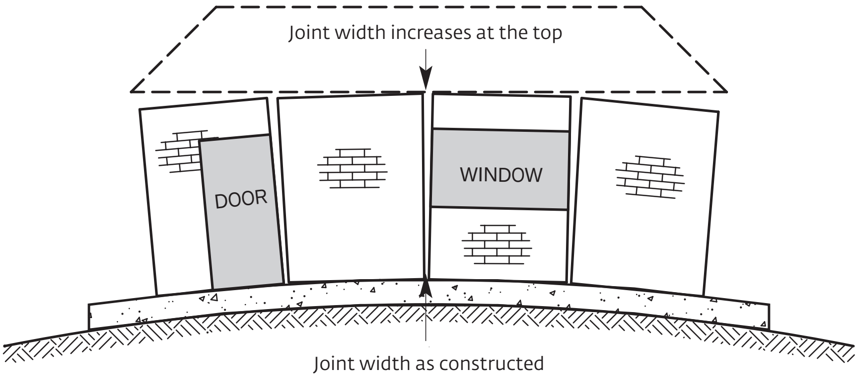
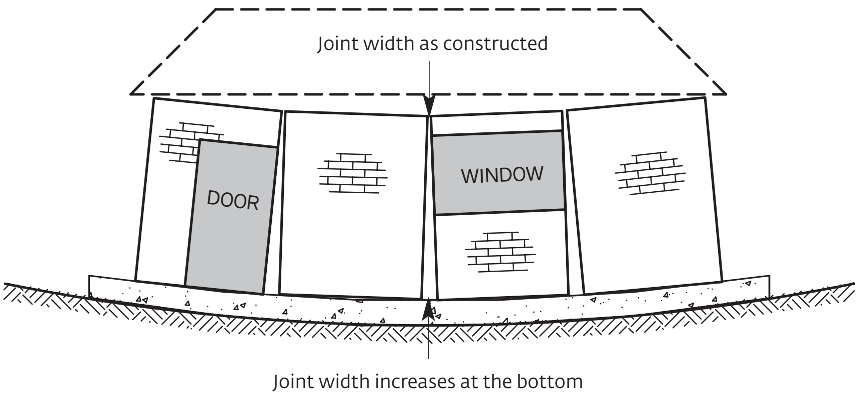


Figure 8. Effect of foundation movement on articulated walls (dishing foundation)



Articulation joints might also be required for internal walls. With good planning, the joints can be incorporated at full height openings such as doorways. Where joints are unavoidable, for example in long unbroken lengths of wall, they should be of the same form as joints in the external walls. More details of these aspects are discussed in Technical Note 61[29].

Table 3. Recommended maximum spacing of articulation joints in walls up to 2.7m high

Site class	Wall construction	Joint spacing (m)
A and S	Any	not required
M and H	Masonry veneer	7.0
	Full masonry • Sheeted and/or faced finish • Rendered or painted finish	 6.5 5.5
E	Masonry veneer (deflection ratio 1/400)	6.0
	Full masonry • Sheeted and/or faced finish (deflection ratio 1/600) • Rendered or painted finish (deflection ratio 1/800)	 5.5 5.0

This is a summary covering simple cases. For more information, refer to TN 61 and AS 4773.

Notes:

1.Site classes are as follows:

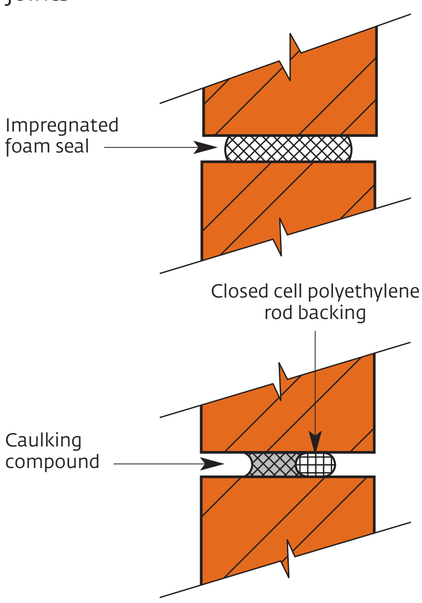
A	=	Most sand and rock sites
S	=	Most silt and some clay sites
M	=	Moderately reactive clay sites
H	=	Highly reactive clay sites
E	=	Extremely reactive clay sites

2.For E class sites, a footing design prepared by an engineer is recommended. Joint spacing will depend on the deflection ratio adopted.

5.4.3 Detailing of articulation joints

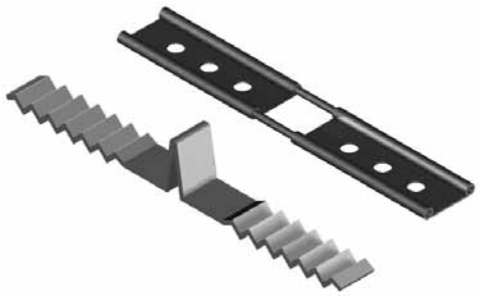
For obvious reasons, articulation joints must be capable of expanding or contracting to cater for the rigid body displacements of the walls as they rotate with the footings. As wall rotation is involved, the joint thickness will vary with height and open or close at the top or bottom of the wall depending on whether the footing is subjected to 'doming' or 'dishing' curvature (see Figure 7 and Figure 8). The joint is usually packed with a compressible filler to provide a backing for the flexible sealant compound applied to the surface of the joint. Alternatively, a circular polyethylene backer-rod can be used as backing for the sealant. It is extremely important that the joint be free of mortar droppings or other obstructions that will impede the closing of the joint. Typical methods of sealing joints are shown in Figure 9.

Figure 9. Typical methods of sealing articulation and control joints



Flexible masonry anchors should be installed between the masonry panels on either side of the joint. These anchors are capable of transmitting shear forces across the joint from loads normal to the wall, but still allow the joint to open or close. Typical types of anchors are illustrated in Figure 10.

Figure 10. Typical flexible masonry anchors for articulation joints



In many cases, articulation joints will also serve as expansion or contraction joints. In clay masonry walls, brick growth will occur over time and tend to close the joint. The initial joint size must allow for this effect and would usually be larger than the common 10 mm joint width. A width of 20 mm would be typical for this situation, but should be determined by considering the need for control joints (see Section 5.4.4).

The use of full height openings for doors and windows is an effective means of articulation. Full height windows, or windows with infill panels below the sill, eliminate the need to form an articulation joint in the masonry. Openings for external doors should also be the full height of the wall if possible. Full height door openings provide an excellent location for articulation joints, which can be covered by the architraves.

5.4.4 Control joints

Control joints are required in clay masonry to relieve the effects of long-term expansion of the units. The detailing of these joints is similar to that for articulation joints.

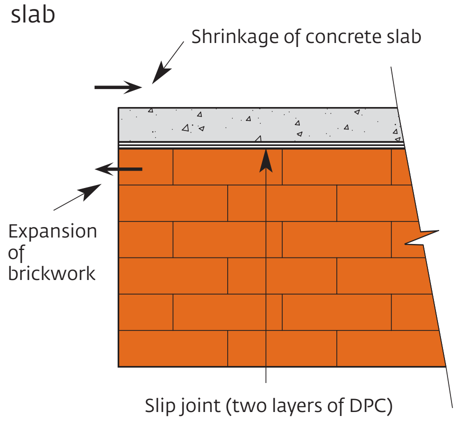
The mechanism of brick growth has been previously described in Section 4.3.4. The expansion is irreversible and takes place in both the horizontal and vertical direction. Control joints must therefore be inserted to absorb this expansion and avoid damage to the masonry. The problem is well understood, and once the long-term expansion value (e_m) for the brick is known, suitable control joints can be designed. Guidelines for design and location of control joints are given in TBA Manual 9, Detailing of Clay Masonry.

Corners are particularly prone to damage as the growth occurs in orthogonal directions in the two intersecting walls. For this reason, a control joint should be located at or near a corner if long lengths of brickwork are involved. As described previously, where articulation is required for other reasons, the articulation joints can also be designed as control joints. In most cases, the need to place control joints in internal walls can be avoided by the use of storey-height openings and by selecting bricks of low characteristic expansion (less than 0.8 mm/m).

5.5 Isolation and slip joints

Masonry distress can also be caused by interaction with other structural elements. To avoid this problem, some form of slip joint or isolation joint is required. Where a concrete slab or other element bears on the top of a masonry wall, or where a masonry wall rests on a concrete slab, there is a potential for longitudinal and transverse relative movement between the slab and the wall. In these situations, slip is desirable between the dissimilar materials, but resistance to sliding is necessary for the lateral stability of the wall. The solution is to provide a joint that slips under the large forces generated when differential movement is restrained, but has sufficient friction to resist the smaller forces resulting from applied loads. This can be achieved by the use of sheet damp-proof course or strips of neoprene placed between the slab and the wall[23]. A typical slip joint arrangement is shown in Figure 11. The same principles should be used to provide an isolation joint between new and old construction.

Figure 11. Typical slip joint between brickwork and a concrete slab



Where an isolation joint is necessary to isolate a wall from the surrounding structure, control joints can be used for this purpose. Flexible anchors such as those used for articulation joints should be incorporated across the joints if transverse wall loads have to be transmitted to a supporting frame.

6. Crack Repair Techniques

6.1 Introduction

As described previously, masonry cracking can result from a variety of causes such as ground movements, dimensional changes in the masonry or interaction with other structural elements. Sometimes the cracking will be structurally significant; in other cases, it will only be aesthetic.

When cracks occur, the most suitable method of repair is determined to some extent by the nature of the cracking. If the bond between mortar and brick has been broken and the structural integrity of the wall is threatened, the aim of the repair should be to restore adequate strength to the cracked area (particularly tensile strength). If the crack is not of structural significance, then re-pointing of the joint might be sufficient. Various repair methods are briefly described as follows.

6.2 Stabilisation of the cause of cracking

Before repair of the cracked area can be carried out, the cause of the cracking must be identified and the movement stabilised to avoid recurrence. This might involve any of the following:

- Underpinning of foundations.
- Stabilisation of soil moisture content by adequate drainage and provision of 'apron' paths around perimeter walls, removal of offending trees, or the placement of an impermeable moisture barrier around the building.
- Insertion of suitable control joints to cater for expected masonry movements.
- Bracing of the structure if cracking is being caused by excessive movements of the roof or other framing systems.

These remedies are described in some detail by Sorenson and Tasker[13].

6.3 Repair methods

6.3.1 Raking and re-pointing

Raking and re-pointing is often carried out when cracking occurs in the mortar joints. The procedure is also used to make good the surface of joints that have been eroded by exposure to a degrading environment. The process requires a skilled tradesperson and involves the raking out of the mortar in the joint to a certain depth and making the joint good with a compatible mortar.

Hand pointing of joints to a depth of 15 mm can be effective if the repair is only for cosmetic reasons. However, it is usually ineffective if the bond strength of the cracked joint must be restored. It is very difficult to fill the joint completely and to generate the required suction of the unit on the mortar when the mortar is, of necessity, of relatively stiff consistency. In addition, shrinkage of the fresh mortar will often cause cracking to recur at the same interface.

Best results are achieved if the joint is raked to a significant depth (50 mm to 60 mm) and then pressure-filled with a polymer-modified cement mortar, which has better penetration and bonding characteristics than a conventional mortar. To allow for colour matching of the finished joint, a conventional mortar can be used for the last outer layer. These techniques have been used with good results in repairs of brickwork damaged in the Newcastle earthquake.

6.3.2 Reconstruction of selected areas

For obvious reasons demolition and re–building of a damaged section of masonry should restore its structural integrity. However, problems are often encountered at the junction of new and existing work unless a control joint can be used to isolate new from old. In many instances, the new masonry is toothed into the existing work to create a key. In these cases, similar problems to those described in raking and re-pointing can be encountered, as bond has to be established at the junction of the new and old masonry.

Bond can usually be achieved in the bed joints below the bricks in the toothed area. However, at the vertical junction of the last perpend joints and the existing construction, and for the top bed joint of the new construction below the existing masonry above, bond depends upon the effective placement of the mortar for the full joint depth and thickness. Unless polymer-modified mortars are used, this is very difficult to achieve.

As for the case of re-pointing, mortar shrinkage can also create subsequent cracking at the interface of new and old. For effective repair work, it is therefore important that skilled tradespeople and the correct materials are used.

6.3.3 Epoxy injection

This method has been used effectively in repairs to damaged masonry housing in Newcastle following the 1989 earthquake. However, it is a skilled operation requiring specialist equipment and personnel, and is usually more expensive than the more conventional repair methods described above. Despite the extra cost, full penetration of cracks and effective bond can be achieved. The technique also has the advantage of being applicable to cracks in the masonry units as well as the mortar joints.

If epoxy repair techniques are to be used, it is important that the correct epoxy mix is chosen. The epoxy must have adequate penetration and wetting characteristics, have sufficient bond capacity, and be of compatible stiffness to the material being repaired. The last of these requirements is to avoid the creation of local regions of high stiffness, which might create local concentrations of stress under subsequent movements from thermal and other causes. Mixes with the appropriate characteristics are available.

7. Design for Durability

7.1 General

For a structure to remain serviceable, it must be durable throughout its life, assuming a reasonable level of building maintenance is carried out. The main causes of durability failure are corrosion of embedded steel items and the effects of crystalline salts in the masonry. Salts can be drawn in from the atmosphere, drawn up from the ground, or be present in building materials such as the sand used to mix the mortar.

To ensure adequate serviceability, AS 3700 requires that members and structures have the necessary durability to withstand the expected wear and deterioration throughout the intended life without the need for excessive maintenance. The required durability depends on the exposure environment and importance of the structure. A typical design life is 50 years.

While AS 3700 is not explicit about the intended life or the importance of the structure, it gives extensive deemed-to-satisfy solutions for each of the wall components and for a range of environmental conditions. In order to satisfy the requirements, each component must be graded in accordance with its respective durability.

The exposure environments referred to in Table 5.1 of AS 3700 are described in more detail in the informative Appendix E of the standard. They are as follows:

- **Mild** – typically inland, not in the tropics and away from industrial areas.
- **Exterior** – exposed walls in non-marine locations. Both the exterior leaf of a cavity wall and the cavity space are regarded as being in an exterior environment.
- **Interior** – all internal walls of a building, including the interior leaf of a cavity wall that is exposed on the exterior.
- **Marine** – between 100 metres and 1 kilometre from a non-surf coast and between 1 kilometre and 10 kilometres from a surf coast. The coast is defined as the mean high-water mark.
- **Severe marine** – up to 100 metres from a non-surf coast and up to 1 kilometre from a surf coast. As before, the coast is defined as the mean high-water mark.

It is important to realise that the classification of exposure environments should be applied to individual elements or members. It cannot be argued, for example, that the cavity space of an external cavity wall is in an interior environment. An external cavity wall of a building is a member in an above-ground exterior environment and the cavity space therefore has this classification.

The design of each of the components of masonry to provide the necessary durability is discussed in the following.

7.2 Masonry units

When masonry absorbs moisture containing dissolved salts, either from the atmosphere (for example, sea spray) or from the ground, it can suffer damage when the moisture subsequently dries out. This damage will usually be either to the mortar joints (if the mortar is soft) or to the units, and sometimes to both.

The mechanism operating is that the dissolved salts crystallise just below the surface as the moisture evaporates and the growth of the crystals causes physical stresses leading to particles being dislodged from the surface; this is referred to as salt attack.

Figure 12 and Figure 13 show typical damage to clay masonry units and mortar from salt attack. Erosion, whether of the masonry units or the mortar joints, will become a severe aesthetic problem long before it becomes a structural one.

A standard salt cycling test is given in AS/NZS 4456.10[30] to measure the resistance of masonry units to salt attack. The available grades, in order of increasing resistance, are Protected, General Purpose and Exposure.

- **Protected** grade bricks are usually used for internal walls above a damp-proof course.
- **General Purpose** grade bricks are suitable for use in external walls in normal exposure conditions.
- **Exposure** grade bricks are suitable for saline environments and should always be used below the damp-proof course and in other locations of severe exposure.

AS 3700 gives the required grade for various locations and this should be specified on the documents for each job and specified to the manufacturer when units are ordered. If there is any doubt about the suitability of units for a particular environment, the manufacturer should be consulted before ordering the units.

Figure 12. Salt attack damage to clay masonry units

Figure 13. Salt attack damage to mortar

7.3 Mortar

The resistance of mortar joints to degradation during the life of a building is related to surface hardness, which is strongly related to cement content. Low hardness will lead to progressive erosion of the surface of the joints by physical damage, wind action, insect attack and the effects of salt crystallisation.

Mortar is classified in AS 3700 as grades M1, M2, M3 or M4. These grades are used for durability requirements as well as for strength properties. Mortar of type M1 can only be used for restoration work to match existing construction and therefore has no corresponding durability provisions.

AS 3700 sets out a range of exposure conditions and lists the required mortar grade for each. Deemed-to-satisfy proportions are given in AS 3700 for achieving the various grades of mortar. AS 3700 includes a test method[31] for mortar durability and acceptance limits for the various mortar grades. The resulting scratch index correlates well with the cement content of the mortar and is also strongly affected by joint tooling and the presence of fines, such as lime, in the mortar mix. The operation of the test is described and illustrated in TBA Manual 10, Construction Guidelines for Clay Masonry.

7.4 Ties, connectors and lintels

Wall ties are readily available for a range of exposure environments in galvanised steel, stainless steel and polymer. Designers and specifiers should consider carefully the consequences of failure during the design life of the building and choose the materials accordingly. Ties and connectors are very expensive to replace if they fail, much more so than many other building components and many times their original cost.
A measure of conservatism is therefore warranted in the use of ties; jeopardising the integrity of the building for a saving of a few dollars does not make sound economic sense.

The Newcastle earthquake in 1989 exposed many cases of corroded wall ties, leading to catastrophic collapse of the masonry. The problem of corroded wall ties is exacerbated by the fact that they cannot be seen until an extreme event such as an earthquake or high wind causes failure, by which time it is too late. Even examination of the cavity using an endoscope is not sufficient to reveal the damage, because it tends to be worst just inside the mortar joint on the cavity side.
A typical example of a corroded cavity tie is shown in Figure 14. The small extra investment required for stainless steel ties would prevent these problems and ensure a lifetime commensurate with that of the clay masonry units.

Figure 14. Corroded tie exposed by a failure during the Newcastle earthquake

Wall ties and other built-in components such as connectors for control joints, connectors for attachment of masonry to building frames, and lintels, are required to have a rating for durability (called a durability class) relevant to the exposure conditions. The durability ratings required by AS 3700 are R0, R1, R2, R3, R4 and R5. AS 3700 sets out a series of locations for masonry elements, related to these environments, and gives a required durability rating for each, using the symbols R0 to R5.

AS/NZS 2699 includes test procedures for establishing durability ratings for wall ties[10], connectors and accessories[32] and lintels[33]. However, these tests are not intended for routine use on individual projects. AS/NZS 2699 is a manufacturing standard and it is the responsibility of manufacturers to establish ratings for their products. This should be done at the time of product development, before bringing the product to market. To ease the burden on manufacturers, the standard contains deemed-to-satisfy durability ratings for steel ties manufactured from sheet and wire. These provisions will be relied upon in most cases and provide a simple means of satisfying the requirements of AS 3700.

Durability class R5 is intended for critical applications in special situations such as tidal and splash zones or areas of heavy chemical pollution. No test criteria or deemed-to-satisfy solutions are given for the R5 rating.

Wall ties manufactured from non-metallic materials such as polymers are also available and can be used provided they have been shown to satisfy the exposure conditions set out in AS/NZS 2699.1 corresponding to the requirements of AS 3700.

AS/NZS 2699.1 requires all ties to be marked on the packaging and on individual ties with the durability rating. For the packaging, this must consist of a reference to AS/NZS 2699.1 and a rating (R0 to R5). For individual ties, they should be stamped with 0 to 4, indicating the corresponding rating R0 to R4, or colour coded as follows:

- R0 and R1 green
- R2 yellow
- R3 red
- R4 white or blue

Wall ties without the appropriate markings should be assumed not to comply with the standard and should not be used.

7.5 Reinforcement

Reinforcing bars can be provided with a corrosion-resistant coating to achieve the required durability rating, but will usually rely on a minimum grout cover to ensure an acceptable level of resistance. The required covers, which do not include the face shell thickness of the unit, are given in AS 3700. For this purpose, the grout is required to have at least 300 kg/m^3 cement content.

Reinforcement embedded in mortar joints must have corrosion protection to achieve a durability rating of R0 to R5, as for ties and accessories, plus a minimum cover of 15 mm of mortar to the outside of the masonry. The requirement for separate protection to provide the durability rating is in recognition of the fact that mortar does not give the same degree of protection to the steel as does cement-rich grout. Similarly, in prestressed masonry, unbonded tendons must be protected to give the required durability rating. No deemed-to-satisfy solutions are provided in AS 3700 for reinforcement in mortar joints or unbonded tendons. The designer must therefore assess the durability rating for each particular material.

8. Robustness

8.1 Design principles

AS 3700 requires masonry members and their connections to have an adequate degree of robustness, regardless of the level of load to which they are subjected, but it does not define what is meant by robustness.

The principle is that even if a wall is designed to satisfy all the prescribed loads, it should not be so slender as to fail under some unintended or accidental load and it should have adequate stiffness. If the wall is capable of withstanding a minimum level of lateral load of about 0.5 kPa, it will usually have the necessary robustness. Since calculations for lateral load are quite complex, deemed-to-satisfy rules are given in AS 3700, based on simplified slenderness ratios.

It is important to realise that all walls, irrespective of their level of loading (and including non-loadbearing walls) must satisfy the robustness requirements of AS 3700.

The rules take a simplified approach to restraint conditions, by considering only three common cases:

- A wall with a free top
- A wall or pier with any loading or support other than a concrete slab
- A wall carrying a concrete slab

Unreinforced isolated piers are more vulnerable than walls and the limiting slenderness ratio for an isolated pier is therefore half the value for a similar wall. A pier has both length and width less than one-fifth of the height.

Robustness is controlled by a set of equations, which give limits on height for one-way and two-way spanning members as follows:

1. For isolated piers –

$$\frac{H}{t_r} \leq C_v$$

2. For walls spanning vertically –

$$\frac{H}{k_t t_r} \leq C_v$$

3. For walls with at least one vertical edge laterally supported and $\frac{L_r}{t_r} \leq C_h$

$$\frac{H}{t_r} = \text{No limit}$$

4. For walls with at least one vertical edge laterally supported and $\frac{L_r}{t_r} > C_h$

$$\frac{H}{t_r} \leq C_v + \frac{C_h}{L_r - C_h t_r}$$

Where –

H = Clear height of the member (in metres)

t_r = Minimum thickness of the member (for a cavity wall = two-thirds the sum of the thicknesses of the two leaves) (in metres)

k_t = thickness coefficient for engaged piers (tabulated in AS 3700)

C_v = Robustness coefficient for vertical span (tabulated in AS 3700)

C_h = Robustness coefficient for horizontal span (tabulated in AS 3700)

L_r = Clear length of the wall, or length to the centre of an opening (in metres)

The stiffening action of engaged piers is only taken into account for walls in pure vertical spanning. Even then, the piers must be quite substantial before they are effective. Note that both leaves of a cavity wall are considered to act together for the purposes of robustness, unlike for compressive strength design.

These design rules can be expressed as limiting heights and lengths for a given wall thickness. These are shown as charts for various wall configurations in Section 8.2.

The equations for walls with side support (leading to two-way bending or panel action) result in a smooth curve, unlike the cases with only top and bottom support, and this recognises the importance and effect of having at least one vertical support to stabilise the wall.

8.2 Limiting dimensions for robustness

The following charts show limiting heights and lengths for single leaf and cavity walls constructed with clay masonry units of common sizes. Support conditions and the applicable slenderness coefficients are indicated by an icon on each chart:

- Where the icon shows hatching along an edge, the corresponding edge of the wall is laterally supported.
- The word SLAB indicates that the loading on the top of the wall is applied through a concrete slab.
- Otherwise the wall supports a roof or floor other than a slab.

The charts for walls supported only at the top and bottom (Chart 7 and Chart 8) show the transition to limiting heights for isolated piers when the length falls below five times the thickness at the left-hand side.

Chart 1. Robustness limits for clay masonry walls supported on four edges and loaded by a concrete slab

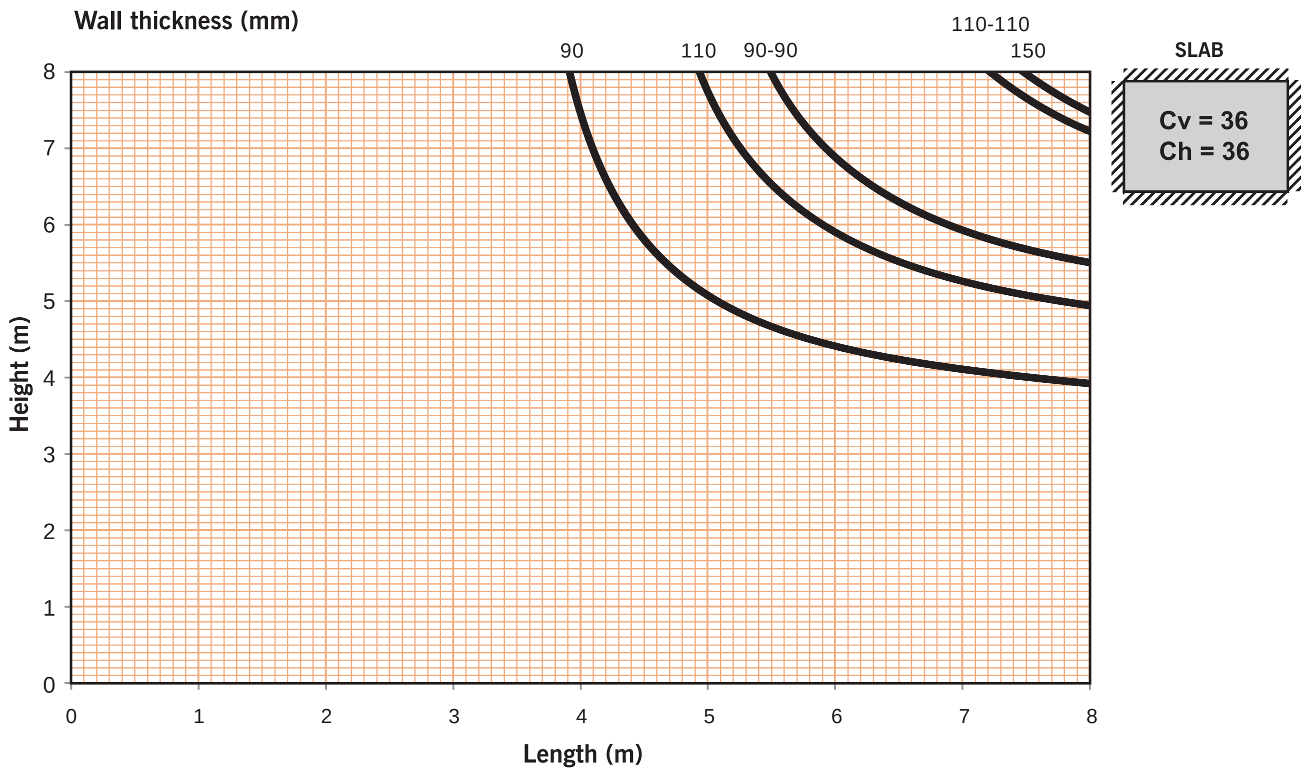


Chart 2. Robustness limits for clay masonry walls supported on four edges and loaded by other than a concrete slab

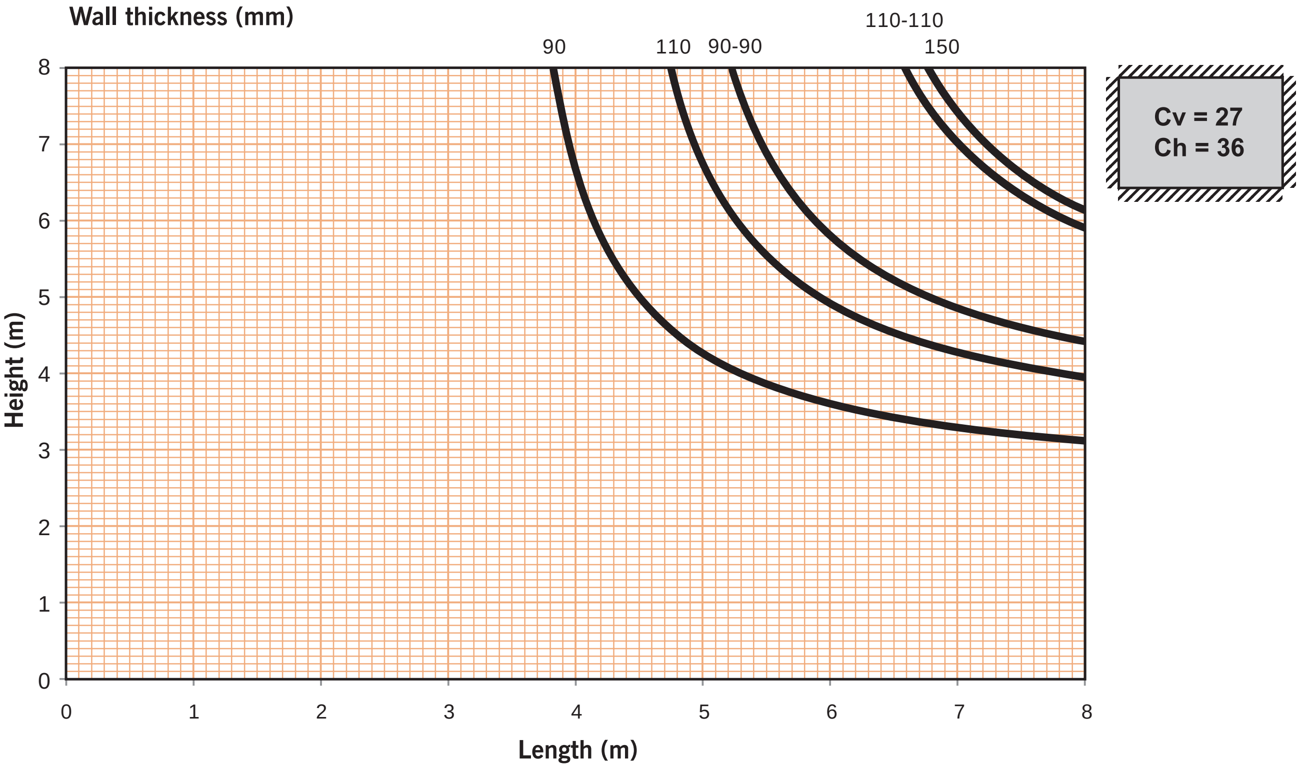


Chart 3. Robustness limits for clay masonry walls supported on three edges and with the top free

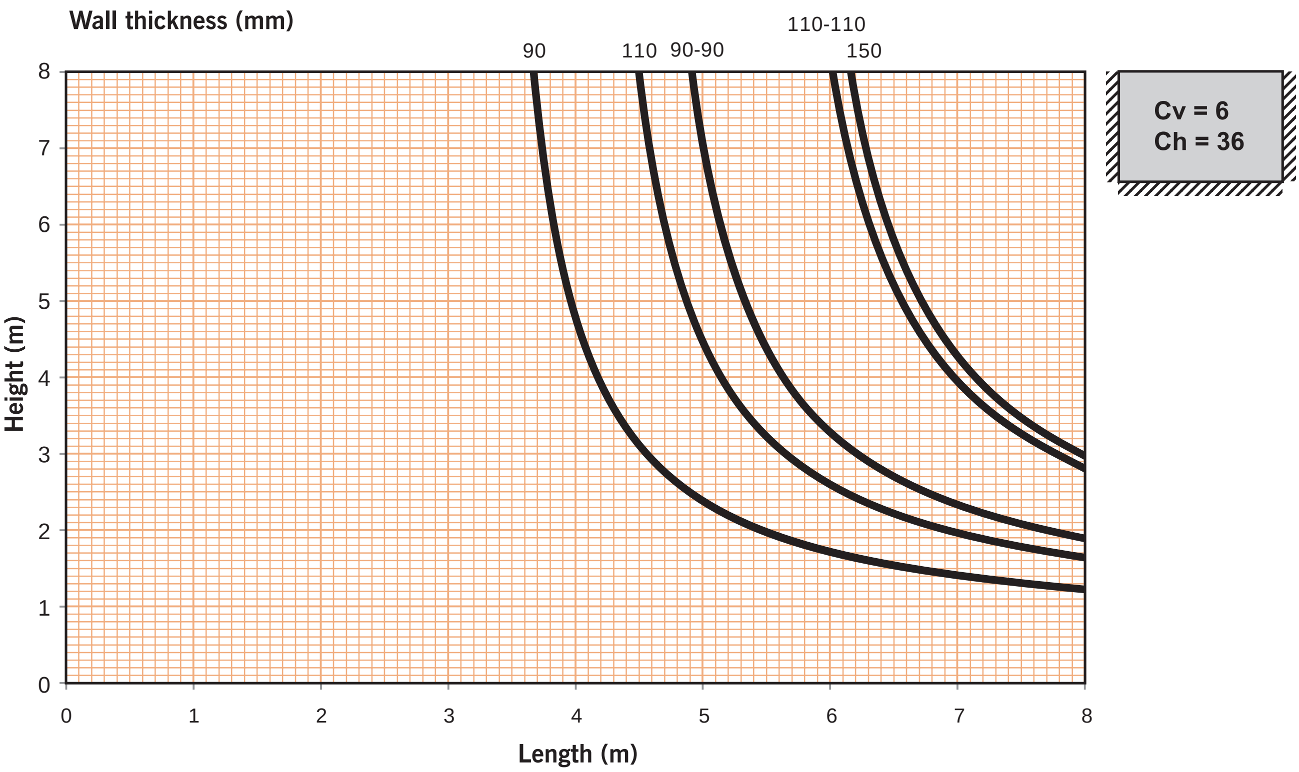


Chart 4. Robustness limits for clay masonry walls with one side free and loaded by a concrete slab

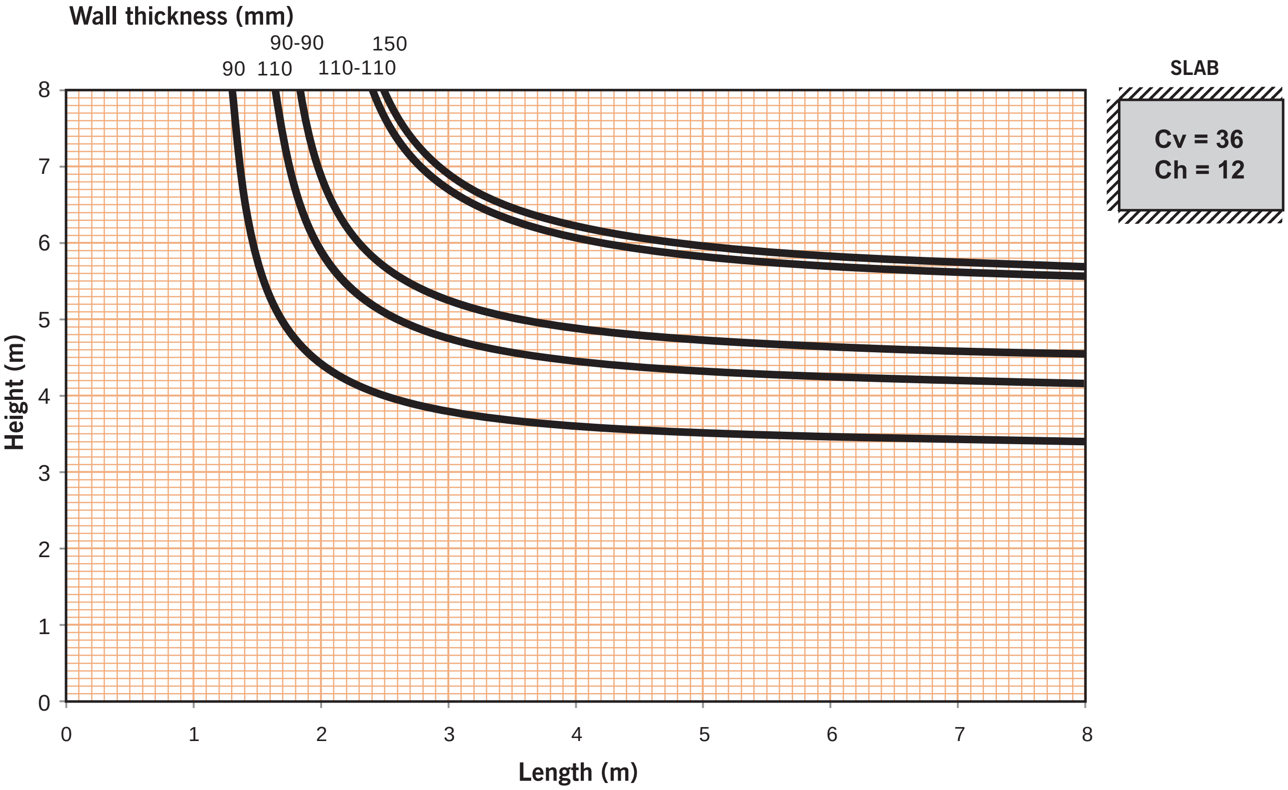


Chart 5. Robustness limits for clay masonry walls with one side free and loaded by other than a concrete slab

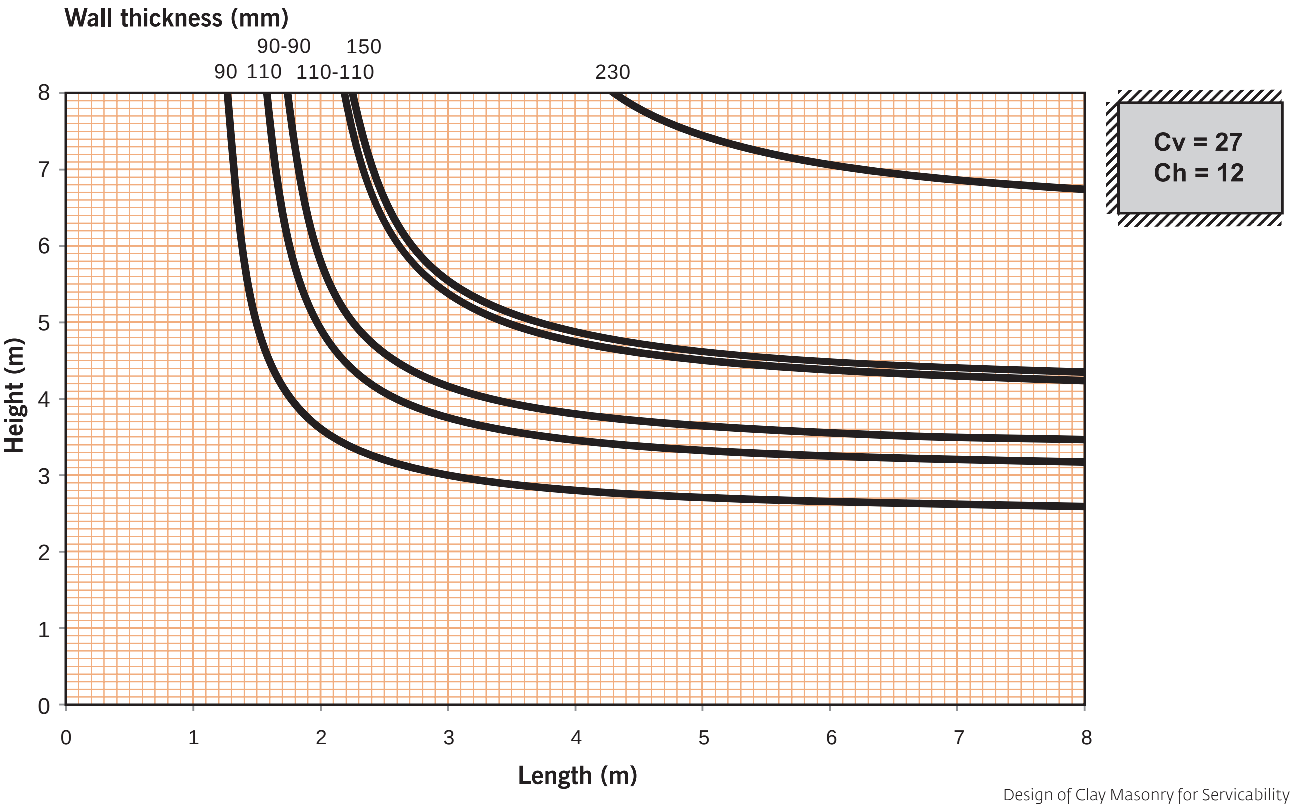


Chart 6. Robustness limits for clay masonry walls supported on two edges

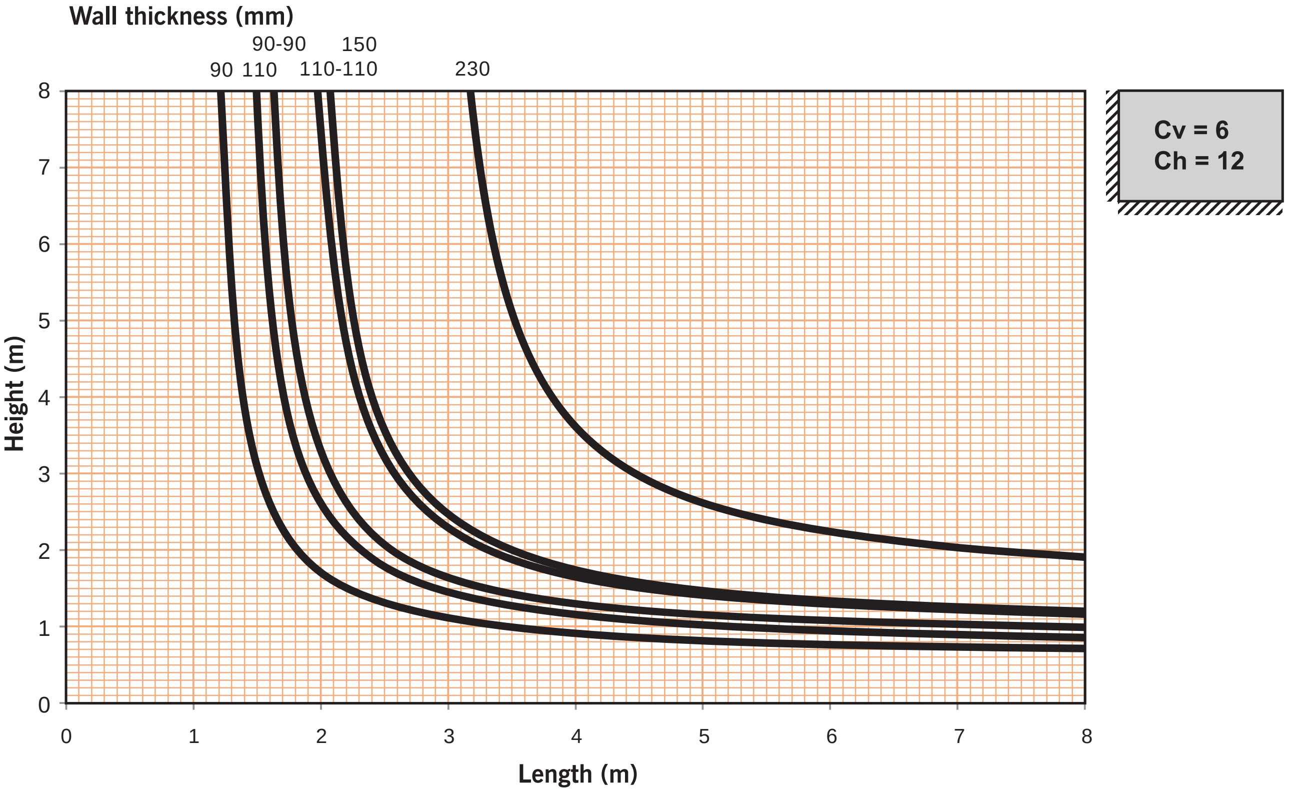


Chart 7. Robustness limits for clay masonry walls supported at top and bottom and loaded by a concrete slab

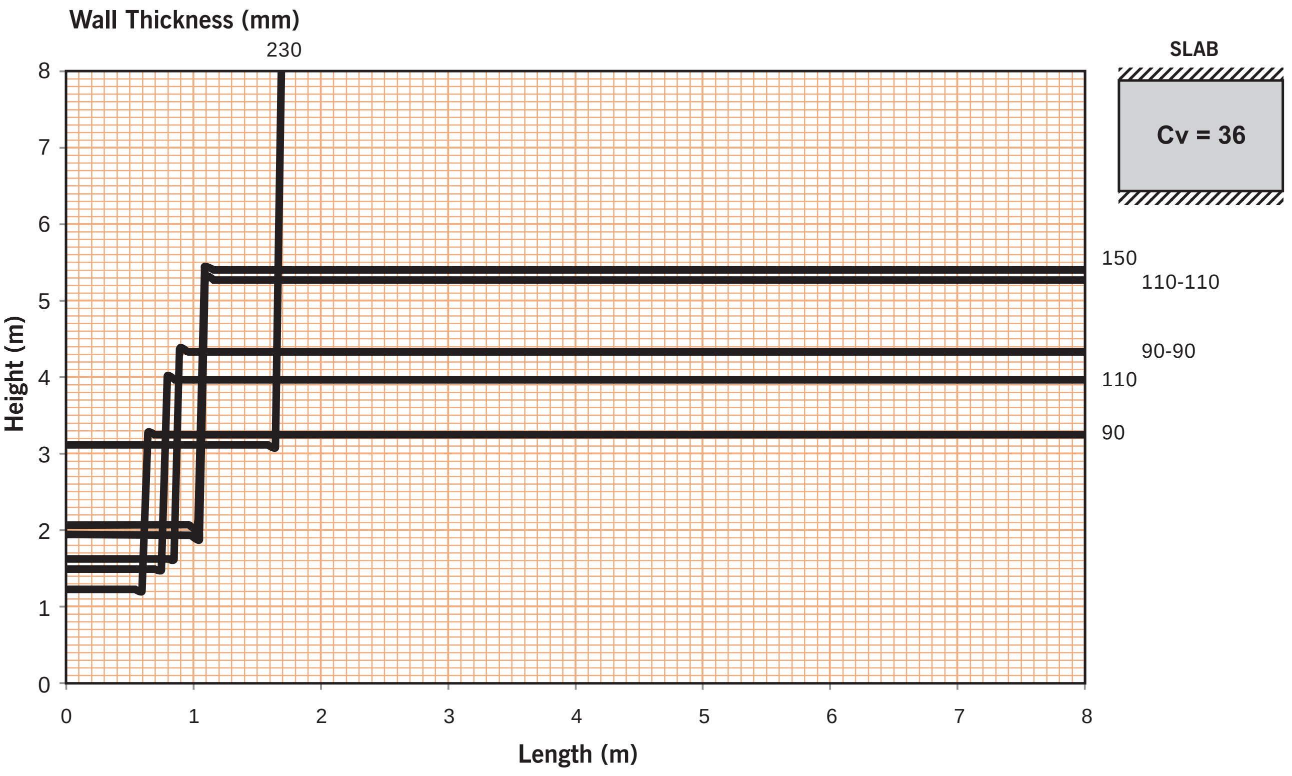
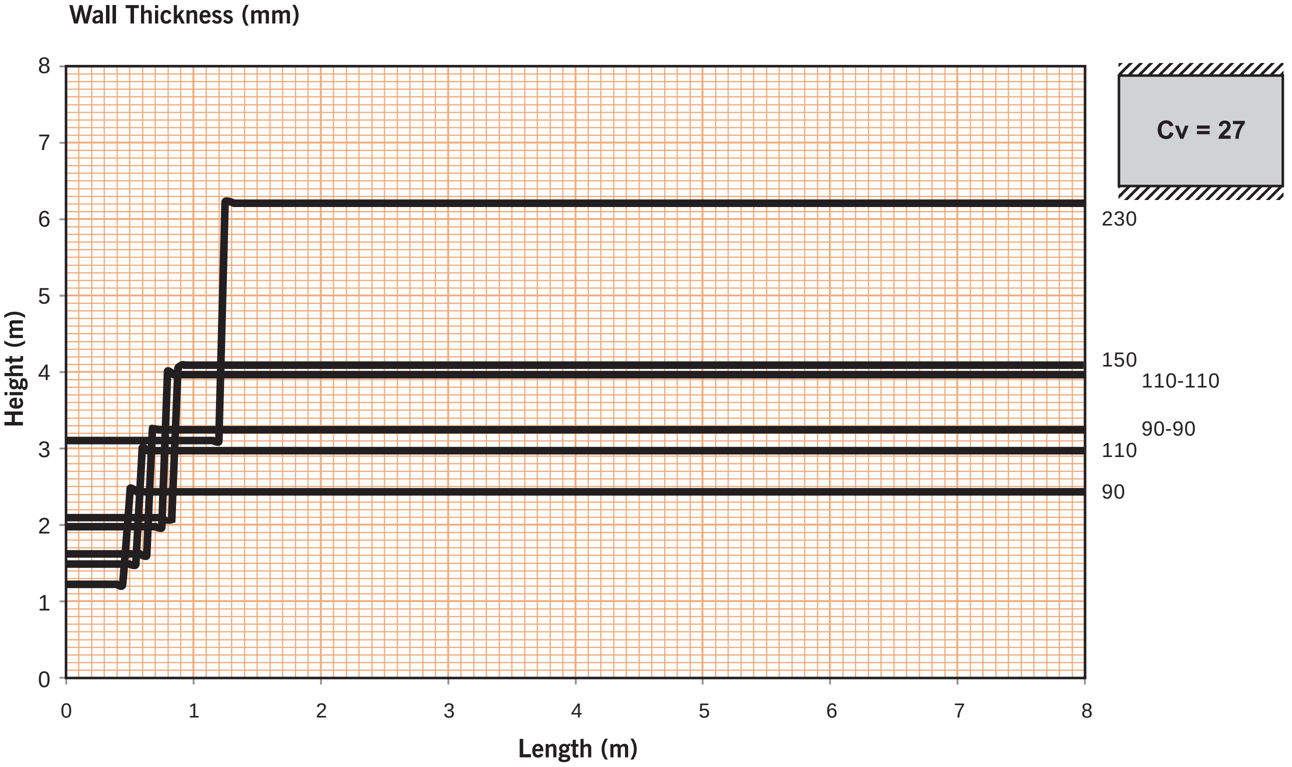


Chart 8. Robustness limits for clay masonry walls supported at top and bottom and loaded by other than a concrete slab



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