A **cement** and **concrete** industry publication

Design and Construction using Insulating Concrete Formwork

A guide for structural design, concrete specifications, workmanship and construction details of ICF structures

A. K . Tovey CEng. FIStructE, MCIArb

Prof. J. J. Roberts BSc(Eng), PhD, CEng, FIStructE, FICE, FBMS, FCMI, FRSA, MICT

M. Kilcommons BEng (civil) with Honours. CEng, MICE, LL.B, FCII

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For information on ICF in the UK visit ICFA (uk) website at **www.icfinfo.org.uk**

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The Concrete Centre
Riverside House, 4 Meadows Business Park, Station Approach, Blackwater, Camberley, Surrey GU17 9AB
Tel: +44 (0)1276 606800 Fax: +44 (0)1276 606801 www.concretecentre.com

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1. Introduction

Insulating concrete formwork (ICF) is an innovative modern method of construction, which combines the inherent strength of concrete with the excellent thermal insulation properties of polystyrene to produce cost-effective and durable structures. The polystyrene is used as permanent formwork for the concrete and is available as either expanded or extruded polystyrene, in a variety of configurations and a number of proprietary systems. The basic structure is typically erected by a team of three or four site operatives and filled by pumping a very workable concrete in storey-height lifts. In addition to providing a strong structure, the concrete provides excellent sound insulation, fire resistance and the ability for thermal capacity. Designers appreciate the basic elegance and simplicity of ICF systems and have been quick to employ them for a variety of applications. The purpose of this guide is to provide designers and contractors with a thorough understanding of Insulating Concrete Formwork.

1.1 Insulating concrete formwork

The normal method of constructing load-bearing concrete elements is to place the concrete into temporary formwork or moulds, which are then removed once the concrete has attained sufficient strength to be self-supporting and avoid damage. Such elements may require secondary temporary supports or be allowed to gain further strength for subsequent handling, construction loads and activities. ICF develops this method further by using economic permanent insulating formwork or systems to replace the conventional metal- or wood-based materials.

ICF has become an established, mainstream method of construction in Germany, France, the USA and Canada, since its introduction in the 1960s. Although its use is relatively new in the UK, there are already examples of residential, commercial and public buildings, including basements, swimming pools and retaining walls. Within the UK, the conditions and requirements are such that use can be made of cost-effective un-reinforced systems.

Also known as permanent insulating formwork (PIF), the insulation is left in place after the concrete has cured, functioning as an integral part of the insulation of the building. The method has developed because the insulation materials, and the manner in which they are assembled to provide the formwork, are capable of supporting and providing dimensional stability to the fluid concrete. This ensures vertical wall surfaces, free from lateral distortion.

The most common materials used for the ICF forms are expanded polystyrene (EPS), or extruded polystyrene (XPS). There are four main systems: blocks, planks, panels and composites. The resulting construction provides both structural capacity and thermal insulation. The thickness/depth of the concrete, available from the various systems, is typically 100mm to 300mm, and the commonly used sizes are 140/150 and 200mm. ICF can be designed to enable significant structural capacity both as un-reinforced and reinforced walls depending on the design loadings. The insulation can be varied to provide for U-values in the range of 0.11 to 0.35W/m^{2}K.

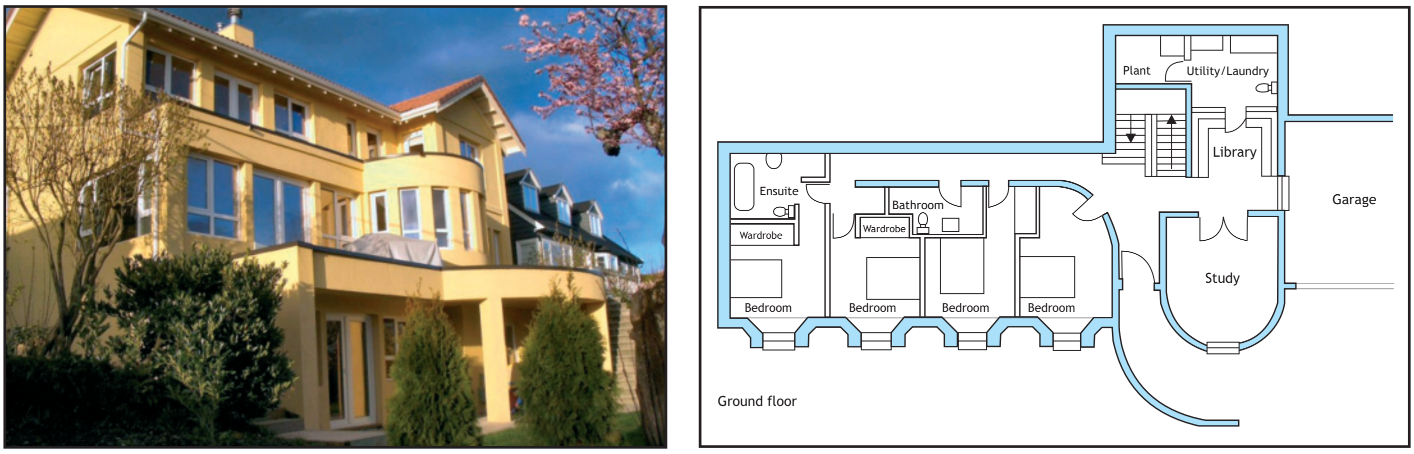
Some designers are reluctant to recognise the specification of plain (i.e. un-reinforced) concrete load-bearing walls, and sometimes specify a minimum amount of steel reinforcing to control cracking, even where the wall section is always in compression. There are many situations where often no reinforcement is needed in ICF construction, because of the beneficial effect that the insulation has on curing and in minimising thermal cycling.

While the method is simple (there are only two components to control, i.e. the formwork and the concrete), this is not to say it is an unskilled operation. The most appropriate craft, and tools required for constructing the formwork, is carpentry. However, as in all seemingly simple operations, practice is what makes it seem so. ICF has a trade body, the Insulating Concrete Formwork Association (ICFA), which has agreed with the Construction Industry Training Board (CITB) an accredited training programme leading to a National Vocational Training (NVQ) qualification. All the ICFA members provide training for contractors new to the method, and it is strongly recommended that designers recognise such training, and possession of NVQ qualifications, within specifications and contract documents, wherever possible.

Although part of the product, the insulation can be removed post construction to improve thermal mass and minimise construction thickness to separating and internal walls.

Figure 1.1 shows an application of an ICF system illustrating its ability to accommodate frequent panel openings for windows and doors, and that curved walls and lintels can be formed without difficulty.

Figure 1.1
Example of ICF used to accommodate changes in shape.



1.2 Scope and applicability of this guide

This guide has been written to provide a detailed technical review of ICF and to outline and present design methods and construction guidance appropriate to UK Codes and Regulations.

Chapter 2 provides an overview of insulating concrete formwork, including more detailed information on the different systems available. It also indicates the types of structures that ICF can be used for.

Chapter 3 covers the general design considerations and the structural regulations, codes and standards. Chapter 3 also covers other aspects of the Building Regulations in respect of sound insulation and noise, thermal insulation, and fire performance. It also touches on desirable, but not mandatory, performance characteristics in relation to flood resilience, environmental sustainability, security and durability, and shows how ICF can be designed to meet these requirements.

Chapter 4 provides detail on the design of unreinforced ICF walls to Eurocode 2 and BS 8110. In many situations in the UK reinforcement for structural purposes is not required.

Chapter 5 provides detail on the design of reinforced ICF walls to Eurocode 2 and BS 8110. Covers requirements to ensure that the appropriate concrete is specified to achieve full compaction.

Chapter 6 covers requirements to ensure that the concrete is appropriately specified to achieve full compaction.

Chapters 7 and 8 covers construction methods and workmanship, together with a selection of construction details covering common building situations.

Appendix A and B provide a detailed commentary on the design of plain ICF to Eurocode 2 and BS 8110, the two principle design codes summarised in Chapter 4. A design example to each is also given.

Together these chapters will provide designers with the basic knowledge and confidence to design ICF structures and make full use of the potential offered by this form of construction.

Guide to presentation

Eurocode 2 12.10	Relevant clauses from Eurocode 2-1-1
Blue shaded text	Examples

2. Overview of generic types and their application

This chapter gives an overview of generic types and reviews the insulation materials commonly in use in the UK, and their applicability to a variety of structural forms. In the introduction, the generic types were listed as block, plank, large panel and composite. The detail of these follows.

2.1 Block systems

Block types consist of a range of different sized and shaped components catering for commonly encountered building situations. The components fit tightly together to create a stable form, which contains the fluid concrete. The basic module consists of parallel sheets of EPS, joined by EPS cavity bridges acting as ties, forming a hollow block, which is filled with concrete (Figure 2.1).

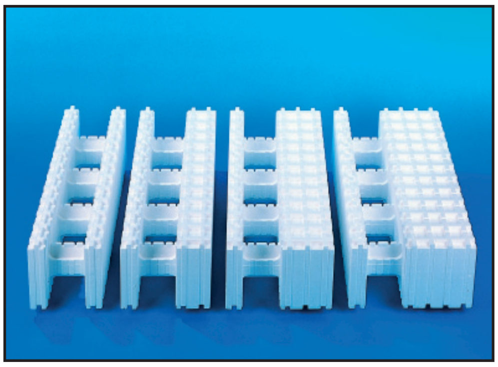
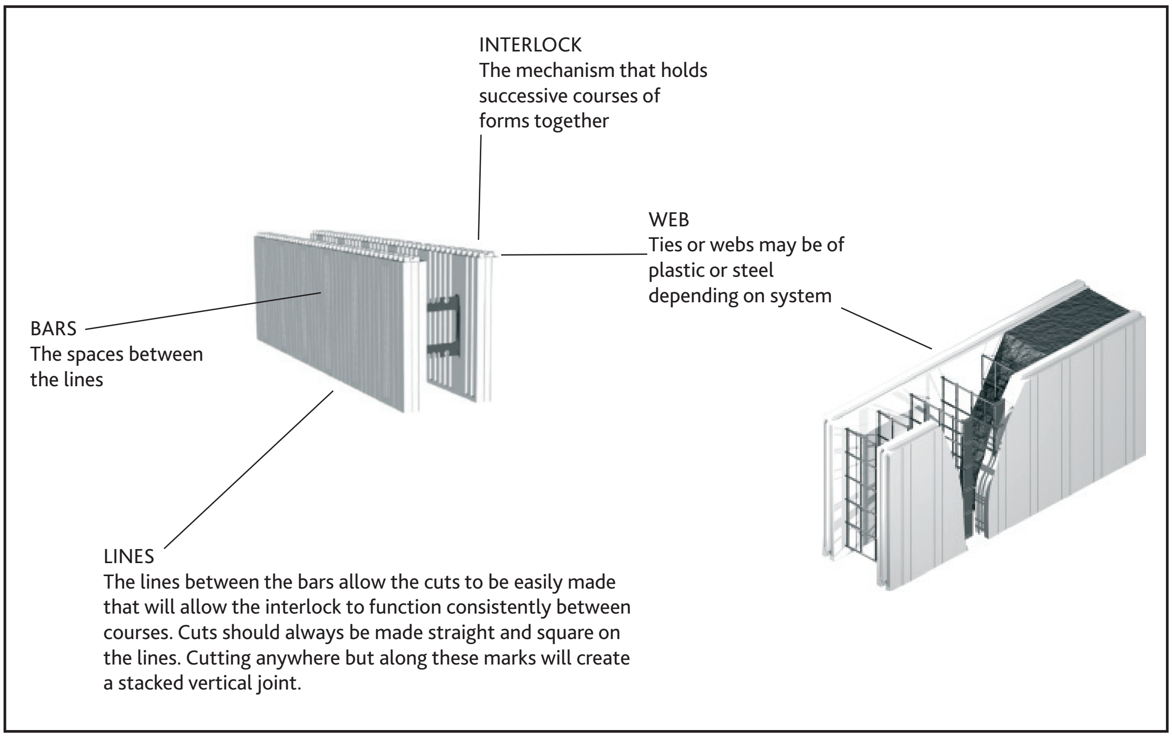


Figure 2.1
ICF block system with EPS bridges.

In a typical range of block components with differing insulation wall thicknesses, the blocks range between 500–1,250mm long and 250–400mm high. The blocks typically fit together by castellation on the horizontal mating surfaces. Vertical joints are staggered as they are typically in blockwork.

The cavity ties can be made of EPS creating a honeycomb structure, as shown in Figure 2.1, or from polypropylene, solid polystyrene or steel mesh (Figure 2.2). Blocks using EPS ties create a waffle wall section requiring less concrete for the same wall thickness, while solid ties are much slimmer in section and produce a solid wall section, offering less congestion if reinforcement is necessary. See Chapters 3, 4 and 5 and the appendices for the performance differences between EPS bridged units and those with smaller solid ties.

Figure 2.2
Blocks with solid ties (typical features).



INTERLOCK
The mechanism that holds successive courses of forms together

WEB
Ties or webs may be of plastic or steel depending on system

BARS
The spaces between the lines

LINES
The lines between the bars allow the cuts to be easily made that will allow the interlock to function consistently between courses. Cuts should always be made straight and square on the lines. Cutting anywhere but along these marks will create a stacked vertical joint.

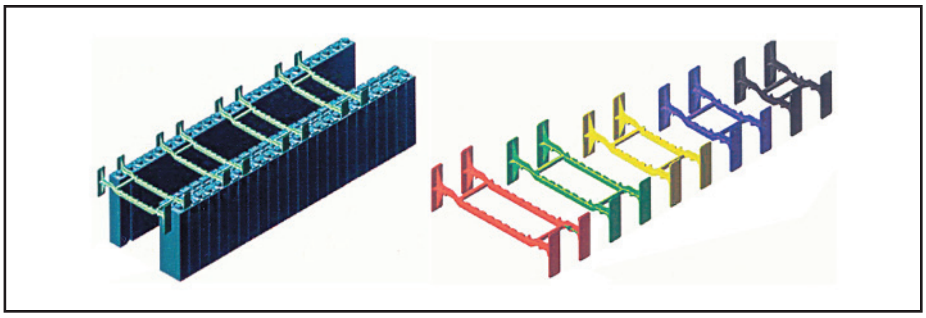
The systems can be produced to provide a range of thicknesses from a typical minimum concrete thickness of 100mm and offer EPS wall thickness from 50–250mm. An ICF wall using 50mm EPS sheets with a 150 core (50/150/50) will provide a U-value of 0.30W/m^{2}K ignoring finishes, while a 50/150/200 wall delivers 0.11W/m^{2}K. The precise value will depend upon the density of the polystyrene used and whether it has been subjected to any special treatment, such as the inclusion of graphite.

Right-angle corner blocks and 45-degree blocks are available, and are used to reduce the need for cutting and fitting on site. Other specially shaped blocks facilitate the fixing of components such as floors and brick cladding.

2.2 Plank systems

ICF plank systems share many of the characteristics of conventional formwork construction. These systems are inherently simple as there are only three basic components: the insulation planks, cavity ties and the rails or fixing channels, which locate the planks. The ties and rails are each available in a variety of sizes, which allow for different core and insulation thicknesses (see Figure 2.3).

Figure 2.3
Separate planks tied together and a range of tie sizes to give different core widths.



One UK system uses extruded polystyrene (XPS) as the insulating plank material rather than EPS. The planks range in thickness from 50mm to 200mm. Each plank is 300mm high, and either 1,250 or 2,500mm long. The XPS plank edges are cut square without tongues or grooves, and are located into 1,524mm lengths of PVC rails or some other form of holding system that supports the planks along the joint. The rails are U-shaped at the bottom and top of the wall, and H-section for intermediate lifts. The rails have a continuous arrow-head extrusion along the internal face, into which wall ties are snap-fixed at 225mm centres to tie the formwork faces together. The ties are available in increments of 50mm providing a core thickness varying from 150–300mm, and occasionally beyond. Other EPS plank systems have the more usual castellated top and bottom surfaces to aid the fixing of plank to plank, as shown in Figure 2.3.

XPS is mechanically stronger, and is a marginally better insulator than EPS, a 50/150/50 wall providing a U-value of 0.27W/m^{2}K compared to 0.30W/m^{2}K for an EPS wall.

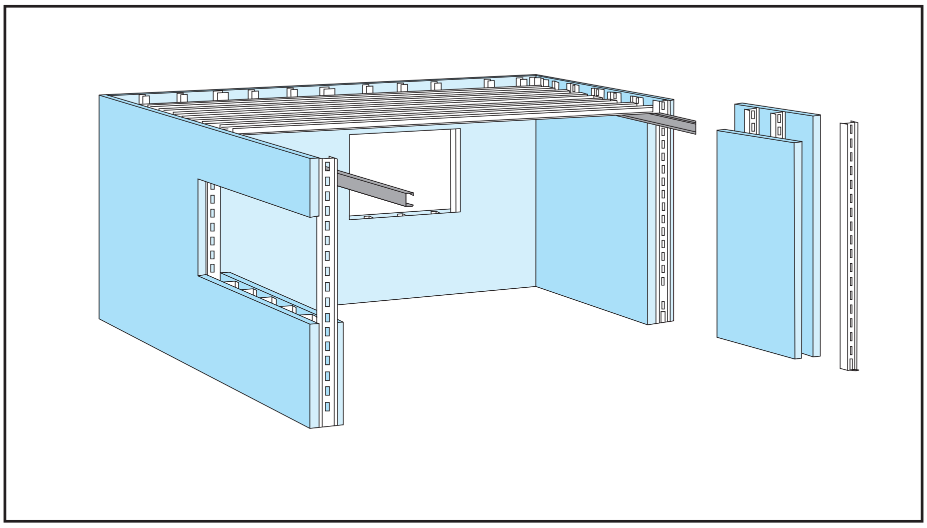
One of the systems offers a special fixing rail, which allows the use of thinner section plywood or other sheet material (provided it can withstand the fluid concrete pressure) to form one of the formwork faces instead of normal insulation. The plywood can be easily removed after casting the wall, allowing the concrete core, now exposed on one face, to provide a high thermal capacity (see Chapter 3 for a fuller discussion). If it is necessary, for structural reasons, for the wall to be reinforced, this system will also allow one form face (ply or insulation) to be erected in advance of the other; individual bars or mesh can be easily wired in place as in normal formwork construction and, when complete, the second form can be assembled.

The nature of the plank system cavity ties enables curved walls to be easily created by simple cutting techniques. This is described in more detail in Chapter 7.

2.3 Panel systems

The larger panel systems usually employ tongued and grooved EPS sheets to adequately contain the fluid concrete without distortion at the panel edges. The panels are typically 1,200mm long and 600mm high, tied together with galvanised steel mesh. The faces are 65mm EPS which provides a U-value of 0.22W/m^{2}K in conjunction with a 150mm core. Although categorised in this guide as a large panel, the rigid nature of the panels given by the cast-in ties means they could equally be categorised as a block type. However, benefits and characteristics deriving from their large size compared with the other block systems more strongly justify inclusion as a panel type.

Figure 2.4
Large panel hybrid system.



A large panel hybrid system, combining EPS insulation with galvanised steel channels to give structural strength, has also been produced for the UK market. The panels are storey height (2,400mm) and 1,200mm wide – see Figure 2.4.

The panels are pre-assembled and delivered to site ready to erect in accordance with the design. The system's standard panels comprise 80mm XPS insulation each side of a concrete core 100mm wide. EPS insulation, alternative insulation thicknesses and a concrete core of 150mm width are offered as options. The standard 80/100/80 XPS panel section provides a U-value of around 0.20W/m^{2}K. The system utilises composite concrete floors that provide bracing to the walls (both temporary and permanent) and the concrete is placed at the same time as the walls. The reinforcing channels are positioned at 300mm centres, and individual panels are connected to each other by means of self-tapping screws and washers fixed through the insulation at the panel ends into steel I beams.

2.4 Composite wall systems

Some ICF systems are available as a composite system where one insulation face is replaced by a hard cement particle board or clay pot face to enable the full benefits of thermal mass to be utilised (see Chapter 3).

2.5 Attributes of ICF construction

In addition to the thermal insulation value provided by the ICF formers, ICF structures have very low air infiltration rates, almost all of which is accounted for by window and door openings. Consequently, there will be very little heat loss due to air changes, and this boosts the thermal insulation effect. Conversely, designers may need to consider the provision of other measures to ensure adequate ventilation.

Both EPS and XPS are closed cell foams, and have very low water absorbency. The core is specified as a highly workable concrete; this results in a low risk of voids. Due to the permanent presence of the insulation both during construction and under operating conditions, the concrete undergoes more controlled shrinkage and thermal strains and, as a result, experiences very little shrinkage cracking. These factors combine to produce walls that are inherently resistant to rain and flood damage. In order to maximise this potential, designers should pay particular attention in the specification of the external and internal finishes, the penetration of walls for utility connections, and the location and routing of services, especially electric cabling and sockets.

ICF systems can provide the additional benefits which a standard concrete wall can provide.

These include:
- Sound insulation
- Inherent fire resistance
- Durable structures with potential for long life
- Security of solid wall construction
- Sustainability

Some proprietary systems available in the UK have independent third-party assessments such as BBA, BRE or LANTAC certification. These are accepted as demonstrating compliance with the relevant building regulations, etc.

2.6 Types of structures

ICF construction is suitable for a wide range of structures. Significant use of ICF has been made in housing where it can be used for single or multi-storey projects. The flexibility of the system makes it suitable for building with both flat and curved elevations. Recent examples cover single-storey residential, two-storey and three-storey houses, and multi-family apartments and flats in both small and large-scale developments; housing projects specified for passive heat energy, houses with basements and projects where ICF is used only for the basements. ICF has also been used for earth-sheltered houses and for commercial and educational structures.

ICF construction has also been used for projects such as churches and administration buildings as well as commercial warehousing. Indeed, ICF can be used for any type of building since it utilises the strength, durability and adaptability of concrete.

3. Design considerations

3.1 Application of regulations, codes and standards to ICF

In-situ concrete is traditionally used with conventional removable formwork to provide the structural components of building frames and other structures. With ICF construction, the conventional formwork is effectively replaced by a permanent formwork system, which also provides insulation and many other benefits discussed later in this chapter.

Since the basic structural element is concrete, in general, the same codes and standards will apply and, hence, the building regulations may be met by following the recommendations given in the documents listed in Section 1 of Approved Document A[3.1], which includes BS 8110[3.2], and other recognised British and European standards. However, there is no obligation to adopt any particular solution contained in an Approved Document including the listed design documents. Approved Documents are only intended to provide guidance for some of the more common building situations and there may well be alternative ways of achieving compliance with the requirements.

Thus in relation to the design of ICF structures, whilst codes provide the essential information for design, there are characteristics of ICF structures that may be used to amend certain normal design or construction practices. For example, the insulating formwork provides a very good environment for the curing of the concrete and its insulating properties would allow concrete to be placed at lower temperatures than normal.

Another important factor detailed in Approved Document A is that it is recognised that there are other suitable forms of construction in use other than conventional concrete and masonry in housing, which have been in common use for a number of years and have demonstrated an adequate performance in compliance with the A1 requirement. Since ICF construction has already been used for numerous housing projects and thus approved by Building Control within the UK, and as it has an established track record of performance in many other countries, it should by the same token be accepted as an alternative form of construction.

The design and construction guide on ICF construction is intended to be the first step towards recognition of ICF as an alternative construction system in Approved Document A[3.1]. From spring 2008, BS 8110 will be with-drawn and all concrete design will be carried out in accordance with Eurocode 2[3.3]. As a result, Eurocode 2 is used as a method of design for the future in this publication.

3.2 Structural codes

The design of ICF concrete is covered in more detail in Chapters 4 and 5 for the design of plain and reinforced ICF respectively. This section is written to provide an introduction or commentary on the use of the general design codes as they may be applied to ICF construction.

3.2.1 Eurocode 2

The structural Eurocode 2[3.3] is used in this publication as a method for designing concrete structures (see Chapter 4). This code also has more detailed design information for plain concrete walls than BS 8110.

3.2.2 BS 8110

The structural design of concrete walls is covered by BS 8110, Section 3–3.9. BS 8110 classifies walls either as reinforced (containing at least a minimum area of reinforcement, specified as 0.4%) or plain (where the reinforcement is less than this minimum amount). For a plain wall, any reinforcement is ignored when considering the strength of the wall. Because of the considerable load capacity provided by the running lengths of wall in ICF construction, they can typically be designed as plain walls for most structures – the provision of reinforcement being confined to certain retaining walls or column sections as may occur between long-span window openings.

BS 8110 requires reinforcement for fire-resistance and structural purposes (columns and beams) and, at times, for certain walls. Reinforcement is also used for serviceability purposes, e.g. distribution of loads and to control cracking. However, the curing conditions and the form of construction will minimise or may negate cracking, as discussed in Chapter 4.

ICF offers a very good curing environment for concrete and, as a result, the minimum reinforcement, which is required for normal concrete construction to cater for early age effects, is not considered to be essential in this type of construction. Eurocode 2[3.3] and BS 8110[3.2] provide scopes for omitting such reinforcement completely, and this is further discussed in Chapters 4 and 5.

The durability requirements for ICF construction are given in Chapter 6. The cover required to protect any reinforcement against corrosion depends on the exposure conditions and the quality of concrete as placed and cured. Generally the concrete within an ICF wall or element will be cured better than conventional concrete placed in removable forms. BS 8110/BS 8500 allow a trade-off between the quality of the concrete and the required cover.

3.2.3 BS 5628

Although the masonry code is not meant to apply to ICF in-situ concrete walls, it is unlikely to result in a structurally inadequate design since the material partial safety factors for masonry are considerably greater than those for concrete (typically 3.5 and 1.5 respectively). However, the differences in test methods between concrete cubes and masonry units will alter this apparent level of safety, largely because of the differences in aspect ratio. The overall effect is still likely to be on the safe side, but will lead to an uneconomic design, particularly if all aspects of design (lateral load capacity, bearing stresses, slenderness limits, etc.) are limited in accordance with BS 5628[3.6].

The masonry code is erroniously referred to by some third party assessment bodies for the design of ICF.

3.3 Other design aspects

3.3.1 LPS 2020

A new Loss Prevention Standard (LPS 2020)[3.8] has been prepared by BRE Certification, at the request of insurers, mortgage lenders, regulators and manufacturers, to provide a single and consistent method of assessing the performance and design of new methods of construction that do not have a track record of use in the UK. As such it provides a route for certification for innovative building systems, sub-assemblies and elements used for domestic construction, but can also be used to assess and compare the performance of all construction methods.

The standard has been developed by insurers, lenders, regulators and other bodies, all of whom have an interest in minimising repair costs to damaged buildings. It applies to modern methods of construction which, by their innovative nature, have not accumulated much experience in use, and sets a number of performance requirements that should be met.

The basic LPS 2020 is supplemented by a number of enhancement standards, which are intended to be used by specifiers where there is a need for material performance better than those required to satisfy the statutory requirements. ICF is expected to be able to satisfy not only the basic LPS 2020, but also the enhanced standards, which set higher performance level for dwellings in terms of fire resistance (LPS 2023), energy efficiency (LPS 2024), security (LPS 2025), flood resilience (LPS 2026) and reduced environmental impact (2027). These additional standards will provide the option for manufacturers to demonstrate that their specialist systems achieve higher levels of performance in these specified areas.

Although the performance levels are yet to be finalised, the concrete industry is confident that its construction systems will surpass them. Not only does concrete provide benefits well in excess of building regulations, but the long-term benefits are such that the whole-life cost of a concrete home should be spread over a minimum 120-year lifetime rather than the 60 years used in current comparisons. ICF construction can provide enhanced performance as required by LPS 2020 as indicated in the following sections:

3.4 Building regulations

The building regulations[3.7] make no specific reference to ICF as a construction method. However, the requirement with respect to several parts can be met by conventional concrete and masonry, and this data can in many instances be applied to ICF on a generic basis. Part A, Structure, provides guidance on meeting the requirements with certain forms of masonry construction for a given range of buildings.

This design guide, in addition to providing formal design methods, also provides simplified guidance in line with that currently used in Part A, Structure.

For applications such as basements for houses, the structure may be designed to meet the requirements of the building regulations for England and Wales by using the *Approved Document – Basements for Dwellings*[3.4] published by the Basement Information Centre. In Section 3B this gives a simple tabular approach to the design of reinforced concrete walls subject to various limitations on overall dimensions and the size and position of openings, etc. An addendum was introduced in 2006 covering the design of plain concrete retaining walls.

3.4.1 Resistance to moisture

Requirement C4 of Approved Document C[3.9] – Site Preparation and Resistance to Moisture – requires that a wall should prevent undue moisture from the ground reaching the inside of the building and, if it is an external wall, adequately resist the penetration of moisture from rain or snow to the inside of the building. Approved Document C does not give guidance on preventing damage resulting from condensation, which is covered by Approved Documents L[3.10] and F[3.11].

Concrete walls formed using ICF should meet the requirement of the regulations with respect to resistance of moisture without difficulty when appropriate external finishes are used. Reference can be made to BS 5628: Part 3[3.12], which gives the recommended thickness of rendered dense concrete masonry walls based on an assessment of their resistance to rain penetration. This ranges from 90mm to 250mm, depending on the exposure category, which is within the typical range of ICF walls, as the core of ICF walls will be denser and thus more resistant than a masonry wall. This indicates that, when correctly applied, a rendered ICF wall provides the necessary resistance even in exposed conditions.

Resistance to water from the ground may be obtained by use of a conventional type DPC provided within the height of the ICF walling, then, as for traditional construction, the DPC should interrupt it to span the full width of the wall. A DPC in the construction supporting the walls will be acceptable provided it is a minimum of 150mm above external ground level. However, this can be difficult to install, and alternative methods are more commonly used. One approach is to use a water-resisting concrete (Type B, BS 8102: 1990[3.5]) at the base of the wall and to turn the DPM up the face of the wall (see Figure 8.3). Where a layer of such concrete is provided, it should extend up to the level at which a conventional DPC would be included. Another method for preventing the passage of moisture from the ground is to use a liquid membrane (see Chapter 8). Since these alternative methods only prevent moisture ingress through the concrete itself, it is particularly important in these cases that good drainage of the soil is provided at ground level.

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BS 8102: 1990 Code of Practice for Protection of Structures Against Water from the Ground includes recommendations for walls subject to ground water pressure, including basement walls. In basement situations, some form of tanking enveloping the whole of the construction below ground will often be required. It should be noted that polystyrene should not be used in contact with membranes based on coal tar pitches or other building materials containing solvents and, therefore, the specific ICF suppliers should be consulted to check compatibility with particular tanking products.

There are a number of guidance documents on waterproofing basements[3.13, 3.14]. These require the use of a Type A wall (also as defined in BS 8102), which is dependent on the use of an appropriate membrane, or a Type B wall in which the integral protection of the wall is used to provide the necessary resistance combined with an additional membrane or other water-proofing measures (waterproofing admixture) under more severe conditions. The construction measures adopted for ICF walls will influence whether it is designated a Type A or a Type B wall.

Polystyrene materials are resistant to moisture, particularly extruded polystyrene which is a closed-cell material and could be beneficial in situations where a structure may be prone to flooding.

LPS 2026

Loss Prevention Standard LPS 2026 looks for enhanced flood resistance[3.15]. ICF can offer this due to the robustness of the concrete core and is likely to be more resilient to flood damage than lightweight construction systems. Concrete, EPS and XPS do not deteriorate in the presence of moisture and cope well with flooding and accidental spillage. ICF construction is particularly suitable for basement construction and can be used with various waterproofing systems to produce effective water-resisting basements for given exposure conditions.

3.4.2 Ventilation

Requirement F1[3.11] states that there should be adequate means of ventilation provided for people in a building. The ventilation should, under normal conditions, be capable of restricting the accumulation of moisture that would otherwise lead to mould growth and pollutants originating within a building, which could become a hazard to occupants' health.

To achieve these objectives the method and degree of ventilation provided should:
- extract water vapour from areas where it is produced in significant quantities;
- rapidly dilute pollutants and water vapour produced in a habitable room;
- make available over long periods a minimum supply of fresh air for occupants.

For domestic buildings there is a requirement for both rapid ventilation and background ventilation, and in some cases, extract ventilation. The most obvious form of rapid ventilation is simply opening a window. The requirement to provide background ventilation can typically be met by including trickle vents in the window design.

The current guidance makes no specific allowance for the fact that walls constructed in ICF will typically result in more airtight construction than other forms of construction. More detailed ventilation requirements will in due course be introduced in Approved Document F, and more stringent requirements for airtightness are to be introduced into Part L[3.10] of the regulations.

The advantages of the more airtight construction resulting from the use of ICF in terms of savings in heating costs are discussed in section 3.4.6

3.4.3 Sound insulation

Approved Document E[3.16] states that:

> dwelling-houses, flats and rooms for residential purposes shall be designed and constructed in such a way that they provide reasonable resistance to sound from other parts of the same building and from adjoining buildings. It also requires dwelling-houses, flats and rooms for residential purposes shall be designed and constructed in such a way that – (a) internal walls between a bedroom or a room containing a water closet, and other rooms; and (b) internal floors, provide reasonable resistance to sound.

The methods to demonstrate that a proposed construction complies with the requirements are as follows:

Separating walls

- Pre-completion testing must be carried out, or the walls should be built in accordance with the design details approved by Robust Details Ltd.
- For pre-completion testing the separating walls in dwellings are required to achieve a sound insulation value set out in Table 1a, which is currently:

  45 $D_{nT,w} + C_{tr}$ dB.

However, this is not straightforward because there are slightly different procedural requirements depending on whether the building control is being carried out by a local authority (Regulation 20A) or by an Approved Inspector (Regulation 12A). There are also different requirements for new-builds and alterations.

The sound insulation testing should be carried out in accordance with the procedure described in Annex B of Approved Document E, and the results of the testing must be recorded in a prescribed manner. The test results must also be given to the building control body in accordance within certain time limits. The person carrying out the building has to arrange for sound insulation testing to be carried out by a test body with appropriate third-party accreditation (preferably UKAS accreditation, or a European equivalent) for field measurements. The performance standards that should be demonstrated by pre-completion testing are set out in Approved Document E, Section 0: Performance – Tables 1a and 1b. The sound insulation values in these tables have a built-in allowance for measurement uncertainty, so if any test shows one of these values not to have been achieved by any margin, the test has failed.

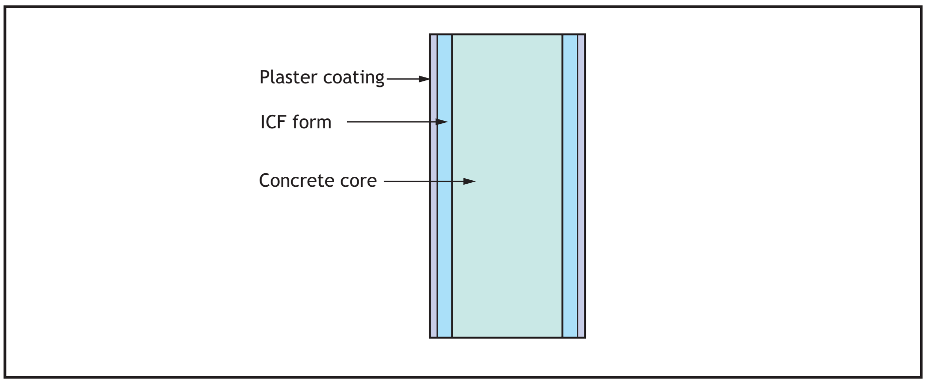
There are further requirements on the bodies carrying out the work and the types/positions of the walls to be tested:

- The results of tests only apply to the particular constructions tested but are indicative of the performance of others of the same type in the same development. Therefore, in order for meaningful inferences to be made from tests, it is essential that developments be considered as a number of notional groups, with the same construction type within each group. This may then require the testing of sub-groups to encompass as wide a range of properties as possible, and for new construction where there is a material change of use.
- A main limitation of adopting the pre-completion route is that a set of tests has failed if any of its individual tests of airborne (or impact sound insulation in the case of floors) do not show sound insulation values equal to or better than those set out in Tables 1a and 1b of Approved Document E. In the event of a failed set of tests, appropriate remedial treatment should be applied to the rooms that failed the test. But a failed set of tests may raise questions or concerns over the sound insulation between other rooms sharing the same separating element in the dwelling-houses, flats or rooms for residential purposes in which the tests were conducted.

Section 2 of Approved Document E gives examples of wall constructions which, if built correctly, should achieve the sound insulation values for dwelling houses and flats set out in Table 1a. These need to be read in conjunction with Section 3, which provides guidance on the requirements for flanking walls. Section 4 gives guidance for material change of use. The guidance in these sections is not exhaustive and other designs, materials or products may be used to achieve the required performance.

ICF construction is not referred to in any section but reference is given to a basic in-situ wall (wall type 1.2, Section 2: Separating walls and associated flanking constructions for new buildings). This suggests that a 190mm solid in-situ concrete wall, when correctly built and with appropriate flanking walls, would be likely to meet the requirements of Part E (see Figure 3.1).

Figure 3.1
Example of an ICF Type 1 wall.



This should only be taken as a guide because the ties in an ICF wall extend through and into the insulation and vary in materials (steel, plastic etc). The presence of the ties may affect the sound insulation compared to that of a normal concrete wall. However, sound tests on an actual building with a continuous core ICF system and with plasterboard attached directly to the separating wall and external wall has shown an airborne sound insulation value of 53 *DnT*,w and 47*DnT*,w + *Ctr*. This is similar to that which would be expected for a normal plastered solid concrete wall, which complies with the building regulations in Scotland, England and Wales.

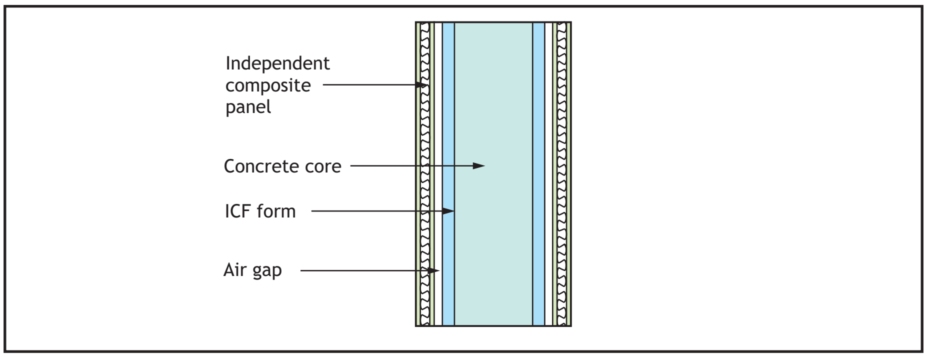
Thus, in the case of a continuous cored panel and block systems, the wall's resistance may typically be estimated by reference to the mass law or from Approved Document E (but note comment on effect of ties, above), and certain laboratory tests. Pre-completion tests will still be required to substantiate the 'as constructed' wall in a given property.

Another separating wall that can be considered is a wall between independent panels as shown in Figure 3.2. This type of wall is referred to as a Type 3 wall in Approved Document E, which gives examples using a masonry wall. There may still be some sound transfer from the ties in this type of wall, compared with that of a wall with plasterboard applied directly to the ICF system. With appropriate discontinuity measures introduced to lessen sound transferred through flanking walls, a specific Type 3 construction for each manufacturer's system, or a generic method or robust detail for all continuous cored ICF systems is a likely outcome. It is also probable that some increase in the ICF core thickness may be required to meet a robust detail solution for a separating wall. However a thicker wall would also be required for a wall built from materials other than concrete.

Insulating concrete formwork systems of block form that use insulation as the tie offer certain economies in construction but will have poorer sound insulation than ICF walls with a continuous core and thus are unlikely to be suitable as separating walls.

A number of ICF systems have been assessed for Robust Details[3.17].

Figure 3.2
Example of an ICF type 3 wall.



Internal walls

There are acoustic requirements for internal walls within a dwelling between a bedroom and another bedroom, or a room containing a water closet and other rooms, to provide reasonable resistance to noise. This may be determined by laboratory tests and the required value is 40 *Rw* dB. Section 5 of Approved Document E provides examples of constructions that should satisfy the regulations, but these are not specific to ICF walls. It only gives Type C (*Concrete block wall* having a minimum mass per unit area, excluding finish 120kg/m^2 with plaster or plaster-board finish on both sides), and Type D (*Aircrete block wall*: minimum mass per unit area, including finish 90kg/m^2 for plasterboard finish, minimum mass per unit area, including finish 75kg/m^2 for masonry walls). Insulating concrete walls will typically have a mass greater than 120kg/m^2 and thus should provide the same or better sound insulation. A 150mm wall will have a mass of around 430kg/m^2.

Some ICF systems can be supplied with narrow cores (100mm), while others will have a minimum thickness of 150mm (see Chapters 4 and 5 with regard to minimum thickness for load-bearing walls). Alternatively, internal walls can be constructed of plain concrete or masonry and these can be used to enhance thermal capacity.

One of the main challenges facing high-density building being advocated by the Government is to adequately deal with noise from neighbouring properties. Here, the heavyweight mass of concrete construction, such as ICF, can be used with advantage to provide improved sound insulation compared to lightweight construction techniques. A number of ICF systems have been assessed for robust details.

3.4.4 Fire-resistance

All manufacturers of ICF systems can provide designs with appropriate finishes to meet the minimum notional fire period of 30 minutes for houses, and are also able to provide options for higher fire-resistance periods of 90 minutes as required for certain flats and maisonettes or walls within a basement. Higher periods (two hours or more) could be designed by reference to Eurocode 2[3.3], BS 8110[3.2], BRE Guide[3.18] or by test. See Chapters 4 and 5 for further information.

3.4.4.1 Structure

The Approved Document B[3.19] states that the building shall be designed and constructed so that, in the event of fire, its stability will be maintained for a reasonable period. This period will vary according to the size, height and use of the building. Specifications for the requirements for the structure (notional fire period and construction form) are given in Approved Document B. Design codes such as Eurocode 2[3.3], BS 8110[3.2] and BS 5628[3.6] also provide design specifications for elements of structure for differing levels of fire resistance. Other publications, such as BRE's guidelines for structural fire resistance[3.18], give further guidance for other forms of construction which would apply to ICF construction.

A wall that is common to two buildings should be designed and constructed so that it restricts the spread of fire between those buildings for a notional period. The wall needs to:

- prevent spread of flame by transfer of heat (insulation),
- prevent spread of flame by transfer of hot gasses (integrity),
- prevent collapse in the case of load-bearing elements (stability).

In domestic house construction, separating walls between semi-detached and terraced properties would be classified in this way.

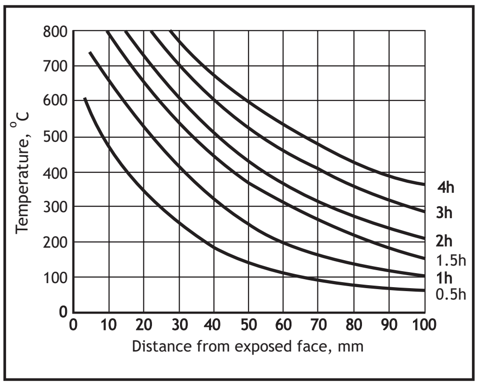
In ICF walling systems, the required resistance is provided by the central concrete core of the wall, and thus has to be designed for the required structural and fire performance. The central core in an ICF wall can be continuous, or intermittent in the case of insulation-bridged block systems that form post and beam elements. The fire-separating function provided by the insulation-bridged ICF blocks is likely to be insufficient for walls that have a separating function due to transfer of flames through the insulation bridge following failure of the surface (plaster/plaster board) finish. However, alternative higher-performance wall finishes are available. Internal walls of this form of ICF could be satisfactory where they are only required to provide a load-bearing and not a separating function.

An ICF wall with a continuous core differs from basic concrete or masonry walls in that the tie runs through the wall and into the insulation and may be of steel or plastic (e.g. polypropylene). Since these are both, in general, protected by the plaster finish and by the concrete they do not affect the wall's fire resistance compared with a normal concrete wall. Therefore, an ICF wall with a continuous concrete core will provide a similar performance to a conventional concrete wall, and the wall's resistance may be determined from Approved Document B[3.19], Eurocode 2 or BS 8110. However, there are some variations which need to be further considered and the structural aspects dealt with in more detail (see Chapters 4 and 5).

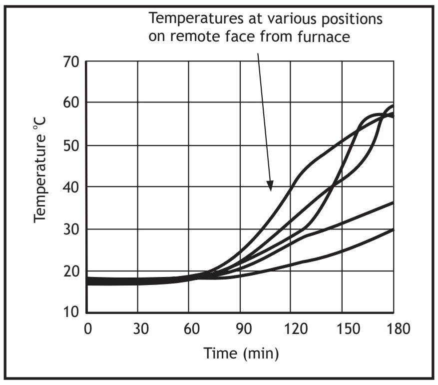
This may be explained by considering the time-temperature profile of a wall subject to fire. The wall thickness required for a separating wall will seldom exceed 175mm with respect to fire, and this will generally be increased to 190mm to cater for sound insulation. The ties used for ICF walls are either plastic or steel. Fire tests carried out on walls with steel ties show that the surrounding concrete prevents detrimental transfer of heat via the wire to the face remote from the fire.

Plastic ties will typically not melt below 150°C[3.20] and, as shown in Figure 3.3[3.22], this will not be exceeded at the remote face of a 100mm-thick wall for a fire period of up to 90 minutes, and it will be considerably longer before the temperature is reached on the remote face of a thicker wall. This demonstrates that ICF walls will effectively behave as normal concrete walls with respect to specific fire periods for dwellings, even with the loss or removal of plaster and insulation. Tests carried out on a 150mm concrete-cored ICF wall to investigate fire wicking via plastic ties[3.22] show the unexposed surface temperatures over various positions on the unheated face (remote face) of an ICF wall construction to have virtually no rise in surface temperature above ambient (16°C) up to 90 minutes and not exceeding 60°C, even after three hours (see Figure 3.4). There was no through melting of the ties, thus no hot gas transfer to the remote face. In these tests the unheated face had a 13mm plaster-board finish, but this was not added to the fire face, which meant the ties were subjected to higher temperatures than would occur where the wall is protected by a normal plaster-board finish. This test confirms the basic prediction of temperatures assessed from standard data[3.22] and that an ICF wall has a fire resistance similar to that of a normal concrete wall, with and without a plasterboard finish.

Right **Figure 3.3**
Temperature distributions in a concrete slab.



Far right **Figure 3.4**
Fire tests on ICF.



In addition, the walls will typically be finished with plaster or plasterboard, which will provide additional protection compared with the exposed concrete wall itself. The plasterboard may be able to be attached with dot and dab or trowelled-on adhesive but, depending on the fire resistance required and the construction details, there may also be a need for mechanical fixings.

Unlike beams and columns, no increase in cover to the reinforcement over that required for durability is required for a wall to achieve a given fire resistance in either Eurocode 2 or BS 8110. The fire resistance of a wall is dictated primarily by its thickness in conjunction with the area of reinforcement relative to that of concrete. For most housing, the required fire resistance period seldom exceeds one hour, and a wall having a thickness of 120 to 140mm for Eurocode 2 or 150mm in the case of BS 8110 will meet this. This applies to walls with less than 0.4% reinforcement and thus would include plain ICF walls. This is discussed further in Chapters 4 and 5. ICF walls typically have a range of concrete thickness from 140mm to 300mm and thus are capable of being used to meet the fire-resistance requirements for housing and indeed most other buildings.

3.4.4.2 Internal fire spread

The Approved Document B gives guidance on the requirements for internal fire spread (Requirement B2 – Linings).

The types of internal finishes used with ICF systems are the same as those used with other forms of construction and are thus subject to the same criteria and meet the necessary performance requirement for surface spread of flame.

The material used for ICF is generally polystyrene, either expanded or extruded, which is combustible. However, it does not contribute to continued combustion once the flame source is removed. The internal plaster finish limits flame and fire spread to the insulating material behind the finishes and for this reason fixings for plasterboard materials should be in accordance with the lining manufacturer's requirements, and may be different for different ICF systems. Generally, the type of polystyrene used with ICF systems incorporates a flame-retardant additive. This will make it more difficult to ignite, but it will not prevent it from being combustible to a naked flame. In practice, the plaster finish will protect it in many commonly found fire conditions. However, the polystyrene will not continue to burn or ignite beyond the flame source. Therefore, it will not contribute to the spread of flame.

The provision of movement joints within the construction, for example in a long terrace of housing, is typically met as with any other structure, for example, by the provision of twin walls at the separating wall junction or by the provision of appropriate fire-resisting joints in the construction. The use of ICF is, in this respect, no different than any other concrete or masonry building.

3.4.4.3 External fire spread

Approved Document B, B4[3.19], requires that the external walls of a building shall resist the spread of fire over the walls and from one building to another, having regard to the height, use and position of the building.

ICF construction typically poses no greater risk of surface spread of flame than other externally insulating forms of construction and the requirements can be met by appropriate assessment of the surface finish. External render products tend to be the most popular finish to ICF systems. They are also the most convenient and cost-effective form of finish to such walls. The building regulations require that the external envelope of a building should not provide mediums for fire spread. The polystyrene is directly attached to the inner concrete and bonded to the external render coat where used. As indicated above, the polystyrene used in ICF does not contribute to the fire load and does not continue fire propagation following removal of the flame source.

Where an external brick, block or stone finish is used, then the situation is no different from that of a typical masonry cavity wall in respect to design for fire. Cavity barriers should be provided in accordance with Approved Document B3. The exclusions with respect to the situation where the gap between the inner surface of the outer finish (e.g. brickwork) and the inner concrete surface is fully filled with insulation will then apply.

LPS 2023

Spread of fire can be seen as an important issue for high-density housing. Homes built with ICF construction will exceed current regulatory requirements for fire and provide enhanced resistance as require by LPS 2023[3.23]. The concrete core in an ICF system is almost always more than 150mm thick. If un-reinforced, such walls provide an assessed fire resistance of more than 60 minutes, and thicker walls can provide four hours or more resistance to fire. This means that an ICF home would be more structurally sound after a fire and could be efficiently repaired, unlike lightweight framed systems, which may need to be demolished.

3.4.5 Aesthetics

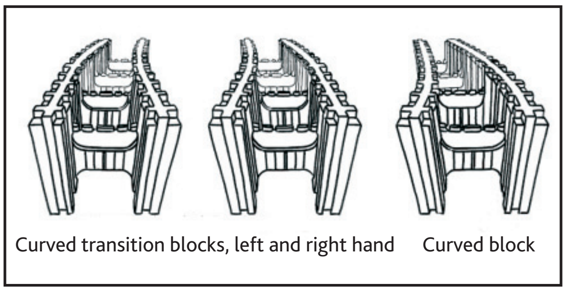
The selection of ICF systems places no limitations on the final external appearance of a project. Completed ICF structures can be indistinguishable from other methods of construction. The external appearance can be anything required by planning considerations. The finish that is probably the most complementary is thin-coat polymer render. This minimises the external footprint, while making full use of the inherently flat and smooth wall surface that ICF structures provide. Traditional sharp sand and cement renders adhere strongly to EPS and XPS, but steep temperature gradients within the render coat on sunny days need to be taken into consideration; expansion joints and additional mechanically attached mesh carrier will normally be required. Guidance on external renders may be found in BS EN 13914-1[3.24]. In all cases, technical advice should be taken from the specialist rendering contractor when specifying rendering to ICF construction.

In the UK, a brick finish is probably the most common for houses. ICF can be finished with brick slips (fixed strictly in accordance with the manufacturer's instructions) or, more usually, conventional brickwork. The brick courses are tied to the ICF wall by a number of different methods depending on the system used (see Chapter 8).

Corbels are also available for use where a change of profile is desirable, e.g. to avoid the expense of extending face stone or brickwork down to the level of the footings (see Figures 8.5 and 8.6). Tile hanging and weatherboarding can be provided (see Figure 8.7).

Curved walls can easily be created in ICF. A number of standard radius curve blocks are typically available in the product range, and special curves can be formed to order either as moulded units or as specially cut and assembled units. Alternatively, curves can be produced by removing slices from the inner face and bending the wall to the desired curve. The curved ICF wall must generally be restrained in its shape until the core is poured and cured. The necessary removal of slices of material is probably best done off-site. Some manufacturers provide this service, aided by computer programs, which determine the size and spacing of the slices to produce the required curvature. However, experienced ICF site personnel can also carry out this work if the required freeform shape is not a mathematical curve suited to computer analysis.

Right **Figure 3.5**
Example of preformed curved unit.



Far right **Figure 3.6**
Project with curved wall.

3.4.6 Energy efficiency

The Approved Document L1A[3.25] for new dwellings indicates a number of changes to the requirements in that reasonable provision shall be made for the conservation of fuel and power in buildings by:

- limiting
  - heat losses through the fabric of the building;
  - excessive solar gains; and
  - heat gains and losses from pipes, ducts and vessels used for space heating, space cooling and hot water storage;
- providing energy-efficient and properly commissioned fixed building services with effective controls;
- providing to the owner sufficient information about the building and its building services so that the building can be operated and maintained in such a manner as to use no more fuel and power than is reasonable in the circumstances.

3.4.6.1 Thermal insulation

Compliance with thermal insulation requirements is achieved by a single method known as the 'Target carbon dioxide Emission Rate' (TER). The TER is the minimum energy-performance requirement for new dwellings approved by the Secretary of State in accordance with Regulation 17B. It is expressed in terms of the mass of CO_2, in units of kg/m^2, of floor area per year emitted as a result of the provision of heating, hot water, ventilation and internal fixed lighting for a standardised household when assessed using approved calculation tools.

The TER for individual dwellings no greater than 450m^2 total floor area is to be determined by the Government's Standard Assessment Procedure (as appropriate at the time) and, for individual dwellings larger than the above threshold, using the Simplified Building Energy Model (SBEM)[3.26]. The target TER is to be calculated in two stages: first by calculating the CO_2 emissions from a notional dwelling of the same size and shape as the actual dwelling using certain defined reference values, but permitting different values of 'air permeability' to be used; and, second, by a given formula, which will include a fuel factor. To comply with regulations the proposed 'Dwelling carbon dioxide Emission Rate' (DER) must be no worse than the TER as calculated.

3.4.6.2 Air permeability

Air permeability is becoming an important design consideration because high rates of leakage are detrimental to the energy efficiency of the structure. Part L1A[3.25] indicates that a reasonable limit for the design of air permeability is 10m^3/m^2/(hr) @ 50 Pa. However, to acheive the TER may necessitate the design air permeability to be better than the limit value. Significantly better standards of air permeability are technically desirable in dwellings with mechanical ventilation, especially when using balanced systems with heat recovery.

ICF construction results in walls that are an effective 'sandwich' of insulation and concrete which is highly impermeable to the passage of air, and this performance is further enhanced by the application of render finishes and lining systems. Clearly, as with any form of construction, effective detailing and construction at openings and joints is important in reducing air infiltration, as is the use of components that achieve a high standard of performance. A recent air tightness test carried out in the UK on an ICF system returned a value of 1.99m^3/m^2/hr, which is significantly lower than both the pending Part L1A upper limit and that which will be typically limited by TER and appropriate, for example, for balanced systems with heat recovery.

3.4.7 Thermal capacity

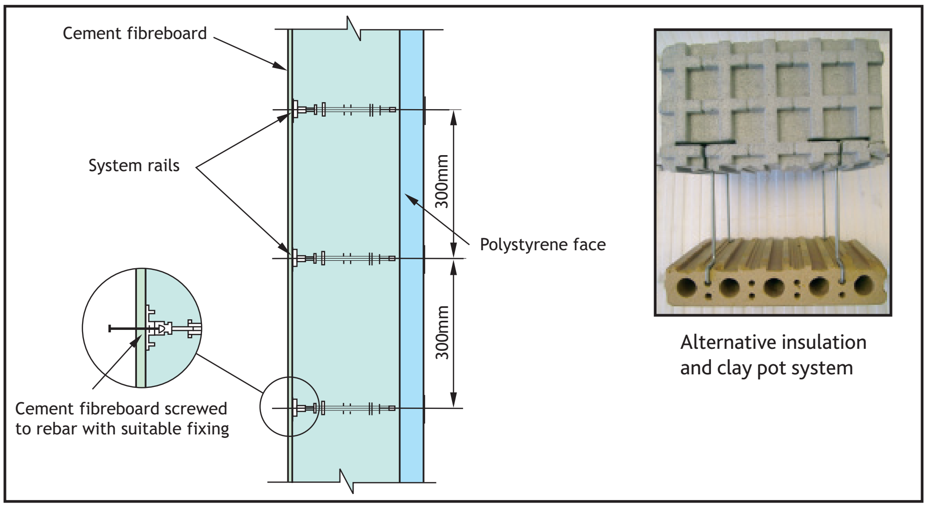
The requirement to restrict solar gain limits the demands on energy for cooling the dwelling or building. The UK Climate Impacts Programme (UKCIP)[3.28] has indicated that the UK annual temperatures could increase by between 2°C to 3.5°C by the 2080s. The summer increase will be roughly twice that seen in winter, giving an increase of approximately 6°C. Overheating is already an issue in many buildings and this will worsen and become more widespread[3.29], increasing the demand for air conditioning, and thus energy for cooling. Designers will therefore be required in the future to pay much more attention to heat gains through windows and the rest of the building fabric. In addition to design of the fabric to limit heat flow into the building, the structure itself can be used to control internal temperature rises by making use of fabric energy storage (FES). This can reduce or even eliminate the need for air conditioning, and thus lower energy requirement and, consequently, CO_2 emissions[3.30].

Thermal mass can have advantages in winter when combined with modern levels of air tightness. It can be used to store solar energy and other heat gains and transmit them back into the space and reduce the temperature drop when the heat source is removed. The benefits of thermal mass are already well established in the design of office blocks and this will increasingly be applied to the design of dwellings.

As indicated earlier, ICF consists of a concrete core sandwiched between inner and outer layers of insulation. This concrete core can be used for fabric energy storage. The effect of this heat capacity will be influenced by the volume of concrete in the wall, by climatic conditions (duration and magnitude of the external temperatures), by the degree of insulation used, and time period over which internal assessment is made. Various studies show the benefits of thermal mass, both for ICF and other concrete structures[3.31]. A typical twin insulating layered ICF systems will not contribute to controlling temperature swings over a 24-hour period to the same extent as a construction with exposed concrete walls, although a wall with unequal insulation thickness could be more effective.

To make maximum use of the thermal storage with an ICF system, some designers have used the construction benefits of ICF and then removed the inner layer of insulation to allow air direct access to the concrete surface. This is somewhat wasteful of materials and, to overcome this, some ICF systems can be supplied with an outer insulation layer and an inner cement fibre board or tile finish (Figure 3.7) which is finished and left exposed. With large panel systems it is possible to replace one of the faces with conventional plywood formwork, which can be stripped off after curing to directly expose the concrete surface.

Figure 3.7
ICF with internal hard surface to enhance thermal capacity.



Alternatively, the provision of concrete floors (with surface exposed for maximum benefit) or internal cement fibreboard or blockwork partitions can be used to improve thermal mass storage within an ICF structure.

LPS 2024

The LPS 2020[3.8] standard sets a number of performance requirements that should be met by efficient methods of construction. One of these, LPS 2024[3.32] covers enhanced energy performance, which can be achieved with ICF in respect of better U-values, reduced air permeability and enhanced thermal storage. This is principally achieved by altering the insulation thickness.

3.4.8 Sustainability

Concrete is an essential component of the built environment and every year in the UK ten million tonnes of concrete is used. The sector as a whole has gone to great lengths to improve its environmental performance and these improvements have been well documented. Reducing construction waste is a key priority and ICF offers an excellent opportunity to employ demolition waste and recycled materials in the concrete core of the walls. Techniques for producing acceptable concrete aggregate from demolition waste, glass, crumb rubber etc., have been developed in recent years and offer the prospect of sustainable concrete when used in conjunction with natural aggregates. The range of cements now available also includes many with components such as pulverised fuel ash and ggbs, which might otherwise be landfilled. These materials are typically added directly by the concrete supplier.

The area in which ICF makes the biggest contribution to a sustainable future is in the production of durable, energy-efficient buildings. The combination of a high standard of thermal insulation coupled with the thermal mass of the concrete results in a building that is able to moderate temperature fluctuations and maintain temperatures during unheated periods, thereby helping to avoid condensation. The flexibility of layout that ICF systems give to the designer means that optimum use can be made of glazing to capture natural light and, with a favourable site and by appropriate design, solar energy can be stored within the fabric of the structure. The loss of energy is further reduced by the airtight nature of the construction resulting in a very low rate of air infiltration.

It is important when examining the long-term sustainability of ICF buildings to recognise that the life of the building will greatly exceed the 60-year period often taken in comparison exercises.

The materials of which the formwork itself is made are usually expanded polystyrene (EPS) or extruded polystyrene (XPS). EPS is a thermoplastic polymer, based on styrene and does not contain CFCs or HCFCs. The small proportion of hydrocarbon blowing agent used in manufacture readily decomposes in the atmosphere and, as a result, EPS does not have any adverse impact on the ozone layer.

The manufacture of extruded polystyrene begins with solid polystyrene crystals. The crystals, along with special additives and a blowing agent, are fed into an extruder. Within the extruder the mixture is combined and melted, under controlled conditions of high temperature and pressure, into a viscous plastic fluid. The hot, thick liquid is then forced in a continuous process through a die. As it emerges from the die, it expands to foam, is shaped, cooled and trimmed to dimension. Extruded polystyrene is characterised by the smooth closed cell nature of the board and again does not contain CFCs and HCFCs.

LPS 2027

LPS 2027[3.33], part of the new enhanced standards, will cover enhanced (i.e. reduced) environmental impact. The concrete used in new construction can be specified to use recycled aggregates, and all the basic ICF materials are recyclable when they reach the end of their very long useful life.

3.4.9 Durability

The durability performance of concrete is something that is often taken for granted. An ICF building can be expected to last with minimum maintenance far in excess of lightweight construction, depending upon the choice of internal and external finishes. Both EPS and XPS are very durable, unaffected by exposure to water and complement the durability of the concrete. The permanent insulating formwork provides excellent protection for the concrete and enables it to cure properly under controlled temperature conditions. This ensures that the concrete achieves the required design strength, and other properties.

In some circumstances, reinforcing steel may need to be incorporated in the construction. When it is used within an ICF structure, care is taken to ensure that the required cover of concrete to the steel is achieved and that the concrete is properly compacted. This will ensure that the reinforcing steel is properly protected.

If steel-fibre reinforcement is specified, this will be incorporated in the concrete at the mixing stage and will be distributed evenly throughout the concrete. It can be added either at the ready-mixed concrete plant or into the drum of the truck mixer on-site. Other than an appropriate mix design, no special measures are needed to safeguard the long-term durability of the fibres.

3.4.10 Flood resistance

LPS 2026[3.34] covers enhanced resilience to flood damage. Changing weather patterns and the need to build on flood plains increases the likelihood of higher costs of repair for water-susceptible materials and construction methods. The materials used in ICF, i.e. concrete, EPS and XPS, do not deteriorate when wet and cope well with flooding and accidental spillage, although the absorption characteristics of XPS are lower than EPS.

This is likely to require standard resilience to flooding of approximately 1m internally. If designers specify suitable internal wall finishes such as cement-based boards instead of conventional plasterboard, robust ground-floor finishes, services routed down from the ceiling rather than up from the ground floor, switches and sockets positioned above the flood height and avoid the use of moisture-sensitive medium-density fibreboard (mdf) or similar mouldings, then the highest resistance to flood damage will be achieved.

3.4.11 Thermal and moisture movement

Thermal movement in concrete is typically considered in two stages:

(1) early thermal movement; and
(2) subsequent environmental temperature changes.

Although insulating formwork will increase the temperature of the concrete during construction, the resulting strain on cooling will occur over a longer period, enabling relief by creep stain. Because the concrete is cured under insulating conditions, the rate of gain, both compressive and tensile strength, will be higher. The insulating formwork will effectively minimise the environmental temperature changes in the wall.

Moisture movement is also considered in two stages:

(1) long-term movement; and
(2) short-term environmental changes.

The permanent insulating formwork, which is also moisture-resistant, will ensure the concrete is cured under well-controlled conditions and will reduce the rate of moisture loss and increase the time to reach equilibrium conditions, and enabling more creep strain to occur.

There is no detailed information on thermal and moisture movement through ICF concrete construction, but it is likely to be less than conventional formwork concrete. This arises from the effect of the controlled environment (more stable temperature and moisture content) benefitting all concrete properties, e.g. strength gain and creep coefficient.

Effect of EPS bridged blocks

The comments on thermal and moisture effects relate in general to continuous core ICF systems and may need to be adjusted for insulation bridged blocks (see Chapter 2), whose properties apart from insulation will not be as stable as continuous core systems (see also Chapter 3, 4 and Appendix B).

3.4.12 Special applications

Security

LPS 2025[3.35] covers enhanced security performance. The concrete core, even when un-reinforced, presents a high resistance to forced entry. Reinforced walls clearly are even more secure. The weaknesses and likely entry points are the door and window openings, and again, careful attention to design detail and workmanship around any openings is necessary to realise the full potential for enhanced security.

Impact and blast

Most ICF systems are particularly suitable for the construction of impact-resistant and blast-resistant structures and can readily be used with high-strength, high-performance concrete. Steel-fibre reinforced concrete, either in the form of randomly distributed short fibres or continuous fibre mesh, offers excellent resistance to impact and blast damage. Forcing secondary cracking that effectively turns the normally brittle concrete into a ductile material can optimise the energy absorption capacity. Very high strength concretes with steel-fibre reinforcement have been produced with a flexural toughness 250 times greater than conventional concrete without fibres, and greatly enhanced penetration resistance[3.36].

In the USA ICF is being specified for public buildings where there is a risk of explosive terrorist attack.

Seismic and adverse-weather performance

Although seismic design is not generally required in the UK, guidance is provided in Eurocode 8[3.37]. In addition to providing overall requirements in great detail, Section 5 contains specific rules for concrete buildings in terms of energy dissipation capacity and ductility classes. ICF construction is useable for buildings that need to comply with these design requirements, and is widely used in seismic regions of the USA. The robustness of insulating concrete formwork structures makes them particularly suitable for resisting hurricane and similar adverse weather conditions.

4. Design of plain ICF

This design and construction guide gives more attention to the design of plain walls, as this is expected to be the most common construction method, with reinforced walls being limited to special needs. Chapter 3 outlined three principle UK design codes for the design of structural elements. These were Eurocode 2, BS 8110 and BS 5628. The Requirements of Structure under the Statutory Instruments[4.1] is simply that:

- The building shall be constructed so that the combined dead, imposed and wind loads are sustained and transmitted by it to the ground –
  - safely; and
  - without causing such deflection or deformation of any part of the building, or such movement of the ground, as will impair the stability of any part of another building.
- In assessing whether a building complies with the above, regard shall be had to the imposed and wind loads to which it is likely to be subjected in the ordinary course of its use for the purpose for which it is intended.

BS 5628: Part 1 is for the design of plain masonry walls, but it has been used in the past for un-reinforced ICF. However, because ICF is not within the scope of this standard, and because of the differences in the methods of tests between masonry units and concrete cubes or cylinders, it is not considered further in this publication.

For these reasons it is recommended in this design guide that design of ICF construction would be better provided for by the use of Eurocode 2 or BS 8110. However, there are aspects of these codes that can be misinterpreted, and which are commented on in Appendix A and B. This also includes comment on laterally loaded walls.

4.1 Design to Eurocode 2

The design of plain concrete structures is covered by Section 12 of Eurocode 2[4.2] and, again, this is expanded upon in Appendix A. The following section summaries Eurocode 2 with respect to the design of plain ICF construction, and includes a general simplification.

4.1.1 Compressive strength and design factors

The compressive strength classes of concrete are given in BS 8500-1[4.3] and a typical example would be C20/25. This means, a minimum characteristic cylinder strength of 20N/mm^2 or a minimum characteristic cube strength of 25N/mm^2. Tests for strength within the UK are still carried out using the cube test. However, the characteristic compressive strength used for design to Eurocode 2 is based on the cylinder strength test, rather than cube strength used for BS 8110. Thus the lower-cylinder strength is used when using the equations in Eurocode 2.

4.1.2 Tensile strength

Tensile strength is one particular area where Eurocode 2 offers advantages over BS 8110 in that it includes equations for the design tensile strength of concrete (BS 8110 only includes for tensile strength in the design of prestressed concrete).

The design flexural strength can be obtained from Eurocode 2 Table 3.1. The values given are rounded to one decimal place from the given equations. For example, a value of 0.6N/mm^2 is given for a concrete class 20/25.

Alternatively, and mainly for use when developing a computer program, the design flexural tensile strength can be determined using the expressions in Eurocode 2 (taking account of the UK National Annex), which in this example results in a value of 0.62N/mm^2 (see Appendix A for this detailed example).

4.1.3 Shear strength

Shear will seldom be a problem in ICF structures but, where necessary, this can be assessed as shown in Appendix A.

4.1.4 Simplified design method for walls and columns

Eurocode 2 12.10

In the absence of a more rigorous approach, the design resistance in terms of axial force for a slender wall in plain concrete may be calculated from:

$$N_{Rd} = b \times h_w \times f_{cd} \times \Phi$$

Where:

N_{Rd} is the axial resistance.
b is the overall width of the cross section.
h_w is the overall depth of the cross section.
f_{cd} is the design value of concrete compressive strength.
Φ is the factor taking into account eccentricity, including second order effects and normal effects of creep.

Note: the minimum thickness for a plain wall should be 120mm.

The equations for Φ are given and developed in Appendix A, and are used in Table 4.1.

Table 4.1
Eurocode 2 wall design eccentricity factors Φ.

l_o/h_w	Eccentricity at top of wall, e_o/h_w						
	0	**0.05**	**0.1**	**0.15**	**0.2**	**0.25**	**0.3**
15	0.76	0.64	0.53	0.41	0.30	0.19	0.07
16	0.73	0.62	0.50	0.39	0.27	0.16	0.05
17	0.70	0.59	0.48	0.36	0.25	0.13	0.02
18	0.68	0.56	0.45	0.34	0.22	0.11	–
19	0.65	0.54	0.42	0.31	0.20	0.08	–
20	0.63	0.51	0.40	0.29	0.17	0.06	–
21	0.60	0.49	0.37	0.26	0.15	0.03	–
22	0.58	0.46	0.35	0.23	0.12	0.01	–
23	0.55	0.44	0.32	0.21	0.09	–	–
24	0.52	0.41	0.30	0.18	0.07	–	–
25	0.50	0.38	0.27	0.16	0.04	–	–

Table A2 in Appendix A gives Φ values down to l_O/h_W of 10.

e_o = the first-order eccentricity inclu-ding, where relevant, the effects of floors (e.g. possible clamping moments transmitted to the wall from a slab) and horizontal actions.

l_o = the effective length of a member

4.1.5 Design load capacity

The detailed calculation procedure for a plain concrete wall in accordance with Eurocode 2 is given in Appendix A.

This, as shown in Appendix A, results in a design load capacity of:

$$N_{Rd} = 0.4 \times \Phi \times b \times h_w \times f_{ck}$$

Where Φ is the load capacity factor from Table 4.1.

4.1.6 Example

Determine the design capacity of a 140mm ICF 20/25 wall having a storey height of 2.7m, with an assumed resultant eccentricity of $0.05h_w$, and supporting concrete floors.

Wall height $l = 2{,}700$mm
Effective height $l_o = 1.0l$
Wall thickness $h_w = 140$mm

$$\frac{l_o}{h} = \frac{1.0 \text{ x } l_o}{140} = \frac{1.0 \text{ x } 2700}{140} = 19.29$$

The capacity factor by linear interpolation from Table 4.1 is:

$$\Phi = 0.54 - (0.54 - 0.51) \text{ x } (19.29 - 19.0) \div (20 - 19) = 0.525$$

The design capacity is obtained from:

$$\begin{aligned} N_{Rd} &= 0.4 \text{ x } \Phi \text{ x } b \text{ x } h_w \text{ x } f_{cd} \\ &= 0.4 \text{ x } 0.525 \text{ x } 1000 \text{ x } 140 \text{ x } 20 \text{ x } 10^{-3} \\ &= 588\text{kN/m} \end{aligned}$$

If the eccentricity is increased to $0.2h_w$ from Table 4.1:

$$\Phi = 0.20 - (0.20 - 0.17) \times (19.29 - 19.0) \div (20 - 19) = 0.19$$

And the design capacity is:

$$\begin{aligned} N_{Rd} &= 0.4 \times \Phi \times b \times h_w \times f_{cd} \\ &= 0.4 \times 0.19 \times 1000 \times 140 \times 20 \times 10^{-3} \\ &= 213\text{kN/m} \end{aligned}$$

4.1.7 Reinforcement requirements

Eurocode 2 does not give any specific values for ‘secondary’ reinforcement in plain walls and simply says plain concrete members may include steel reinforcement needed to satisfy serviceability and/or durability requirements and reinforcement in certain parts of the members.

Appendix A gives more detail on design of plain ICF to Eurocode 2.

4.2 Design to BS 8110

Section 3.9 of BS 8110 covers the structural design of walls, and the design procedures given can in essence be applied to ICF walls, subject also to the provisions of concrete, materials, specifications and construction being complied with. As given in Appendix B, ICF construction may be designed in accordance with clause 3.9.4 of BS 8110. Such walls should be designed on the basis that the design ultimate force acting on it is calculated on the assumption that the beams and floor slabs transmitting forces into it are simply supported. This will be the general case.

The stability of an ICF plain wall construction, as with conventional plain walls, should not rely on unbraced walls alone. This is seldom an issue, as most structures will have walls in two directions with floors capable of re-transmitting forces to other bracing walls.

Designs for housing will typically have walls in both directions to provide stability and robustness, which is also a requirement of the simple rules to the building regulations, and in most constructions the walls will be designed as braced. In these circumstances the provisions, guidance and specifications as embodied in this guide will enable ICF construction to be designed and perform as conventional concrete walls, subject to the application of appropriate partial safety factors for materials.

4.2.1 Partial safety factors

Where the concrete is placed and compacted in the same way to that for a wall cast in conventional formwork, then an ICF wall will achieve the same strength, durability and other properties as a conventional plain wall. This will require supervised full height controlled construction, with concrete specification and placing in accordance with Chapter 7, and for this situation a partial factor for materials $\gamma_m = 2.25$ may be adopted.

4.2.2 Steps in the simplified design process

The steps for overall design for rectangular profile* ICF are as follows:

1. Determine design life. This will normally be category 4.
2. Assess actions on the wall. Loads will be determined in accordance with BS 6399[4.4].
3. Determine which combinations of actions are applicable. This may be found in 2.4.2.4 of BS 8110[4.5].
4. Analyse the structure using the simplified approach in this chapter. Which is:
    - Determine slenderness ratio.
    - Determine resultant eccentricity of applied loads.
    - Determine capacity reduction factors from Table 4.2.
    - Check capacity exceeds applied design load.

Note

* This applies to ICF systems having a continuous solid concrete cross-section. For non-rectangular and block systems with an insulating web, refer to Appendix B.

4.2.3 Effective height and slenderness

The effective height of walls is also examined in Appendix A, but for simplicity an effective height of 1.0 times the clear height can be used to cover all floor types in a braced structure.

This, when used with a partial safety factor for materials of 2.25, will be conservative when using concrete floors but will still provide a load-bearing capacity greater than the walls given in Approved Document A[4.6] and BS 8103[4.7] shown later in this chapter (section 4.6).

The slenderness ratio l_e/h of an ICF wall should not exceed 30, as with other plain walls.

In this expression:

h is the wall thickness, and

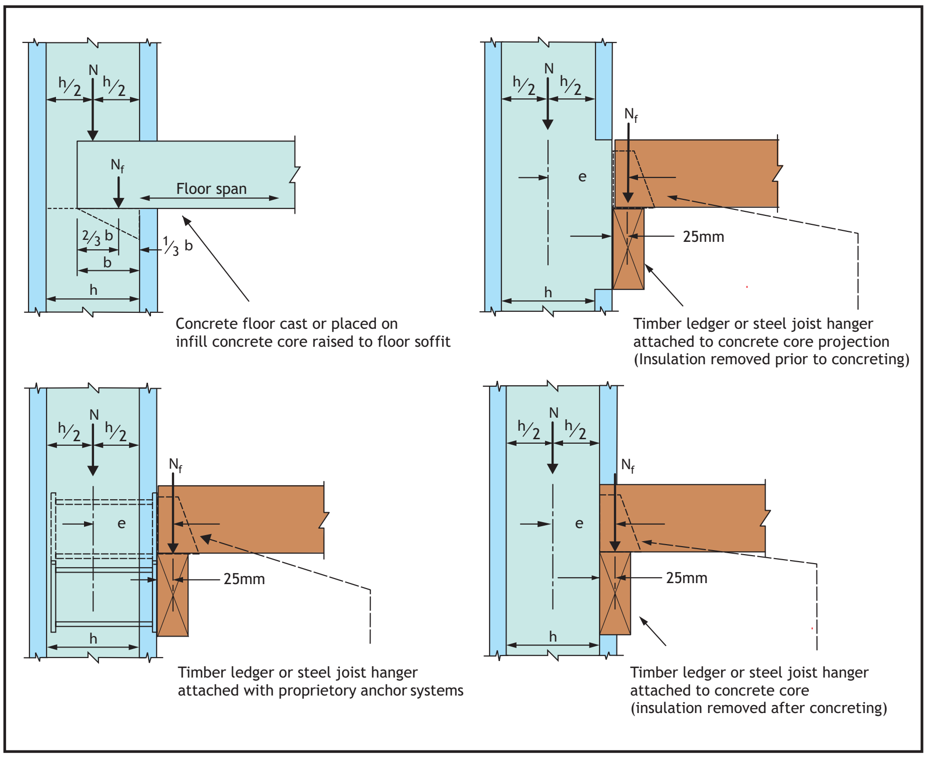
l_e is the clear height in the cases of concrete floors or the storey height where the floor(s) are of timber construction.

4.2.4 Design eccentricities

The eccentricities as given in BS 8110 for plain concrete walls may be applied to plain ICF walls. The vertical load applied to a wall may be taken to be positioned axially at its base.

Loads from floors may be assumed to act at one-third of the depth of bearing. BS 8110 does not specifically cover the case of floors supported on joist hangers or ledgers, but a value of 25mm from the face of the wall would equate with that given in BS 5628.

Figure 4.1
Application of loads from wall and floor.



Concrete floor cast or placed on infill concrete core raised to floor soffit

Timber ledger or steel joist hanger attached to concrete core projection (Insulation removed prior to concreting)

Timber ledger or steel joist hanger attached with proprietory anchor systems

Timber ledger or steel joist hanger attached to concrete core (insulation removed after concreting)

The resultant eccentricity for loads on an external wall may be determined from:

$$e_x = \frac{N_f e_n}{N + N_f}$$

where e_n is the eccentricity between the applied vertical and floor load as given in Figure 4.1

But not less than $h/20$

Where:

N	is the total applied load from the upper floors and walls (assumed axial).
N_f	is the total load applied by the floor.
h	is the thickness of the concrete in the wall.

4.2.5 Design eccentricity factors

The maximum unit axial load is affected by the wall's slenderness and the resultant eccentricity of the applied load. Appendix B shows the design procedure for developing capacity-reduction factors as given in Table 4.2.

4.2.6 Design load capacity

The detailed calculation procedure for a plain concrete wall in accordance with BS 8110 is given in Appendix B.

This approach results in a design load capacity of:

$$n = 0.3\ \Phi\ f_{cu}$$

Where:

Φ is the design eccentricity factor from Table 4.2

f_{cu} is characteristic strengths of the concrete

Table 4.2
BS 8110 design eccentricity factors Φ.

l_e/h	Eccentricity at top of wall, e_x/h					
	≤ 0.05	0.1	0.15	0.2	0.2	0.3
≤ 15	0.90	0.80	0.70	0.60	0.50	0.40
16	0.74	0.68	0.62	0.56	0.50	0.40
17	0.71	0.65	0.59	0.53	0.47	0.41
18	0.68	0.62	0.56	0.50	0.44	0.38
19	0.65	0.59	0.53	0.47	0.41	0.35
20	0.62	0.56	0.50	0.44	0.38	0.32
21	0.59	0.53	0.47	0.41	0.35	0.29
22	0.55	0.49	0.43	0.37	0.31	0.25
23	0.52	0.46	0.40	0.34	0.28	0.22
24	0.48	0.42	0.36	0.30	0.24	0.18
25	0.44	0.38	0.32	0.26	0.20	0.14
26	0.40	0.34	0.28	0.22	0.16	0.10
27	0.36	0.30	0.24	0.18	0.12	0.06
28	0.31	0.25	0.19	0.13	0.07	0.01
29	0.27	0.21	0.15	0.09	0.03	-
30	0.22	0.16	0.10	0.04	-	-

Note
Φ is used for the purpose of this guide and is not a BS 8110 symbol.

4.2.7 Example

Determine the design capacity of a 140mm ICF C20/25, i.e. $f_{cu} = 25\mathrm{N/mm^2}$ wall having a storey height of 2.7m, with an assumed resultant eccentricity of 0.05h, and supporting concrete floors. (This is the same as that used in the Eurocode 2 example, 4.2.6.)

Wall height $l = 2{,}700\mathrm{mm}$
Effective height $l_e = 0.75l$
Wall thickness $h = 140$ mm

$$\frac{l_e}{h} = \frac{0.75 \times l}{140} = \frac{0.75 \times 2700}{140} = 14.46$$

Wall is stocky (see Appendix A, A.2.3)

The eccentricity factor Φ from Table 4.2 = 0.9.

The design capacity is obtained from:

$$n = 0.30\ \Phi\ f_{cu} = 0.30 \times 0.9 \times 25 \times 140 = 954\mathrm{kN/m}$$

The capacity at a resultant eccentricity of 0.2*h* is given by:

$$n = 0.30 \times 0.6 \times 25 \times 140 = 630\mathrm{kN/m}$$

4.2.8 Specific reinforcement requirements

There has been some debate, or confusion, as to whether there is a need for reinforcement in ICF walls. Reinforcement is typically used in concrete and masonry walls to increase flexural or vertical capacity, and/or to control stresses due to thermal and shrinkage movement. Reinforcement in ICF walls is typically only necessary where required for structural purposes, to enable specific ultimate or design capacity to be achieved, and this is in line with BS 8110 recommendations.

In the case of ICF for housing, the vertical loads will seldom be at a level where reinforcement is required for vertical capacity. It is most unlikely that this would be required for walling and will only be a consideration for slender column sections, such as between two large openings. In that situation it may be more appropriate to redesign the layout plan to eliminate the need for such reinforcement.

4.2.9 Reinforcement for control of cracking from movement

The concrete surface of an external ICF wall is protected by an insulating layer, which protects the inner concrete from the extremes of weather and this significantly minimises temperature movement (see also Chapter 3). The insulation will also have a beneficial effect on strength gain and this, together with the controlled environment, will reduce or eliminate the effects of thermal shrinkage that would otherwise affect an exposed element, as covered by BS 8110 clause 3.9.4.20. The strain relief provided by the polystyrene and the high strain capacity of the polymer renders, normally used on ICF, is such that any cracking of the concrete should not be manifest as a crack in the rendering. It is, therefore, considered that clause 3.9.4.20-22 need not be specifically applied to ICF construction for either external or internal walls. See Appendix B for a more detailed assessment of this recommendation.

4.2.10 Reinforcement for structural purpose

Reinforcement may need to be used in areas where structural capacity cannot be obtained from the plain walls alone. For example, reinforcement will typically need to be introduced at openings to cater for the loads transmitted to the beam sections from floors. There may be a need to provide reinforcement where in-plane flexural tensile stress occur in walls, but this will seldom occur in low-rise (four-storey or less) dwelling structures.

Reference should be made to Chapter 5 where reinforcement is used to provide structural capacity, such as in lintels and to meet the requirements of accidental damage in accordance with code and building regulations.

It should be noted that the introduction of such reinforcement does not deem the wall a ‘reinforced wall’ because the overall wall will not have sufficient reinforcement to comply with the code requirements. Therefore, it remains a plain wall for design classification.

The use or need for specific reinforcement will typically be limited to lintels, but another example can be cited by reference to the *Approved Document – Basements for Dwellings*[4.8]. This contains design tables for plain concrete basement retaining walls. The walls in this document are designed for flexural capacity in accordance with Eurocode 2 (Eurocode 2 being used because BS 8110 does not give flexural strength values, but this is further considered in Appendix B).

4.2.11 Concentrated loads

A check should be made on local bearing stresses, but these will seldom be a problem. The design stress under local concentrated loads (e.g. from beam bearings) on a plain ICF wall should not exceed $0.5f_{cu}$, or $0.6f_{cu}$ for concrete class C20/25 or above.

4.3 Laterally loaded walls

The effect of lateral wind load on a vertically loaded wall within the general size requirements for housing will be minimal due to the expected notable reserve of strength of such walls. Appendix A describes methods for assessment of larger walls, either predominately laterally loaded walls (e.g. wind loads on infill walls to a framed structure), or walls carrying both vertical and lateral loads.

4.4 Effect of using EPS bridged ICF blocks

The guidance in sections 4.2 and 4.3 relate in general to continuous cored ICF systems (Figures 2.2 and 2.3) and will need to be adjusted for EPS bridged blocks (Figure 2.1), whose properties apart from insulation will be lower that continuous core systems, but may still be sufficient for housing and some other buildings. Appendix A gives further information on the effect of EPS bridged systems.

4.5 Application with respect to regulations and codes

This section examines the use of ICF construction against the requirements in Approved Document A and BS 8103-2[4.7] covering low-rise masonry walls for housing. These are intended to provide safe designs without the need for calculations of loading and strength criteria.

These two design documents give guidance on the requirements for certain dwellings. They give prescriptive guidance on the sizing of walls within a range of limitations for a given range of low-rise houses for walls up to 9m high. With a typical storey height of 2.35m, this represents dwellings up to four storeys.

Approved Document A[4.6] stipulates a 7.3N/mm^2, 140mm block for a solid internal load-bearing wall, which from BS 5628 has a load-bearing capacity of 144kN/m. It also indicates that 90mm, 7.3N/mm^2 block will meet the requirements for an external cavity wall (90mm minimum leaf thickness) in a low-rise housing structure (defined by the limitations of the code) where the storey height does not exceed 2.7m and having floors of precast concrete or timber not exceeding 6.0m span. This wall would have an axial load-bearing design capacity of around 133kN/m, which is more than exceeded by the 140mm ICF structural wall shown in the design examples for both Eurocode 2 and BS 8110 (see Sections 4.2.6 and 4.3.7).

BS 8103 states that it is written for those with expertise in building construction but not necessarily in structural engineering design. Low-rise buildings constructed within the limitations stated in the relevant clauses will not require additional specialist advice. For any conditions outside the limitations of this code, appropriate specialist advice should be obtained. It should not be expected that the recommendations made in this part of the code can be proved by calculation as they are based on traditional prescriptive guidance substantiated by long experience.

BS 8103 indicates that, in formulating the guidance, the worst combination of circumstances likely to arise was taken into account. It goes on to say that it may be appropriate to consider a minor departure from the recommendations of this part of the code and show adequacy by calculation. However, in cases where the recommendations of BS 8103 clause 6 for conditions relating to a wall are not able to be met or are inappropriate, then reference should be made to BS 5628-1.

Although giving prescriptive guidance, it is stated that when using the code it is important to assess that the overall stability of the building is achieved, and that the work of any specialist engaged is properly co-ordinated.

This gives effectively the same requirements as Approved Document A, which can again be shown to be exceeded by a 140mm ICF wall.

ICF construction is not within the scope of either Approved Document A or BS 8103 and, therefore, cannot be used to specifically confirm the design of insulated concrete formwork construction for housing. However, the comments above show that a typical ICF construction will provide a structural capacity typically exceeding the requirements of both of these documents. Thus ICF dwellings having a minimum thickness of approximately 140mm, and otherwise constructed within the general limits of Approved Document A or BS 8103 as appropriate, are likely to provide an adequate structure in terms of the regulations.

5. Design of reinforced ICF

Reinforced ICF may be designed as conventional reinforced concrete using Eurocode 2[5.1] or BS 8110[5.2]. Due allowance needs to be made for the section size produced by the ICF system being used and any constraints on the location of the main reinforcement. While some ICF systems will readily accommodate a conventional reinforcement cage, other systems may impose limitations, particularly with respect to the location of horizontal steel. For some applications a proportion of the secondary steel could be replaced by chopped steel fibres in the concrete.

Both Eurocode 2 and BS 8110 contain similar design guidance for the design of reinforced concrete walls and essentially adopt the method used for the design of columns. In most domestic scale construction the vertical load on the wall is relatively modest compared with the capacity of the section and it is possible to design the section primarily to resist bending. This approach may be used for typical basement walls and is likely to result in the most economic design solution.

This chapter introduces the basis of reinforced concrete design to Eurocode 2 and BS 8110, and presents information that extends the solutions contained in the *Approved Document – Basements for Dwellings*[5.3] to cover the wall thickness achieved by the slimmest ICF wall section currently in use in the UK. More detailed information on the design of reinforced elements may be found elsewhere[5.4].

For detailing and durability requirements, see either BS EN 1992-1-1 (Eurocode 2)[5.1] or BS 8110[5.2].

5.1 Reinforced wall design to Eurocode 2

Eurocode 2[5.1] provides a design method for reinforced concrete walls which effectively treats the wall as a column, subject to some changes in the detailing requirements that are specific to walls.

5.1.1 Steps in the design process

The complete design process is summarised in the following steps as given elsewhere[5.5]:

1. Determine design life*. This will normally be category 4, i.e. 50 years.
2. Assess actions on the wall. Actions will be determined in accordance with BS EN 1991.[5.6]
3. Determine which combinations of actions are applicable. This may be found in the National Annex to BS EN 1990.[5.7]
4. Assess durability requirements and determine concrete strength. Refer to BS 8500[5.8] which incorporates references to BS EN 206.[5.9]
5. Check cover requirements for the necessary fire resistance period. This should be determined by reference to Approved Document B[5.20] of the building regulations and BS EN 1992-1-2, section 5.[5.10]
6. Calculate minimum cover based on durability, fire and bar size. This can be determined by reference to BS EN 1992-1-1, clause 4.4.1.[5.1] and BS EN 1992-1-2, clause 5.4.2.[5.10]

Note
*The indicative design life is selected from clause 2.3 of BS EN 1990:2002 Eurocode – Basis of Structural Design. Category 4 is 50 years and Category 5 is 100 years. These values should not be interpreted as implying any difference in expected performance when compared with established UK practice using BS 8110.

7. Analyse structure. Refer to BS EN 1992-1-1, section 5.
8. Check slenderness and determine area of reinforcement required. This can be determined by reference to BS EN 1992-1-1, sections 5.8 and 6.1.
9. Check spacing of bars. Refer to BS EN 1992-1-1, sections 8 and 9.

Eurocode 2[5.1] provides guidance on the detailing of reinforced concrete walls in section 9.6. This clause covers walls with a length-to-thickness ratio of 4 or more. The strut-and-tie model (clause 6.5) may be used for design. Where walls are subjected predominantly to out-of-plane bending, the rules for slabs apply (clause 9.3).

The area of vertical reinforcement should lie between $A_{s,vmin}$ and $A_{s,vmax}$. In the UK National Annex[5.1] these values are given as follows:

$A_{s,vmin} = 0.002A_c$
$A_{s,vmax} = 0.004A_c$ (outside lap locations)
Where A_c is the cross-sectional area of concrete.

Where the minimum area of reinforcement controls design, the code requires that half of this area should be located in each face. There is also a requirement that the distance between adjacent vertical bars should not exceed three times the wall thickness or 400mm, whichever is the lesser.

Horizontal reinforcement should be provided and should not be less that $A_{s,hmin}$ which for the UK is 25% of the vertical reinforcement or $0.001A_c$, whichever is the greater. The vertical spacing between two adjacent horizontal bars should not be greater than 400mm.

If, in any part of the wall, the total area of the vertical reinforcement in the two faces exceeds $0.002A_c$, transverse reinforcement in the form of links should be provided in accordance with the following guidance:

- The diameter of the transverse reinforcement should not be less than 6mm or one-quarter of the maximum diameter of the longitudinal bars, whichever is the greater. The diameter of the wires of welded mesh fabric should not be less than 5mm.
- The transverse reinforcement should be adequately anchored.
- The spacing of the transverse reinforcement should not exceed $S_{cl,tmax}$ which is the lesser of 20 times the minimum diameter of the longitudinal bars, the lesser dimension of the wall or 400mm.
- The maximum spacing required in the previous point should be reduced by a factor of 0.6 in sections within a distance equal to the larger dimension of the wall cross-section (but need not be taken as greater than four-times the wall thickness) above or below a beam or slab; near lapped joints, if the maximum diameter of the longitudinal bars is greater than 14mm. A minimum of three bars evenly placed in the lap length are required.
- Where the direction of the longitudinal bars changes (e.g. at changes in wall size), the transverse reinforcement should be calculated, taking account of the lateral forces involved. These effects may be ignored if the change in direction is less than or equal to 1-in-12.
- Every longitudinal bar or bundle of bars placed in a corner should be held by transverse reinforcement. No bar within a compression zone should be further than 150mm from a restrained bar.

Where the main reinforcement is placed nearest to the wall faces, transverse reinforcement should also be provided in the form of links with at least four per m^2 of wall area. Transverse reinforcement need not be provided where welded mesh and bars of diameter $ø \leq 16$mm are used with concrete cover larger than 2ø.

5.1.2 Design for vertical load

ICF walls will typically have sufficient strength without the need for reinforcement to cater for vertical compressive actions and it is likely to be more cost-effective to increase the section size than to introduce vertical compression reinforcement together with the additional constraining reinforcement which that will require. As a result it is expected that the introduction of structural reinforcement will be limited to provision of bending capacity.

5.1.3 Design for bending

Steps in the design process [5.11]:

1. Determine K:

$K = M/bd^2f_{ck}$

Where:

M = Bending moment.

b = Overall width of the cross-section.

d = Effective depth of the cross-section.

f_{ck} = Characteristic compressive cylinder strength of concrete at 28 days.

2. Determine K':

$K' = 0{,}60\delta - 0{,}18\delta^2 - 0.21$

Where δ = redistribution ratio ≤ 1.0.

3. If $K > K'$ then compression reinforcement will be required, but this will seldom be a requirement for walls and would be best avoided by increasing the section size.

4. If $K \leq K'$ no compression reinforcement is required and the section can be designed as follows.

5. Obtain lever arm z:

$z = d/2(1 + \sqrt{(1-3.53K)}) \leq 0.95d$

6. Calculate tension reinforcement from:

$A_s = M/f_{yd}z$

Where:

A_s = cross-sectional area of reinforcement.

f_{yd} = design yield strength of reinforcement.

7. Check minimum reinforcement:

$A_{s,min} = 0.26 f_{ctm} b_t d / f_{yk}$ where $f_{ck} \geq 25$

Where:

$A_{s,min}$ = minimum cross-sectional area of reinforcement.
f_{ctm} = mean value of axial tensile strength of concrete.
f_{yk} = characteristic yield strength of reinforcement.

8. Check maximum reinforcement limit:

$A_{s,max} = 0.04 A_c$

Where:

$A_{s,max}$ = maximum cross-sectional area of reinforcement.
A_c = cross-sectional area of concrete.

5.1.4 Shear strength

Shear will seldom be a problem in reinforced ICF structures but, where necessary, this can be assessed as shown in Appendix A.

5.2 Reinforced wall design to BS 8110

Where the section is subjected to an axial load less than or equal to $0.1f_{cu}$ times the cross-sectional area, the section may be designed for bending using the method contained in clause 3.4.4 of BS 8110.

5.2.1 Design for vertical load

BS 8110 defines a wall as 'a vertical loadbearing member whose length exceeds four times its thickness'. Design should be carried out in accordance with the requirements of section 3.9. For a reinforced monolithic ICF wall, the effective height of the wall, l_e, should be assessed as though the wall is a column subject to bending at right angles to the plane of the wall. If the construction transmitting load to a reinforced wall is, or is assumed to be, simply supported, the effective height should be assessed as for a plain wall as shown in Chapter 4.

In BS 8110, a stocky wall is defined as a wall where the effective height divided by the thickness (l_e/h) does not exceed 15 (braced) or 10 (unbraced). In most domestic-scale construction, the ICF wall will be braced and therefore l_e/h must not exceed 15. In practice this means that, for many ICF systems, the wall thickness will be such that a storey-height wall may be considered as stocky. An ICF wall in a dwelling is unlikely to be subjected to significant moments and such a wall can therefore be designed so that the design ultimate axial load does not exceed the value of N given by:

$N = 0.4f_{cu}A_c + 0.8A_{sc}f_y$ (which includes an allowance for γ_m, partial safety factor)

Where:
N = design axial force.
f_{cu} = characteristic strength of concrete.
A_c = area of concrete section.
A_{sc} = area of vertical reinforcement.
f_y = characteristic strength of reinforcement.

However, if the main reinforcement is to be used to resist compression, links or ties, at least 6mm diameter (or one-quarter of the largest compression bar diameter, whichever is the larger) need to be provided at a maximum spacing of 12 times the size of the smallest compression bar. For some of the ICF systems, this is clearly impractical and the strength of the section in compression may be designed based on the concrete section only.

In situations where the main vertical reinforcement is used to resist compression and does not exceed 2% of the concrete area, then it is necessary to provide, as a minimum, the following percentages of horizontal reinforcement:

where $f_y = 250\text{N/mm}^2$ - 0.30% of concrete area.
or for $f_y = 500\text{N/mm}^2$ - 0.25% of concrete area.

These horizontal bars should be evenly spaced and be not less than one-quarter of the size of the vertical bars and not less than 6mm.

It is unlikely that percentages of steel in excess of 2% will be used in ICF, while BS 8110 does not permit the area of vertical reinforcement in walls to exceed 4% of the gross cross-sectional area of the concrete.

5.2.2 Design for bending

It is expected that designers will be fully familiar with the design of concrete sections in bending to BS 8110 and no further coverage is given in this section other than the requirements for lap length as may be influenced by ICF construction techniques. Section 5.3 makes reference to a possible need to amend effective depth if location collars are used.

5.3 Lapping of reinforcement in ICF construction

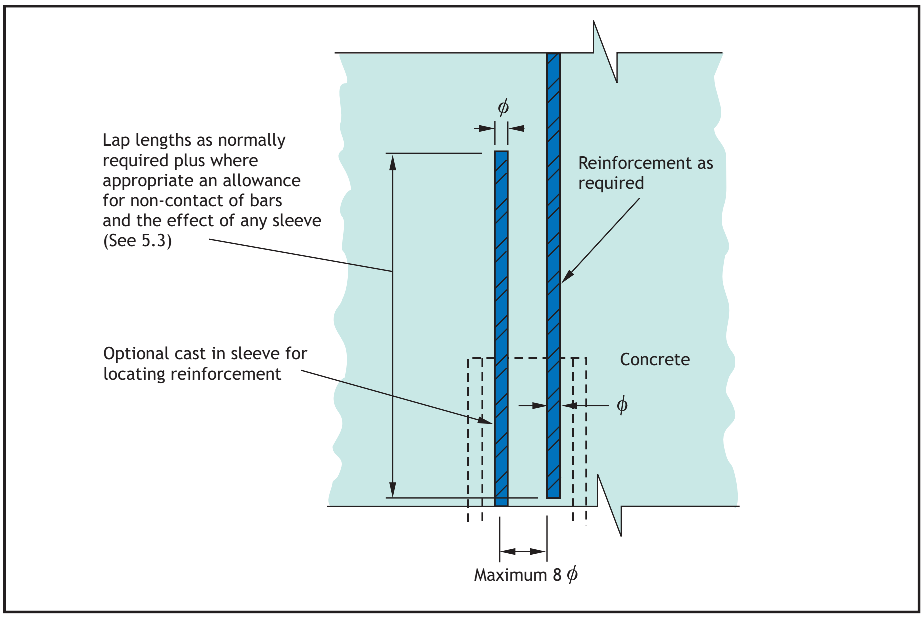
Reinforcement bars parallel to each other may be conventionally tied, or placed into jointing collars, as mentioned in Chapter 8, or as facilitated by system ties. In these latter situations, the bars are not physically tied together and this will require assessment as follows. Experience from the USA is that load transfer between non-contact parallel bars is achieved if the bars are located within eight bar diameters of each other[5.12], with an overlap of 40 bar diameters. However, the American figure is a general value and will need to be compared to that required by Eurocode 2 or BS 8110 as appropriate.

Eurocode 2 requires that laps between bars should be staggered except when in one layer (which will typically be the case for ICF walls), and that the clear distance between bars should be not greater than four-times the bar diameter or 50mm, otherwise the lap length should be increased by a length equal to the clear distance between the bars. No upper limit is given but limiting to a clear distance of seven-times the bar diameter would align with the American figure of a maximum centre-to-centre of eight-times the bar diameter, as indicated for ICF construction.

BS 8110 does not specifically deal with bars that are not in contact, but it suggested that in this situation the lap length should be as normally required and as stipulated by Eurocode 2, which is effectively to increase the lap length by the distance between the bars, when the distance between the bars is greater than four.

However, neither Eurocode 2 nor BS 8110 account for the effect of the collar on bond length and it is recommended in this guide that, in addition to the requirements as imposed above, the lap length should be increased by the length of the collar (see Chapter 7). The diameter and length of the sleeve should be sufficient to enable concrete fill.

Figure 5.1
Non-contact splicing of reinforcement in ICF system.



Although appropriate lap strength for compression or general tensile forces can be developed in this way, it will affect the location of the reinforcement and thus the lever arm for members in flexure. Hence in situations such as in a retaining wall, where use is made of collars for bar location, then appropriate allowance will need to be made to the effective depth.

5.4 Control of early age cracking

Horizontal reinforcement is normally specified in reinforced concrete with the objective of controlling early age movements, but there may not be a need to provide such reinforcement in ICF systems. The insulated forms provide an ideal environment for curing the concrete (see Section 3.4.11) and if any fine cracking should occur it is very unlikely to manifest this to the finished surface or have a major effect on the structural stability of a wall in a low-rise construction.

Where it is essential to limit the crack width then guidance is available in Eurocode 2. This can be simplified in terms of the maximum bar size or spacing to limit crack width as shown in Table 5.1.[5.13]

Table 5.1
Maximum bar size or spacing to limit crack width.

Steel Stress σ_s (N/mm^2)	**w_{max} = 0.4 mm**			**w_{max} = 0.3 mm**		
	Maximum bar size (mm)		**Maximum bar spacing (mm)**	**Maximum bar size (mm)**		**Maximum bar spacing (mm)**
160	40	or	300	32	or	300
200	32		300	25		250
240	20		250	16		200
280	16		200	12		150
320	12		150	10		100
360	10		100	8		50

5.5 Steel fabric reinforcement

The use of steel fabric reinforcement is a very convenient way of installing the reinforcement within a wall in systems that allow the two faces of the formwork to be erected independently (as with ICF panel systems, for example), but care needs to be taken to maintain the necessary cover.

5.6 Fibre reinforcement

In many situations it may be possible to replace reinforcement with a suitable proportion of structural fibres (either steel fibres or macro synthetic fibres) in the concrete. A defined amount of fibre reinforcement can be added either by your ready-mix supplier or into the ready-mixed concrete truck at the site. Design methods for concretes containing steel fibres are limited[5.14, 5.15, 5.16] but the RILEM document[5.15] can be used as a basis for calculating the dosage required to replace a given proportion of conventional bar reinforcement. Less guidance is available for macro synthetic fibres, though design approaches based on those for steel fibres are being developed. There is no doubt that fibre reinforcement at an appropriate dosage can change the failure mode of the concrete from a brittle failure to a ductile failure.

It should be noted that the slump of the concrete will be affected by the type, dosage, length and diameter of the fibre. It is therefore important to take account of the manufacturers' recommendations and data provided in accordance with the European Standard for fibres, BS EN 14889[5.17,5.18-5.19]. Normally the ready-mixed concrete supplier will increase the fines content for a pumpable mix, and when fibre is incorporated, a slump of around 100mm should be specified. The maximum aggregate size should be 14mm but, again, the manufacturer will provide product-specific guidance, and 10mm aggregate is more common and used in the concrete specifications in Chapter 6.

5.7 Basements

An addendum to the *Approved Document – Basements for Dwellings*[5.3] issued in 2007 provides new design information for plain walls. Section 3B contains a tabular approach to the design of reinforced concrete basement walls, subject to certain limitations on overall dimensions and the size and proportions of openings, etc. The tables provide for a limited range of wall thicknesses, but it is possible to use the design approach to accommodate the section sizes typically associated with ICF systems. Section 3D provides for the design of plain concrete basement walls. Again, it is possible to adapt the design approach to accommodate the thicknesses commonly associated with ICF systems. Table 3B.1 is reproduced below from the Basement Approved Document to show the range of wall thicknesses covered. A modified table for a wall thickness down to 147mm is also shown. This additional table was developed using the same approach as that used for the *Approved Document – Basements for Dwellings*[5.3]. These tables should not, however, be used without reference to the source document because there are a number of conditions that are required to be met in order to comply with the building regulations.

Table 5.2

(*Approved Document – Basements for Dwellings*): minimum reinforcement requirements for propped wall retaining a maximum of 2.7m of soil.

Foundation type	Soil type (well drained)	Vertical load (kN/m) up to	Moment taken as acting at base of wall (kNm/m)	Area of reinforcement As (mm^2/m)	
				Wall thickness (mm)	
				200	300
Raft	Clay and granular	70	20	500	390*
		50	15	370	390*
		30	10	260	390*
Strip	Clay	Any	17	420	390*
	Granular		12	290	390*

Note

* This is minimum reinforcement and provides for a moment capacity of 10kNm/m with a 200mm wall and 25kNm/m with a 300mm wall. Other sizes may be determined by calculation.

Table 5.3

Modified Table 5.2 (*Approved Document – Basements for Dwellings*): minimum reinforcement requirements for propped wall retaining a maximum of 2.7m of soil.

Foundation type	Soil type (well drained)	Vertical load (kN/m) up to	Moment taken as acting at base of wall (kNm/m)	Area of reinforcement As (mm^2/m)	
				Wall thickness 147mm	
				External face	Basement face
Raft	Clay and granular	70	20	850	400
		50	15	610	290
		30	10	400	200
Strip	Clay	Any	17	700	330
	Granular		12	480	230

6. Concrete design and specification

The design of the concrete to be used in ICF is central to achieving both good structural performance and the long-term durability of the building. The choice of concrete will depend upon whether or not the ICF is reinforced and the space available within the cavity, e.g. between the faces of the units and any reinforcing steel.

6.1 Concrete design parameters

6.1.1 Durability

The cover of concrete to the reinforcing steel is set to satisfy three main functions:

- To safely transmit bond forces.
- To provide adequate durability of the reinforcement.
- To provide adequate fire-resistance.

The cover of concrete to the reinforcing steel is an important parameter in ensuring that the reinforcing steel remains in a passive state and does not corrode during the design life of the building. In making recommendations about cover, the assumption is that the concrete is properly compacted so that the rate of carbonation of the concrete can be predicted with reasonable accuracy. In ICF construction, unlike normal concrete construction, the formwork is not removed after the concrete has been placed and visual inspection of the concrete is not possible. When unprotected conventional reinforcement is used with ICF systems it is essential that a pumpable free-flowing (high-slump) concrete is specified and that the concrete is fully compacted.

In BS 8500[6.1], exposure class X0 relates to concrete without reinforcement or embedded metal where there is no significant freeze/thaw, abrasion or chemical attack, but is not recommended for reinforced concrete. Class XC1 applies to concrete surfaces inside structures except where subjected to high humidity. XC3 applies to a range of conditions including vertical surfaces protected from direct rainfall. For most buildings, class XC1 or XC3 will apply to ICF construction and the following tables show the requirements for the concrete and cover for an intended working life of 50 years.

Table 6.1
Concrete and cover required for exposure class XC1.

Nominal cover	25mm
Strength class	C20/25
Maximum w/c ratio	0.70
Minimum cement or combination content kg/m³	280
Equivalent designated concrete	RC20/25

Table 6.2
Concrete and cover required for exposure class XC3/4.

Nominal cover	30mm	35mm	40mm	45mm
Strength class	C40/50	C30/37	C28/35	C25/30
Maximum w/c ratio	0.45	0.55	0.60	0.65
Minimum cement or combination content kg/m³	360	340	320	300
Equivalent designated concrete	RC40/50	RC30/37	RC28/35	RC25/30

The nominal covers are derived based on the value of Δc_{dev} of 10mm as specified in the UK National Annex to Eurocode 2[6.2]. The designer will need to assess the accuracy to which the steel is located for a given ICF system and may need to increase the value accordingly. It should be noted that the ICF units do not contribute to the cover to be provided to the reinforcing, as shown in the above table, and the cover should be measured from the inside face of the units.

6.1.2 Maximum aggregate size

To ensure that the infilling concrete readily flows around the reinforcement, particularly where more complex intersections occur (e.g. at corners), it is recommended that the maximum aggregate size used should normally be 10mm which is assumed for tables 6.1, 6.2, 6.3, 6.4. Some manufacturers may specify a maximum aggregate size of 20mm for their systems which will allow a reduction in the minimum cement content.

6.1.3 Consistence (Workability)

The workability required for concrete supplied for ICF construction will depend on the placement methods and degree of vibration used for a particular system. The concrete needs to be properly compacted and the ease with which the concrete can flow into place will depend on obstructions to the flow such as the size of opening through the ICF units, and any reinforcing steel present. Care needs to be taken that the rate of placement is controlled in order to avoid too much pressure being exerted on the permanent formwork units.

A manufacturer's recommendations on concrete type including consistence class should take precedence over the following general recommendations:

6.1.4 Unreinforced Walls

For walls containing no reinforcement, a pumpable C20/25 concrete consistence class S3 (with an average slump of 125mm) is recommended as detailed in Table 6.3. Alternatively specify a pumpable RC20/25 designated concrete of maximum aggregate size 10mm and consistence class S3.

Table 6.3
Minimum concrete specification for unreinforced ICF.

Requirement	Value
Compressive strength class	C20/25
Maximum w/c ratio	0.70
Minimum cement/combination content	2.80
Cement or combination types	CEM 1, IIA, IIB, IIIA, IIIB, IVB
Maximum aggregate size	10mm
Chloride class	Cl 1,0
Consistence	S3
Additional requirements	Pumpable

6.1.5 Reinforced Walls

For walls containing conventional reinforcement, a pumpable C25/30 concrete consistence class S4 (with an average slump of 185mm) is recommended as detailed in Table 6.4 Alternatively specify a pumpable RC25/30 designated concrete of maximum aggregate size 10mm and consistence class S4.

With reference to Table 6.2 this concrete is suitable for exposure class XC 3/4 based on a minimum 45mm cover to the reinforcement from the inside face of the ICF units and a 50 year design life.

Table 6.4
Minimum concrete specification for reinforced ICF.

Requirement	Value
Compressive strength class	C25/30
Maximum w/c ratio	0.65
Minimum cement/combination content	300kg/m^3
Cement or combination types	CEM 1, IIA, IIB, IIIA
Maximum aggregate size	10mm
Chloride class	Cl 0,40
Consistence	S4
Additional requirements	Pumpable

6.1.6 Special concretes

Where concrete is used below ground level it is sometimes necessary to prevent moisture movement by specifying water-resistant concrete. Typically, a water-resistant concrete will be designed with high fines content, possibly using a blended cement, and contain a proprietary admixture. The concrete supplier will need to be contacted in advance of ordering the concrete in order to agree the performance required and how it will be achieved.

Where steel fibres are to be used to improve the tensile strength of the concrete, the mix specification will need to be adjusted to suit the type and shape of the fibres that are to be used. The fibre manufacturer will be able to provide more detailed guidance on the adjustments that need to be made to the concrete specification.

Foamed concrete

Foamed concrete potentially offers a very sustainable infill material for low-rise ICF construction. Foam may be injected into the ready-mixed concrete truck on site or added to the site batching plant thereby greatly increasing the volume of material available for filling the ICF. Its use is probably best restricted to un-reinforced walls but, to date, there is little experience of using foamed concrete with ICF systems in the UK. One big potential advantage is, of course, a substantial reduction in the pressure exerted on the formwork, although this may be offset to some extent by the need to fill at a rate that will not cause the foam to collapse. The unrestrained shrinkage of foamed in-situ concrete can be very high, and care will be needed, especially if long walls are to be filled.

7. Construction and workmanship

This chapter covers the generic construction and workmanship requirements for ICF systems, but it is important to recognise that there are important variations in practice for different systems and the manufacturer's instructions should be carefully followed. As with all construction, effective planning is important and the availability of the correct tools and equipment is an important consideration. Relatively few ancillary components are required for ICF work, simplifying delivery and on-site storage.

7.1 The erection team

Most contractors suggest that a workforce of three or four is the optimum for erecting ICF houses. The team would normally include a carpenter, a person experienced in concreting and a labourer.

7.2 Planning

7.2.1 Foundations

ICF buildings are constructed on normal foundations and the usual assessments of ground conditions and bearing capacity need to be made. Increasingly, basements are being incorporated into new houses and it is good practice to make the thickness of the basement wall (which may be ICF) the same as that of the ICF wall above it. Accuracy is important when using an ICF system and time spent in providing an accurate foundation will ensure rapid construction of the walls.

Where the wall is to be conventionally reinforced, starter bars will have to be placed to line up with the cavities of the particular ICF system in use. The designing structural engineer will need to be aware of a particular system's requirements to ensure ease of installation on site (see Section 7.5).

7.2.2 Receiving ICF materials on site

The delivery of the ICF units to site should be timed to meet the requirements of the sequence of operations on site. ICF units will be delivered to site either as ready-assembled units in the form of blocks up to about 1m in length, as planks 2m (or more) long or as storey-height panels. Time needs to be allowed for assembly of the units as the work progresses.

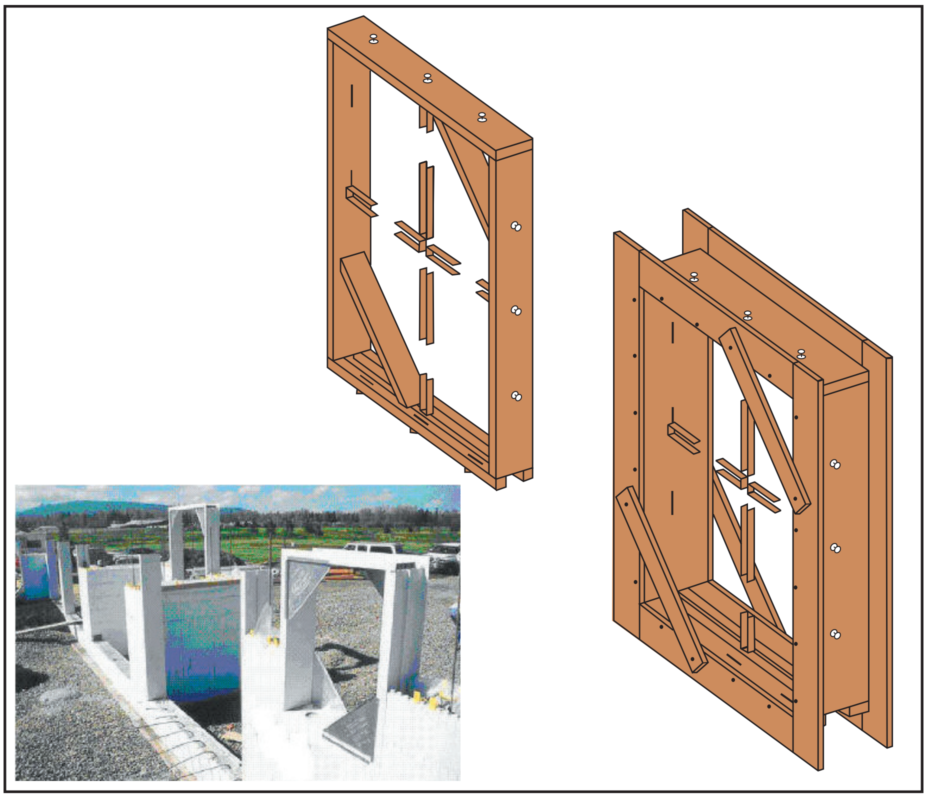
7.3 Setting forms

7.3.1 Setting block systems

A key requirement is to ensure that the vertical cores of the system in use correctly align to enable the required section dimensions to be formed when the forms are filled with concrete. In the case of flat block systems that rely on the use of ties, these should be constructed so that they align in the finished wall. Some ties have a further role in providing a point for fixings and it is important for fixing plasterboard and external finishes to be able to reliably locate the fixing point.

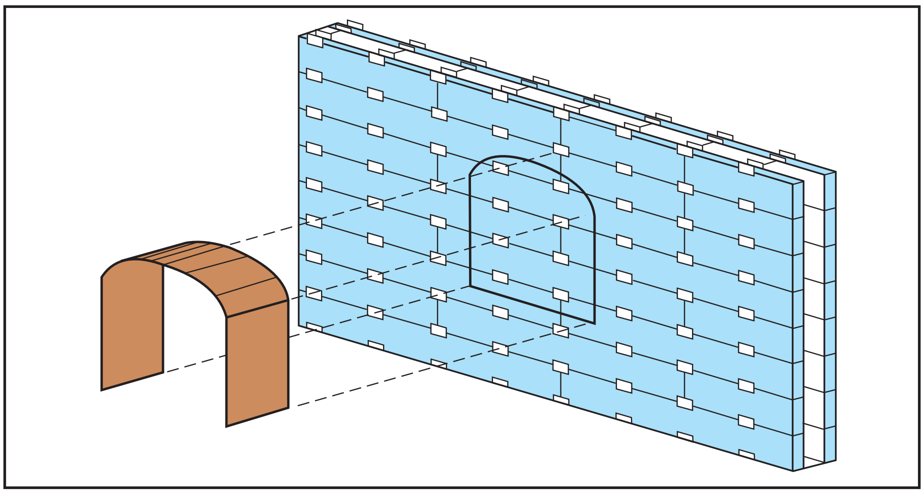
In advance of placing the units, provision needs to be made to assemble formwork for boxing out openings, as shown in Figure 7.1, and sufficient ICF units need to be assembled and on hand to erect the ground-floor walls. However, boxing out for vertical openings may not be necessary when using block systems, some of which have tapering grooves running vertically on their inner faces. These are to receive the wedge-shaped tongues of EPS inserts, which are used to form continuous vertical stop ends, acting as the reveals around openings for doors and windows etc. The stop-end inserts are effective in reducing the effect of cold bridging at these openings. They are shaped so as to effectively anchor the reveals firmly to the concrete core, providing a stable substrate for fixing the frames for doors, etc.

Figure 7.1
Typical formwork for boxing out for an opening.



A particular advantage of ICF systems is the ease with which curved openings can be formed, using simple building techniques. If the shape can be achieved using ply or other flexible sheet materials, openings such as arches and circles can easily and cheaply be created (see Figure 7.2).

Figure 7.2
Forming a curved opening.



Such openings can be formed without the expense of forming a separate timber formwork. The desired shape can be cut directly out of the inner and outer wall surfaces, and narrow sections of the sheet material glued to the ICF around its perimeter to define the opening. The polystyrene cut-outs are then replaced to support the sheet material during the pour.

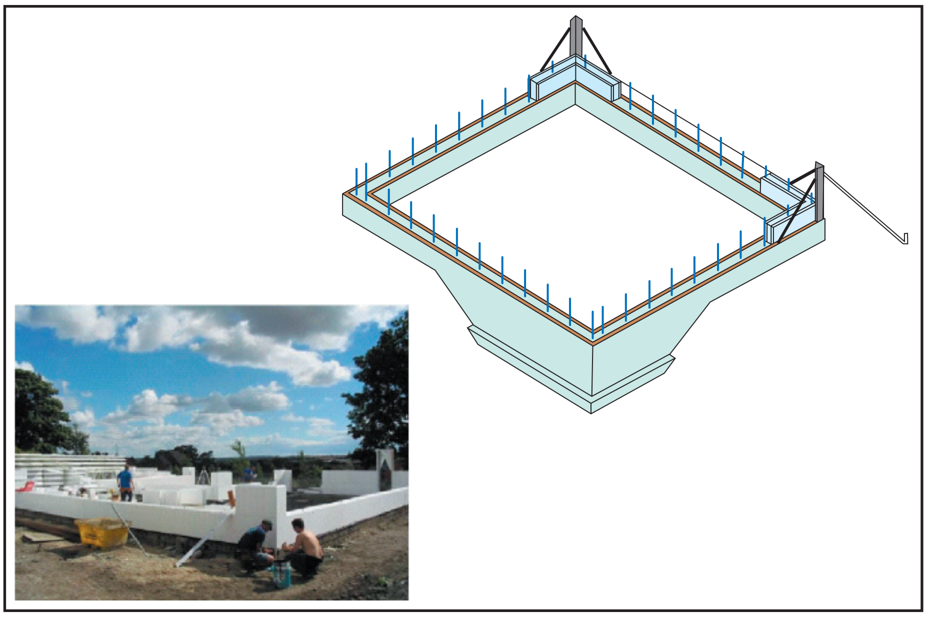
The first course

Mark out the location of the units around the perimeter of the house and use 100 x 50mm timber to form guides to hold each side of the form in place. Erect the boxing out frames for the doors in the correct position and support with diagonal bracing. Mark out on the timber guides the position of the windows.

The first course is commenced by setting the corner blocks as shown in Figure 7.3.

If reinforcing steel needs to be incorporated in the wall, it is important that this is set out to ensure correct alignment with the block system being used so that the steel is in the correct position within the blocks.

Figure 7.3
Setting the first course from the corners.



Some ICF systems use special preformed corner blocks, while other systems rely on the overlap of intersecting units to form a bonding pattern. One system uses standard units that can interlock in either the parallel or orthogonal orientation. Special end pieces are used to close off the units at corners.

Once the corners have been formed, they should be braced to keep them plumb during the setting of the remaining units and while the concrete is being placed. A line can then be run from corner to corner and the remaining units shimmed or trimmed to level working from one corner. Some systems will require the units to be glued into place but some are designed to interlock without glue. Where walls are to be reinforced, it will be necessary to thread the units over the starter bars.

At the end of the run it may well be necessary to trim the length of the final unit to fit before it is glued or locked into place. Where the cut has weakened the unit by removing a cavity tie, for instance, local shoring of the unit prior to pouring should be considered. Where a door opening occurs, the units will need to be cut to fit to the frame. On the other side of the frame, depending upon the type of ICF system being used, it may be necessary to cut the block to be in exactly the same orientation and position that would have been achieved had the opening not been present, in order to ensure that the vertical cores align correctly.

Any gaps between the units or the units and the base concrete need to be filled with adhesive foam. Sleeves for service penetrations can now be incorporated and sealed before the first storey concrete is placed.

The second course

The second course can then be erected, starting from the corners as before. The units will normally be laid in running bond so that in the second course the units overlap half-way along the unit below. Care will need to be taken to ensure that units trimmed to fit in length still retain the correct clear vertical cavity configuration. Units that require gluing should be glued and, at the corners, all types of unit will need to be tied to the corner bracing as recommended by the manufacturer. Where a lintel unit is to be used across an opening, it will need to be trimmed to the required height to course with the units either side of the opening. Some types of unit may require holes and openings in the lintel units to be opened up to allow the free flow of the concrete fill. The second course can be finished by filling any gaps with adhesive foam.

The subsequent courses can then be placed following the same procedure. Scaffolding will be required and this is normally located on the inside of the wall. Some systems use special scaffolding that also serves to brace the wall and this should always be used in accordance with the manufacturer's instructions.

Finishing the wall at storey height

The last course of the wall will need to accept fixing and supports for the roof, concrete floors or timber floor joists if timber floors are to be used and a further storey is to be built.

Figure 7.4 shows a typical detail for a concrete floor and Figures 7.5 and 7.6 show details for timber floors. Further examples of the use of concrete and timber floors are shown in Chapter 8. With some systems, the last course will need to be constructed with lintel blocks so that a clear horizontal channel is available to work with.

Figure 7.4
Typical detail for concrete beam and block floor.

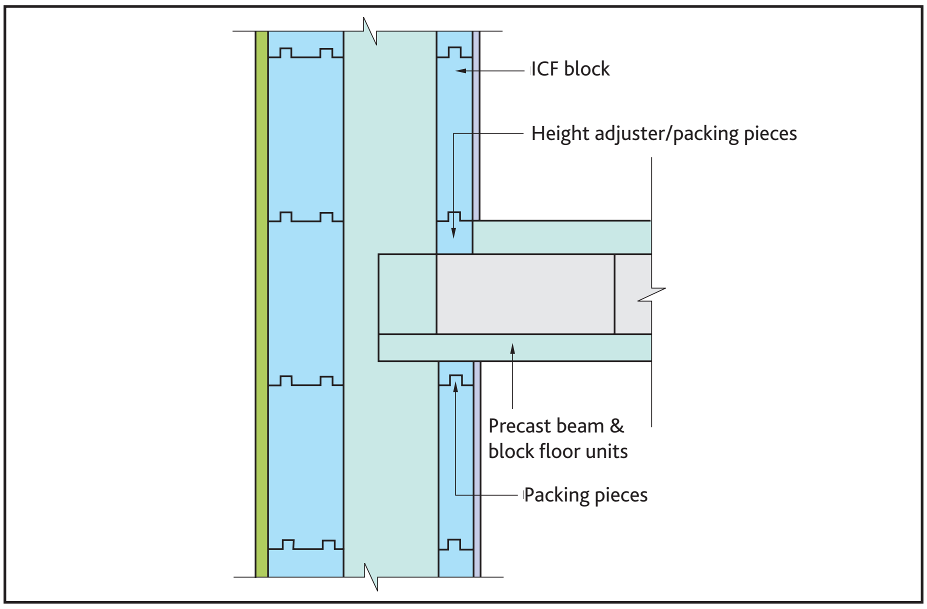


Figure 7.5
The pocket method for supporting timber floor joists.

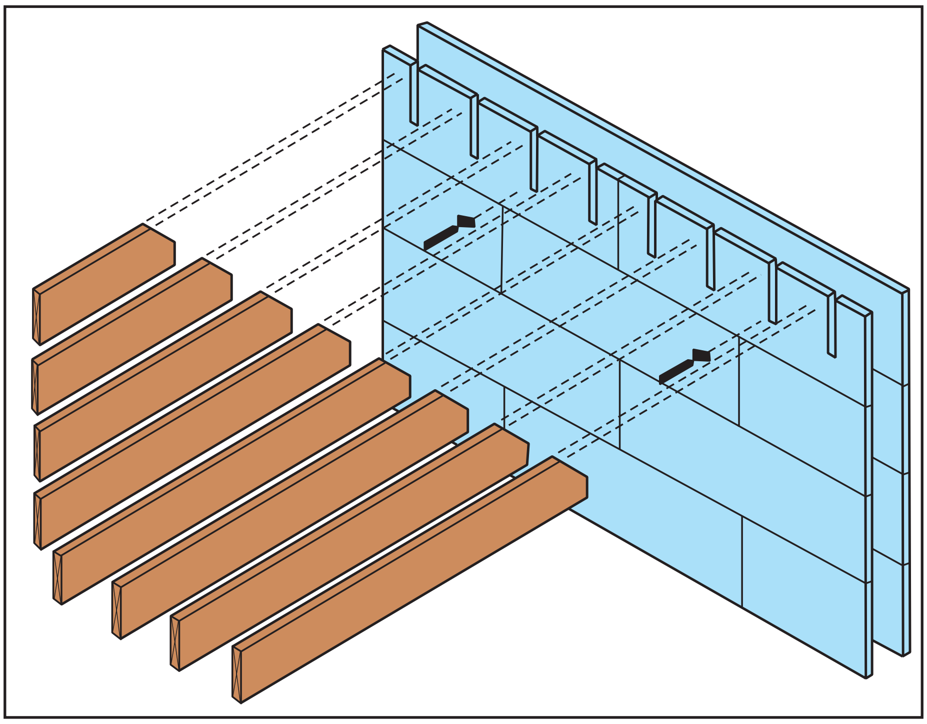
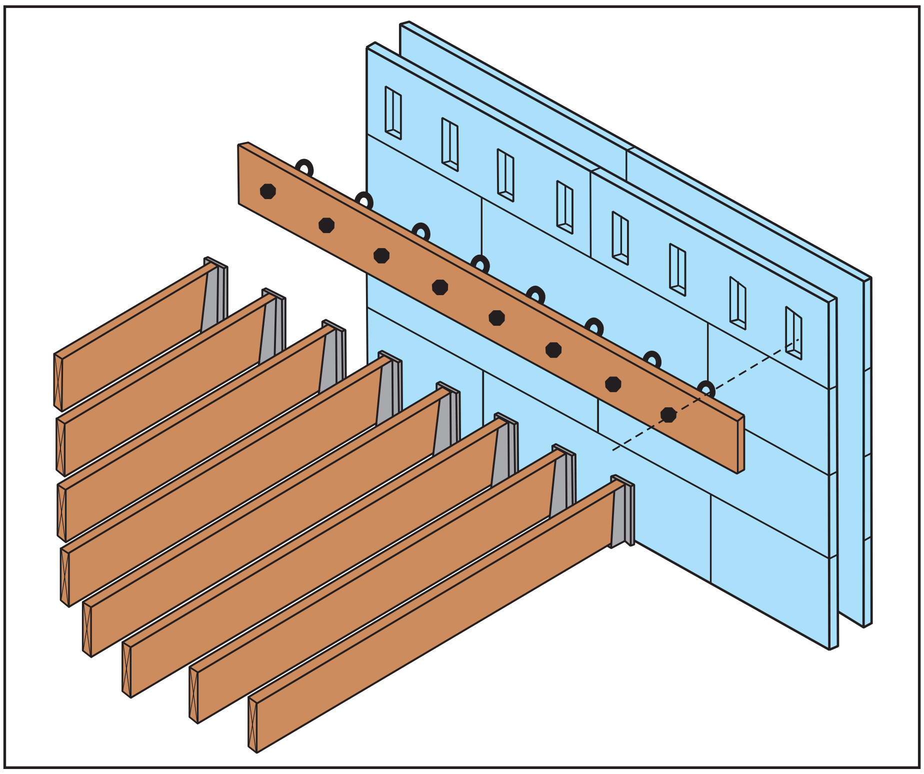


Figure 7.6

The ledger and joist hanger for supporting timber floor joists.



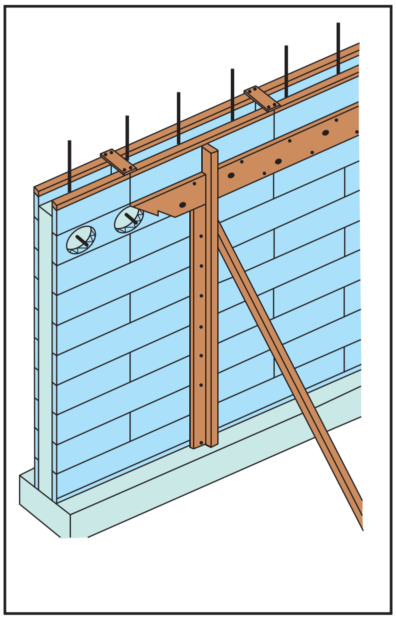
At roof level, the formwork will normally extend above the required roofline. The exact roofline will need to be marked on the formwork and the formwork cut to the correct level.

At the top of the storey, when building is to continue above, the correct storey height will also need to be achieved by trimming. If timber floor joists are to be used, provision will need to be made for supporting the joists. The two common methods are either to create pockets in the formwork to receive the joists or to use fixings to fix a board to the wall and subsequently fix joist hangers to the board.

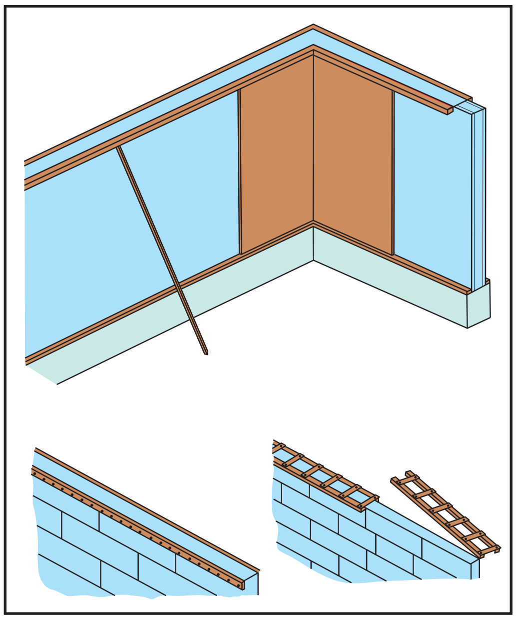
Some systems are available with light steel joists into which special EPS or XPS blocks may be fitted before a concrete topping is placed over the floor. It is also possible to use precast concrete wide slab and beam and block floors with most ICF systems to provide higher standards of within-dwelling sound performance.

Final bracing before filling with concrete

Concrete filling normally takes place one storey at a time. Before filling can take place, the walls need to be properly braced. This will be the contractor's responsibility under enabling works but manufacturers will be able to provide information on support systems. The top edge of the wall needs to be braced to stop it from spreading out during filling and to provide support for diagonal bracing. Figure 7.7 shows the stringer fitted and the wall braced. Figure 7.8 shows basic bracing, while Figure 7.9 shows photographs of variations in bracing. It is important to check that walls are still plumb before placing the concrete.



Right **Figure 7.7**
Detail showing bracing and support for timber stringer.



Far right **Figure 7.8**
Typical wall bracing.

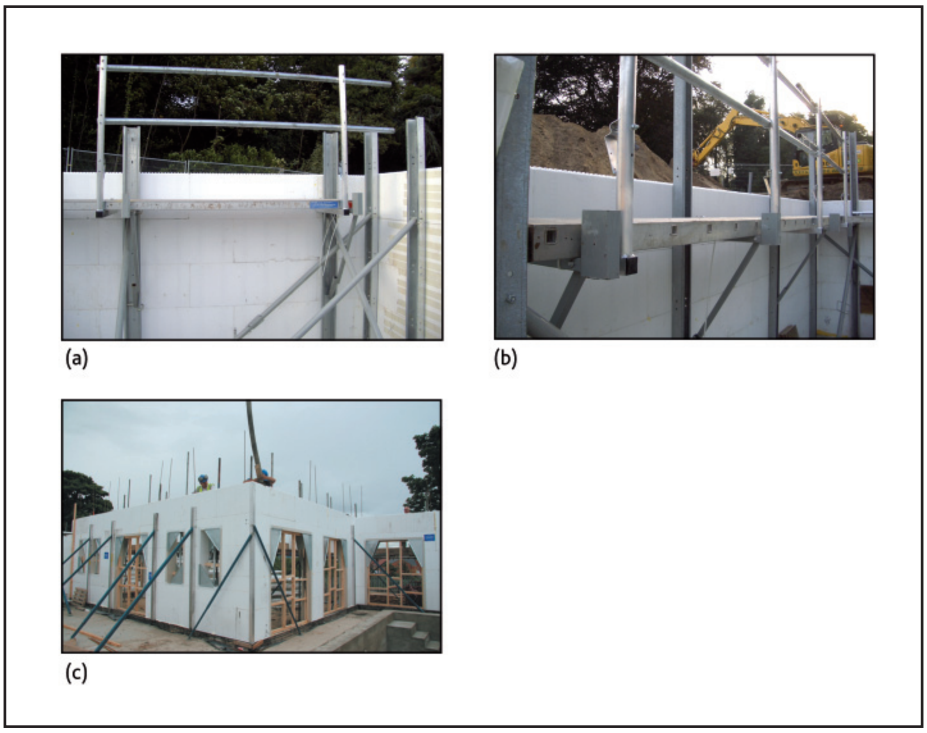


Figure 7.9
Photographs of actual wall bracing.
(a) Bracing using stability frames, (b) and (c) Proprietary bracing systems.

Constructing subsequent storeys

Once the first storey has been filled, work can proceed using essentially the same procedure as before. If the formwork extends up higher than the finished floor level, blocks will have to be trimmed at door openings. Set the corners and check for level and plumb. Blocks can be placed directly on the blocks below, making sure that the cores align correctly.

Gable ends

Gable ends are constructed using the same procedure as for normal walls and trimmed on the diagonal to the correct pitch, as shown in Figure 7.10. Wall plates with holding down bolts should be fixed in place, as shown in Figure 7.11.

Figure 7.10
Blocks stacked for a gable end.

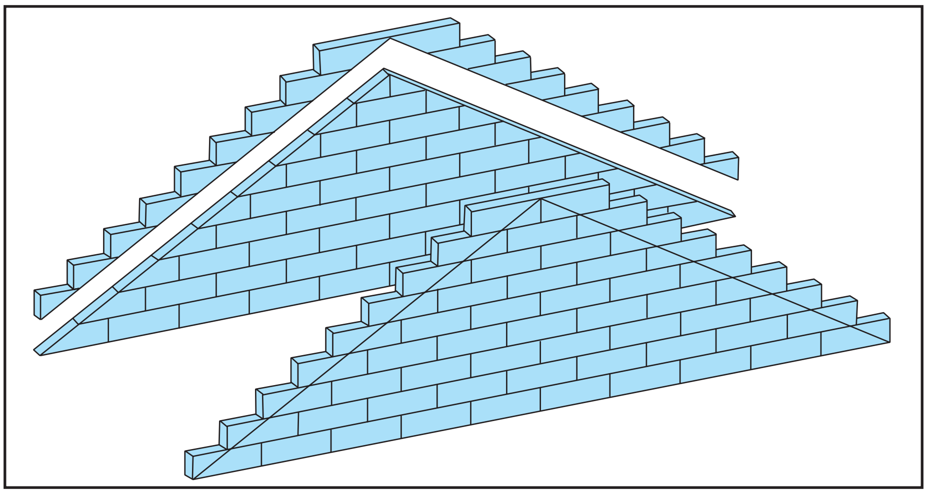
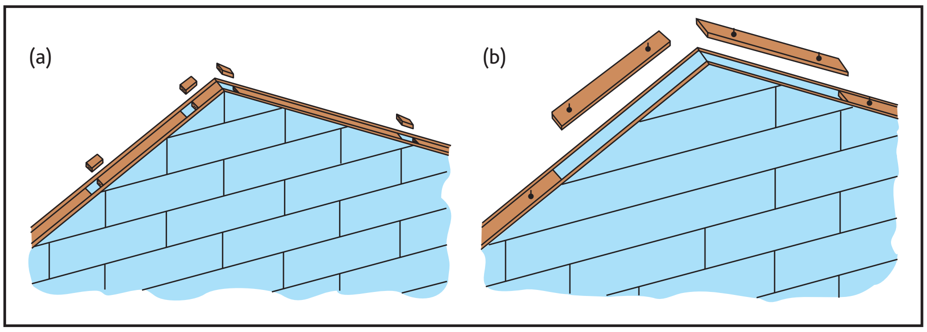


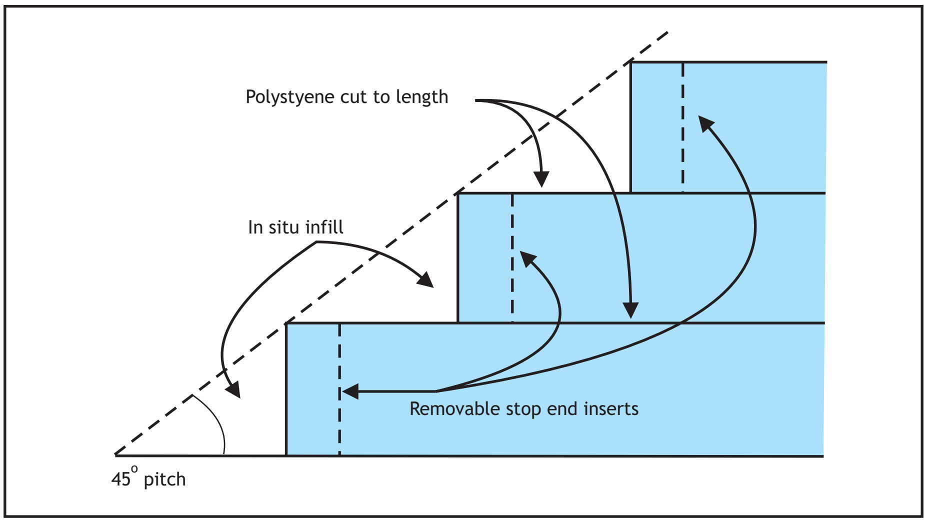
Figure 7.11
Inserting wall plates into a gable end.



Gables that slope less steeply than the slump of the mix in use can be formed by attaching timber battens to the required height and angle, and trimming the ICF formwork to follow the slope. The concrete is then poured in the usual manner, and simply trowelled off to finish. It will usually be inconvenient to cast in any gable ladders at this stage, so pockets for the ladders should be cast in, to avoid the need to cut out later as part of the roof construction work.

Where gable ends are pitched at angles greater than the slump, an alternative method must be used. The wall plates, as mentioned above, can be placed apart with removable sections to facilitate filling (Figure 7.11a) or placed and filled sequentially (Figure 7.11b). When the concrete begins to stiffen, the inserts must be removed (if left in place, they will weaken the wall where the truss restraints are to be located) and the voids filled either with cut masonry blocks and strong cement mortar, or with concrete set aside during the main pour and allowed to stiffen sufficiently to remain in place after trowelling to the slope without slumping. Stop-end inserts may be used to create a stepped gable, corresponding to the required slope (see Figure 7.12).

Figure 7.12
A method of forming a gable end in an ICF system.



Curved walls and unusual openings

Many manufacturers are able to supply curved units (see Chapter 2) to suit the requirements of the designer. Where these are not available, it can be possible to modify blocks by cutting and gluing to allow the formation of curved walls. Irregular openings are often best formed by marking and cutting a completed wall and then constructing a frame to fit.

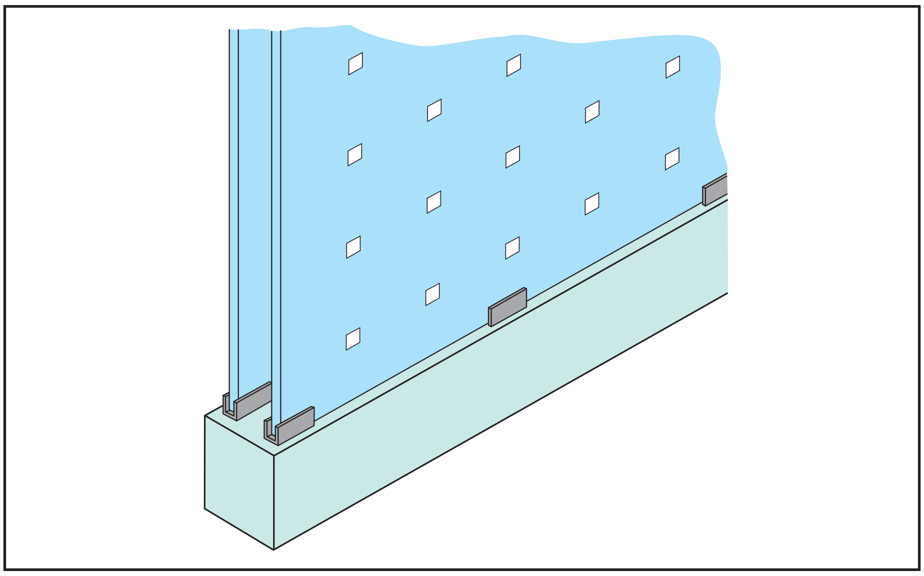
7.3.2 Setting large panel systems

Panels are much larger than blocks and are usually joined with metal or plastic components. It is not necessary to worry about a bonding pattern with panels but some systems use ties that provide a fixing for subsequent finishes and it is important that these are properly aligned.

The first course

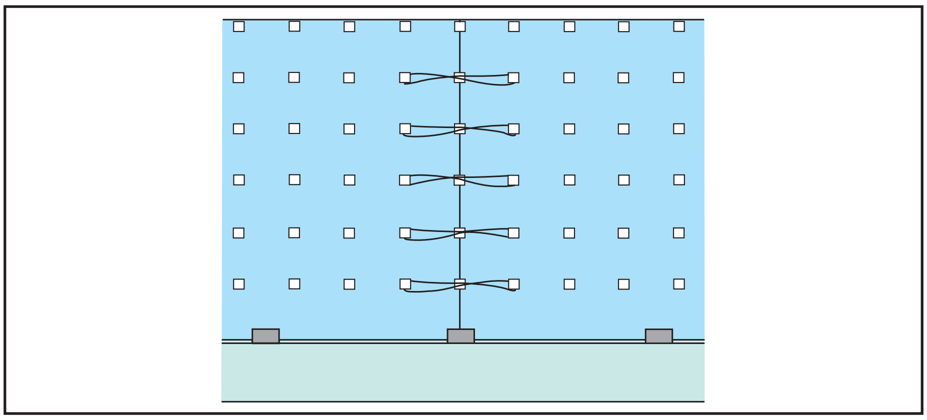
Some panel systems use timber guides in the same way as the block systems but others use metal channels, as shown in Figure 7.13.

Figure 7.13
Panel system located in metal channels.



Corners are formed by cutting the panels to length and joining them with the proprietary connection provided by the manufacturer. Working from the corner, the first course can be set. Panels should be shimmed or trimmed as necessary to achieve the correct level and adhesive foam used to seal any gaps. At openings the panel should be trimmed flush to butt up to the frame and a new panel commenced on the other side of the frame. A make-up piece can then be cut to fill the space above the frame. In some systems the joints between adjacent panels are strengthened with wire, as shown in Figure 7.14.

Figure 7.14
Joint between adjacent panels strengthened with wire.



The second course

Many panel systems are a full storey in height and, once placed and braced in accordance with the manufacturer's instructions, can be filled with concrete. Fixings and wall plates are installed in a similar way to that recommended for block systems. Subsequent courses are built up on the first course following the same procedures.

Gable ends

With large panels it is easier to cut them roughly to size before installation and then carry out the final accurate trimming in situ.

Curved walls and unusual openings

Curved walls may be formed by either cutting slots, gluing the edges and bending the panels to shape, or by cutting through the panels to form bevelled edges, which can then be glued together.

7.3.3 Setting plank systems

Plank systems are usually assembled as the work proceeds. The systems are set by placing the individual planks in position (using guides fixed to the concrete slab) and then placing the plastic or metal ties at the top edges of the planks. The next course of planks are then located on the ties already in place and secured at the top edge with more ties. Some systems require the planks to be staggered while others do not require any bonding to be retained. Preformed corners are available with some products and it is important to follow the manufacturer's recommendations. Subsequent storeys are completed in the same manner. As with the panel systems, slots may be cut to enable curved walling to be produced. Alternatively, the panel may be cut with bevelled edges and assembled together using ties.

Composite panels

These systems use posts and beams or other framing to support the insulation and can also provide in-situ support for concrete floors. Much of the detailed design will need to be carried out in conjunction with the manufacturer who will provide detailed assembly instructions for the system.

7.4 Incorporating reinforcement

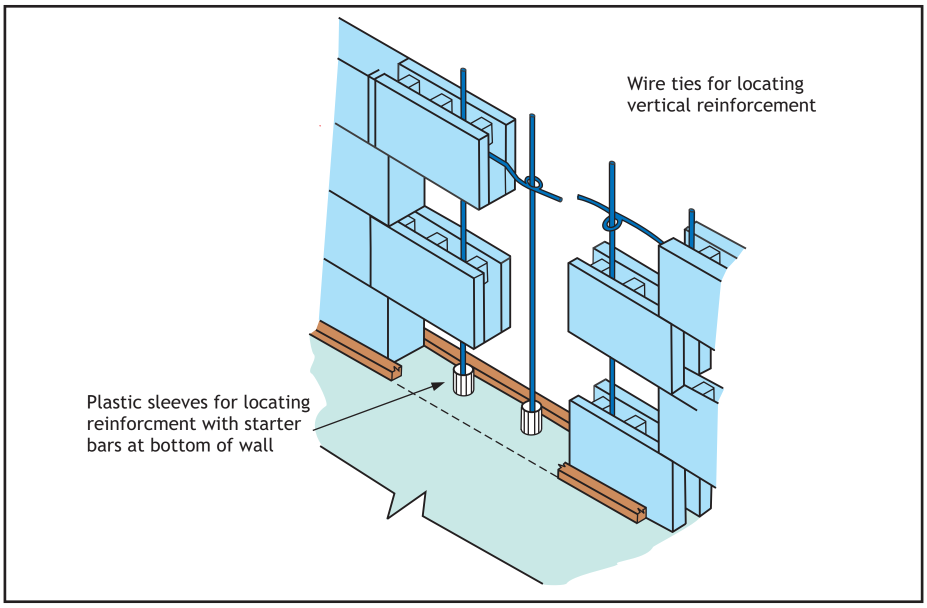
Most ICF systems are such that both wall faces must be raised simultaneously and all of the block, and some plank systems, feature rigid web connectors cast into the ICF components on a regular grid. In reinforced ICF systems, this grid should be adopted as the centre-to-centre pitch of the reinforcement for both slab and walls, and the starter bars. If not, there will be interference between the web connectors and reinforcement. Clearly, mesh is not suitable for most ICF wall construction. While raising both faces together does allow horizontal reinforcement to be located as work progresses, the vertical bars must be either retro-fixed from the top of the storey or the blocks/planks threaded individually over the bars.

Where conventional reinforcement is required, the starter bars from the base slab will need to be carefully set out to suit the type of ICF system that is to be used. The manufacturer should provide the reinforcement spacing required. An effective and fast method of splicing bars is to place short lengths of PVC sleeve over the starter bar on the foundation, wide enough to accept and properly locate the reinforcing bar lowered from above. The collar internal diameter should allow for both bar diameters plus a small tolerance. See Section 5.3 regarding design strength and lap-length when adopting such a collar and the reinforcement is not tied together.

The top of the main steel will then need to be fixed and this can typically be done by using wire ties, as shown in figure 7.15 Non-contact splicing is useful to overcome mismatches between the pitch of the slab starter bars and the main wall reinforcement, or where the web ties interfere with the pitch.

The tops of the vertical reinforcement are accessible for securing to the topmost horizontal reinforcing bar. If additional fixings part the way up the lift are necessary, small hand holes can be cut with a pad saw to allow additional tying of the vertical reinforcement to the part-height horizontals. Hand holes should be made good by gluing the cut-outs back in place, or by expanding gap-filling foam, before concreting.

Figure 7.15
Wire used to hold reinforcing steel in place.



7.5 Placing the concrete

Final checks should be made to ensure that all bracing is in position (see Section 7.3), and that any joist slots, wall plates and fixing points have been provided and sleeves placed for services. The amount of concrete required should be carefully calculated and an allowance made for wastage. Manufacturers issue placing (rate and maximum height) and restraint information specifically designed for their system and this should be followed carefully. The following generic guidelines give an overview of the principles involved.

The concrete will normally be placed with a line pump or a swing pump (Figure 7.16). The line pump will typically have a diameter of 75mm and may be used directly to place the concrete. The more powerful swing pump will need to incorporate a diameter reducer to 75mm and one or more elbows to reduce the pressure at the point of placement. It should be noted that some suppliers prefer 100mm-sized nozzles, but this needs to be discussed with the ICF supplier. It is important to check the concrete against what was ordered, including the slump, before placing it in the walls. The first output of concrete through the pump will often need to be discarded (do not pump slurry into the walls) until a homogeneous concrete is flowing and arrangement needs to be made to receive this waste.

Normally placement commences at one corner and proceeds around the perimeter of the walls. Care must be taken to place the concrete carefully around openings, which are often filled in advance of the adjoining walls. Walls are usually filled in layers around 500mm deep on a continuous basis for the full height of the panel, which for housing will be around 2.5m, or as may be limited by the manufacturer's specifications for construction practice, which is typically 3.0m. Pour heights in excess of this should be discussed with the manufacturers at pre-construction meetings. The site team need to be alert to any points where the concrete does not fully fill the formwork.

Figure 7.16
ICF filling using boom pump.

The high slump (see Chapter 6) of the concrete means that it is largely free-flowing, making careful hand-rodding an acceptable means of achieving compaction with most systems. Where reinforcing steel is incorporated in the wall a small poker vibrator may be used to ensure proper compaction is achieved. By tapping the wall during the placement of the concrete it is relatively easy to determine if a particular section of wall has not been filled and take action to fill it.

If the formwork bulges or blows out, a plywood panel is needed to cover the affected area and a local repair can be made to the insulation. After 24 hours, the bracing can be removed along with any panels covering blowouts. The insulation and protection of the concrete provided by the formwork means that concrete can be placed in a wide range of weather conditions and still cure properly.

7.6 Services

Service provision needs to be carefully planned and suitable openings formed where services are to penetrate the ICF walls. Once the services have been run through the wall, the service duct should be effectively sealed and fire-stopped as required. Particular care should be taken when incorporating services in basements and the guidance given in the *Approved Document for Basements* should be followed.

Where block systems with a polystyrene cross web are used, it is possible to run small diameter services through the web in a finished wall.

7.7 Internal walls

Where high-performance internal walls are required, for example as a separating wall between dwellings, care will need to be taken to construct the wall and the intersections with the outer walls before the concrete is placed in order to ensure adequate resistance to the passage of sound. Intermediate walls to support floors may also be constructed using the ICF system but, alternatively, these may be constructed using plain concrete formwork or concrete blockwork, to reduce the overall wall thickness.

Partition walls may be constructed of lightweight metal framing with insulation panels, concrete blockwork or timber studding. Care will need to be taken to follow the manufacturer's guidance on joining internal walls to the ICF external wall.

Chases can be cut into the insulation for central heating and other pipework, and cable runs, which may need to be upgraded due to the surrounding insulation.

7.8 Finishes

7.8.1 External finishes

A common finish for ICF walls is a render system. These systems often incorporate scrim reinforcement or a metal carrier and allow a range of colours and textures to be used. Polymer modified through coloured renders can be applied directly to the surface of the insulation. The design, preparation and application of external rendering should be in accordance with BS EN 13914 -1. This gives guidance on how to render on a range of substrates, including EPS, and indicates where movement joints should be incorporated[7.1]. However, in all cases the plaster manufacturer's specifications should be adhered to.

Various types of cladding and tile hanging, including brick tiles, can also be affixed to the walls with mechanical fixings (see Chapter 8).

7.8.2 Internal finishes

Although some systems can be plastered directly,[7.2] the most common internal finish is plasterboard. Mechanical fixings, not only for wallboards but also for fixing most other attachments, can most conveniently be made into the formwork where the web plates are located. Some web plates have T-shaped ends embedded into the formwork. These ends are prominently marked, for the purpose of identifying secure fixing locations, into the polystyrene, polypropylene or steel mesh web components, as the case may be. If long fixing screws for any early-stage fixings, e.g. of stringer beams etc., are used before the concrete core is cast, the concrete will set around the thread, providing extra security to the fixing.

Normal plasterboard may be fixed mechanically by picking up on the ties, which are designed to accommodate them. Alternatively, plasterboard may be fixed on normal dabs using a compatible multipurpose adhesive or on multiple small dabs using a specialist adhesive. Some manufacturers recommend a continuous proprietary adhesive. Where adhesive fixing is used, it would be normal practice to incorporate mechanical fixings near to the top of each board to provide additional support in case of fire.

Tiles and other decorative finishes may also be stuck directly onto the surface of the ICF material subject to this being acceptable to the tile manufacturer or as may be limited by the contract specifications, which may vary depending on area, height and location.

7.9 Checklist of basic tools for use with ICF systems

The following is a list of basic tools required for straightforward ICF construction:

- Keyhole saw
- Woodcutting saw
- Circular saw
- Reciprocating saw
- Hand rasps
- Sandpaper
- Adhesive (compatible with ICF form material)
- Foam for filling gaps
- Steel fixing wire
- Rebar bending and cutting
- Mason's trowel for finishing
- Router for chases

7.10 Health and safety aspects

The basic ICF components are inherently light and are easy to transport on site. The guidance on working practice provided by manufacturers needs to be understood and followed by the workforce but does not rely on specialist skills or expertise. The concrete is placed by pump and does not otherwise require site handling.

The current emphasis on off-site fabrication has resulted in an increase in the use of large-panel ICF assemblies with windows, doors and possibly services installed and these panels need to be handled by crane. Clearly the safe transport and handling of large panels is a significant safety consideration and the manufacturer will provide appropriate method statements for handling the panels in addition to guidance on construction.

8. Typical construction details

This chapter provides typical ICF construction details at ground level, floor level and roof level.

8.1 Ground level

Work at ground level includes basement construction, ground bearing and suspended flooring, horizontal DPCs and wall penetrations for installation of building services.

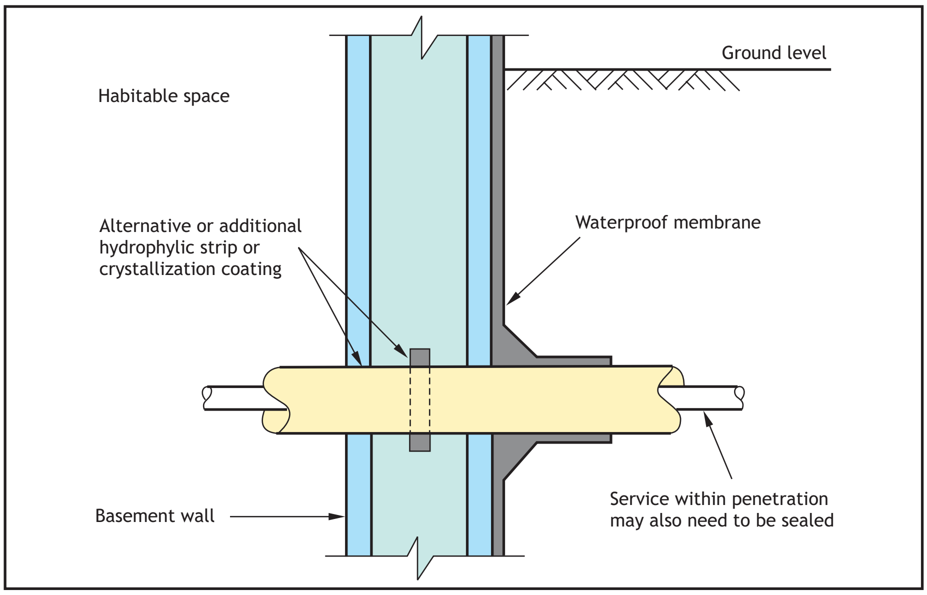
8.1.1 Basements

Basements will generally be constructed using structurally reinforced walls and floor slabs. Some plank systems can be erected between storey junctions one formwork face at a time. This allows the reinforcement to be selected and fixed within the core in the normal manner (and also allows for mesh to be used), following which the web ties are inserted and the remaining wall formwork fixed, ready for concreting.

8.1.2 Service opening

Service entries through the walls can be accommodated by casting in an appropriately sized sleeve, or by boxing out prior to concrete pouring (see Figure 8.1). However, although this detail is shown, it should be noted that the *Approved Document – Basements for Dwellings*[8.2] indicates that such a detail should be avoided wherever possible. This is because it penetrates the waterproofing system and allows water to track behind the waterproofing system. This results in water ingress elsewhere along the wall, such as at wall and floor junctions. If such a detail is unavoidable, then careful detailing and installation will be necessary to avoid water penetration and particularly so when below ground, see Figure 8.1[8.2]. After the service is installed, any gaps between sleeve and the service pipe or cable, etc., should be plugged with a compatible inert, waterproofing material.

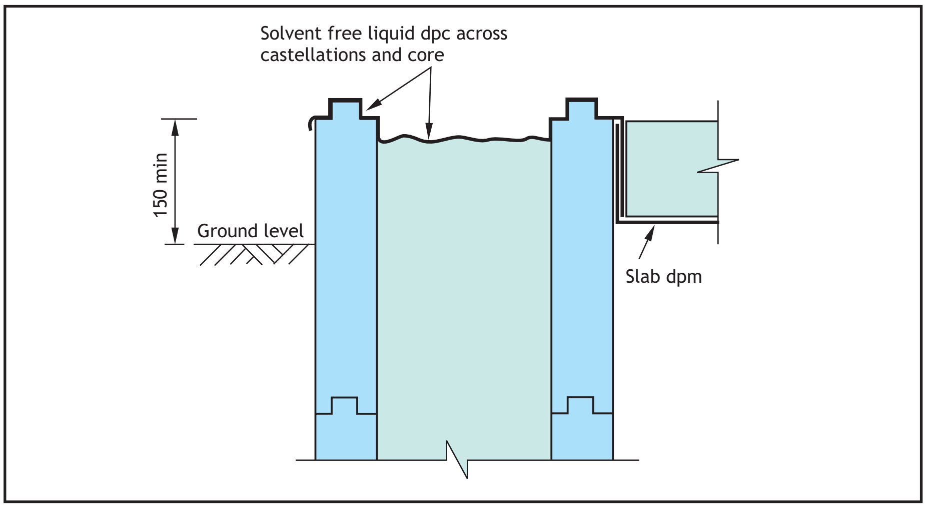
Figure 8.1
Provision of services through an ICF.



8.1.3 Ground-floor wall junctions

Damp-proofing of the vertical ICF walls against rising damp can be provided by a variety of methods, dependent on the type of ICF system in use. The conventional masonry method of satisfying the building regulations is to install a horizontal DPC, and this can be done with ICF using a liquid DPC. However, if a block system is being used, care will be required to avoid physical damage or concrete spillage spoiling the fit of the castellation. Duct tape secured along the tops of the formwork faces is an effective protection during the pour. One method uses a solvent-free liquid DPC, applied across the surface of the castellated block abutting the slab, and dressed down to the underside of the slab (see Figure 8.2). If the upturned edge of the slab DPM is pressed firmly onto the vertical surface of the DPC while it is still tacky, and before casting the slab, this will increase the effectiveness and minimise the risk of capillary action. The concrete used below-ground is the same specification as the above-ground work. This method does, however, require the pour to be interrupted at DPC height, to allow the concrete to set and the liquid DPC applied across the core.

Figure 8.2
Application of liquid dpc to ICF interlocking block system.



Clearly, the use of rigid or semi-rigid plastic PVC types of DPC requires the castellations to be cut off and the upper walls effectively restarted from a smooth base.

More conveniently, if the concrete core is specified as a water-resistant concrete and this concrete is continued to at least 150mm above the external finished ground level, this may adequately resist rising damp in the core. The water-resisting core is itself the DPC. Any wall DPC detail must, however, be considered in conjunction with the internal ground-floor detail. The use of water-resisting concrete in this way is common in the USA and other countries where ICF is extensively uised.

A cost-effective method when water-resistant concrete is intended as the DPC, suitable for ICF square-edged boards or plank systems, or when castellations are to be filled, is to bring up the slab DPM against the inner plank face, dress it over the top and turn it down into the cavity. This creates a long path length which, taken in conjunction with the hydrophobic nature of the polystyrene formwork, effectively eliminates the possibility of capillary action between slab and wall. This method maintains the recommended continuity between wall DPC and slab DPM (see Figure 8.3). A variation on this method is to dress the slab DPM up the face of the wall, and fix it to the wall above DPC level with duct tape.

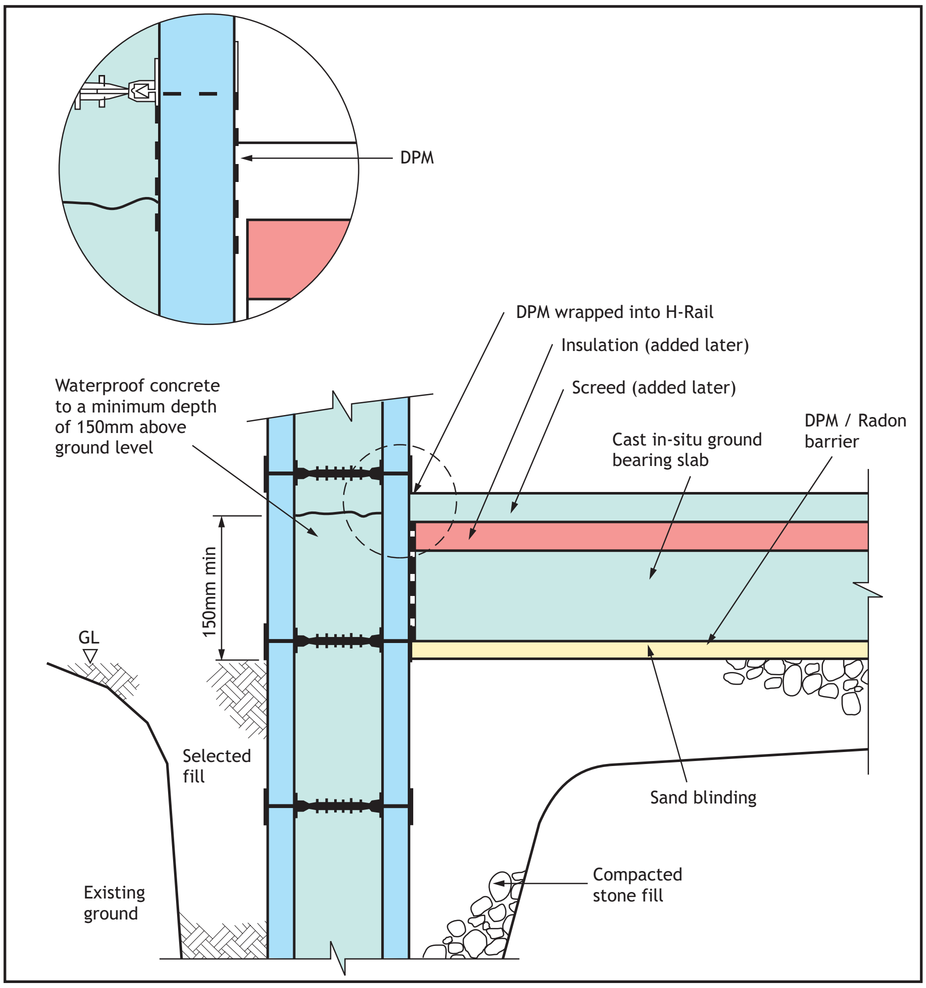
Suspended ground floors do not have the complications of an under-slab DPM. However, the same precautions regarding the installation of a dpc against rising damp need to be considered (Figure 8.4), although the possibility of capillary action, when using a non-ground bearing slab, may be disregarded.

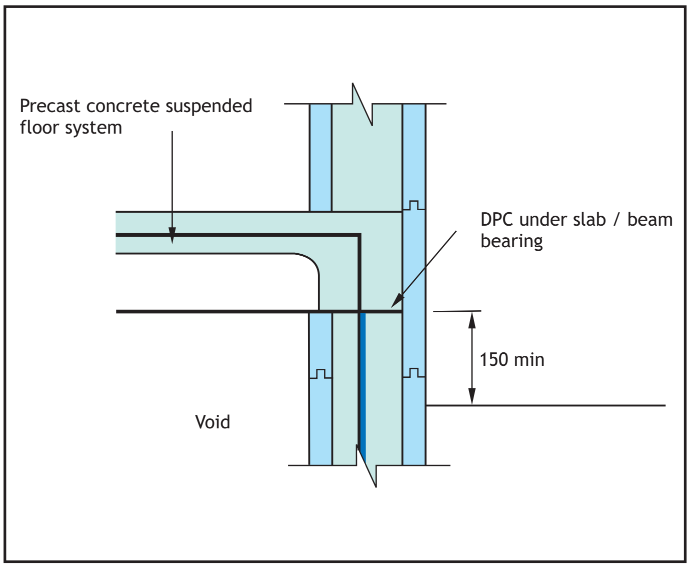
When expensive brick or stone cladding is to be used and the foundations are deep, some systems offer a corbel. These are useful and cost-effective because they reduce the need for wasteful under-building below ground level (see Figure 8.5).

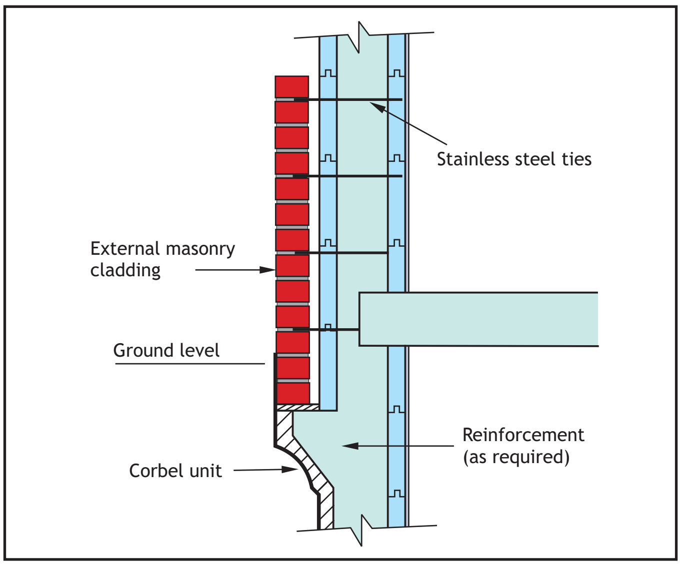
The last three paragraphs make reference to the use of concrete with the addition of a water-proofing admixture used to control rising damp. This method may be considered as a DPC in certain ground conditions. The exception is where account needs to be taken of radon or other gases, where it will be necessary to provide a specific continuous gas membrane, which will also act as the DPC.

The provision of a DPC is to control water rising by capillary action and it will also generally control ingress of water-vapour, when of a membrane form. A water resisting concrete may not control water-vapour to the same extent as a membrane, however due to the presence of the insulation the wall, the inside temperature will typically be higher above ground than below, which will tend to make water vapour move downwards rather than upwards.

Figure 8.3
Positioning of DPM membrane on a water-resisting concrete wall dpc.





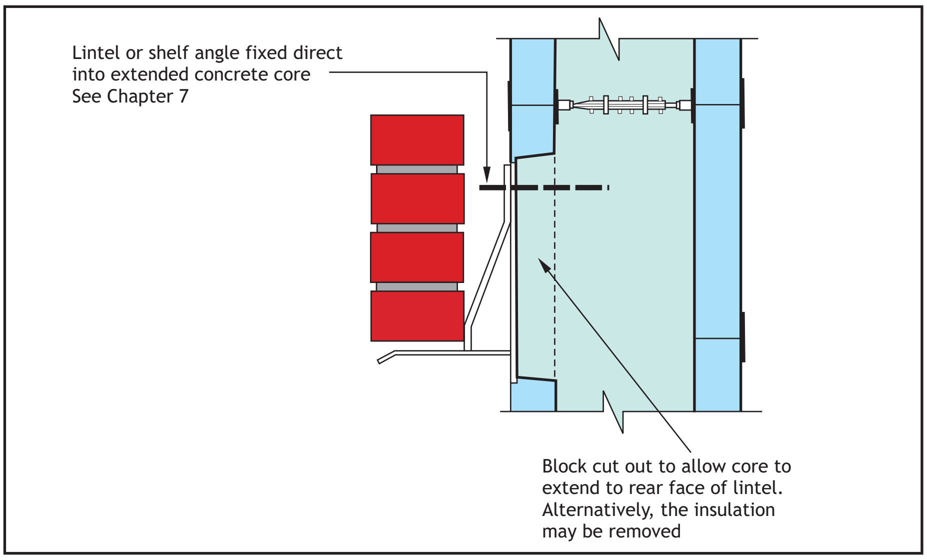


Above left **Figure 8.4**
Example of DPC in a wall supporting a suspended slab.

Above right **Figure 8.5**
Example of a proprietary corbel.

If a proprietary corbel is not available, an alternative is to use a galvanised pressed steel lintel or shelf angle (see Figure 8.6). Alternatively, the insulation may be removed after concreting and the angle then fixed to the core.

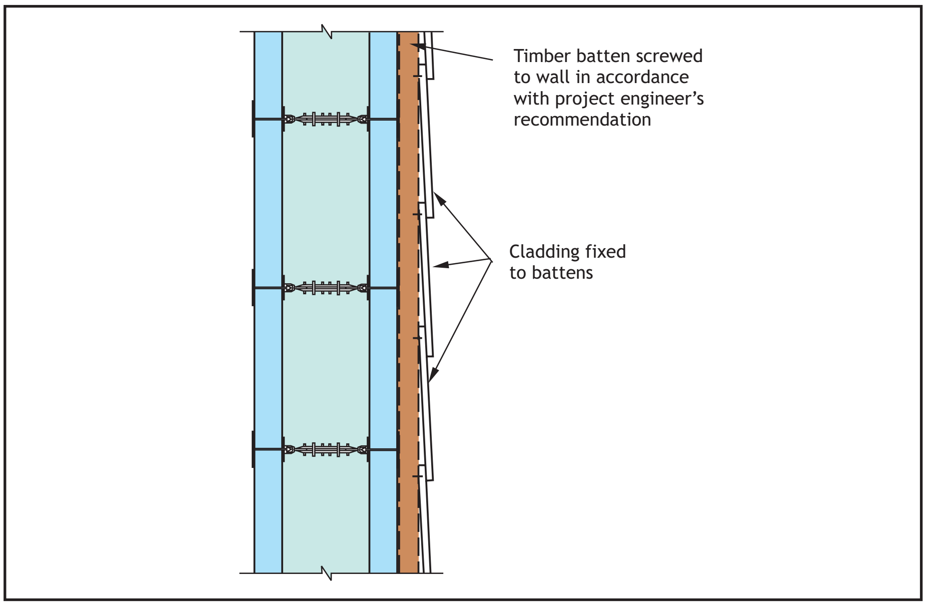
Figure 8.6
Alternative steel bracket support system to an outer masonry skin.



8.2 Cladding and brickwork attachment

Tile hanging and weatherboarding can be provided by screw fixing the battens to the flat ends of the system ties, as shown in Figure 8.7.

Figure 8.7
A method of attaching battens and tile hanging.



Brick courses are tied to the ICF wall by a number of different methods depending on the system used. Some use ties that are cast in during the concrete core pour, and others are screw fixed to the flat ends of the cavity ties used in some of the systems to hold the inner and outer faces together. A system using anchor channels can also be used and is particularly suitable for an un-coursed stone finish where it is not possible to predetermine course heights.

Figure 8.8
Cast in spiral ties and screw fixed ties.

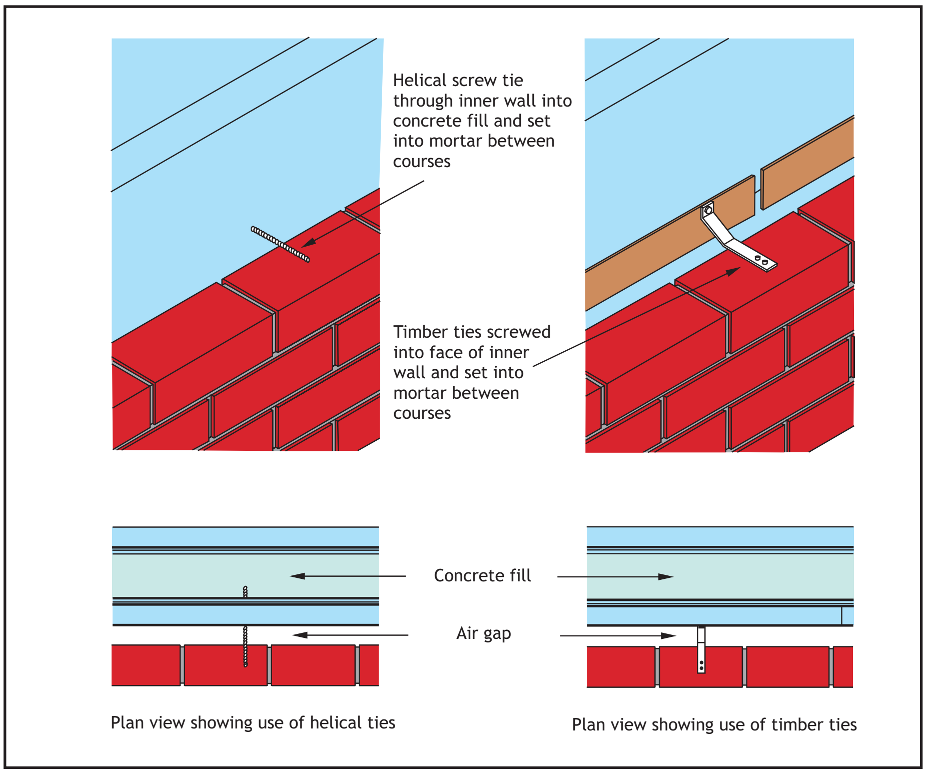
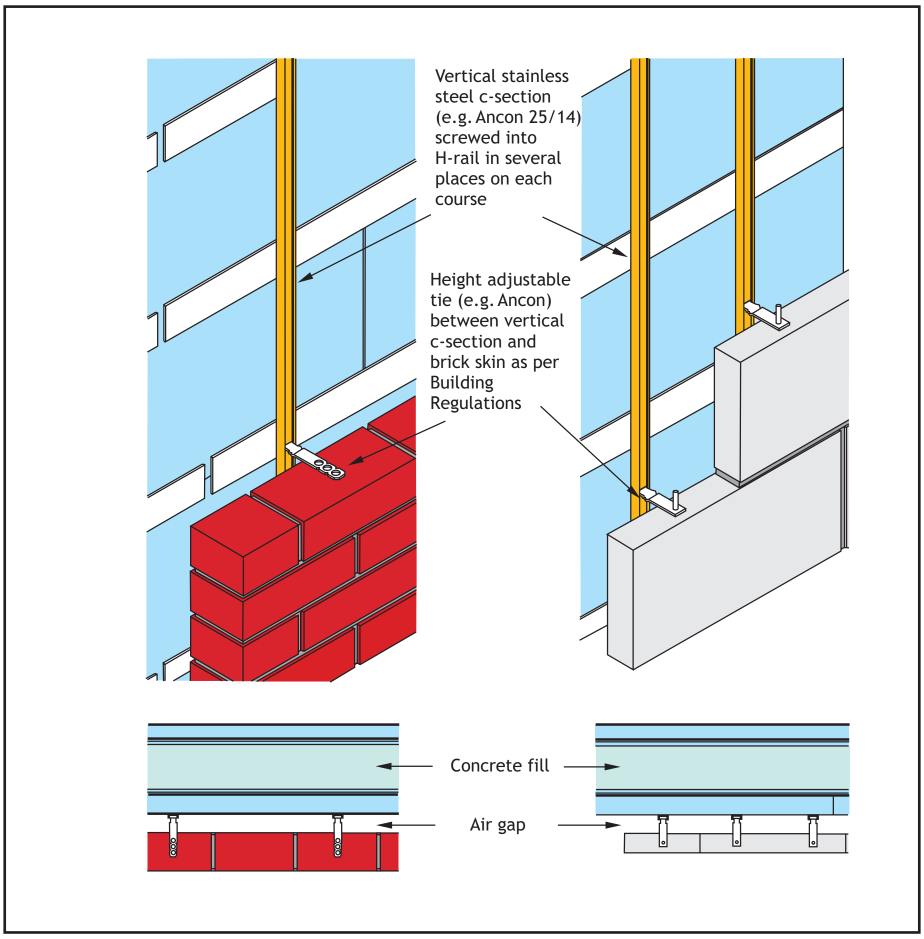


Figure 8.9
Channel anchor system.

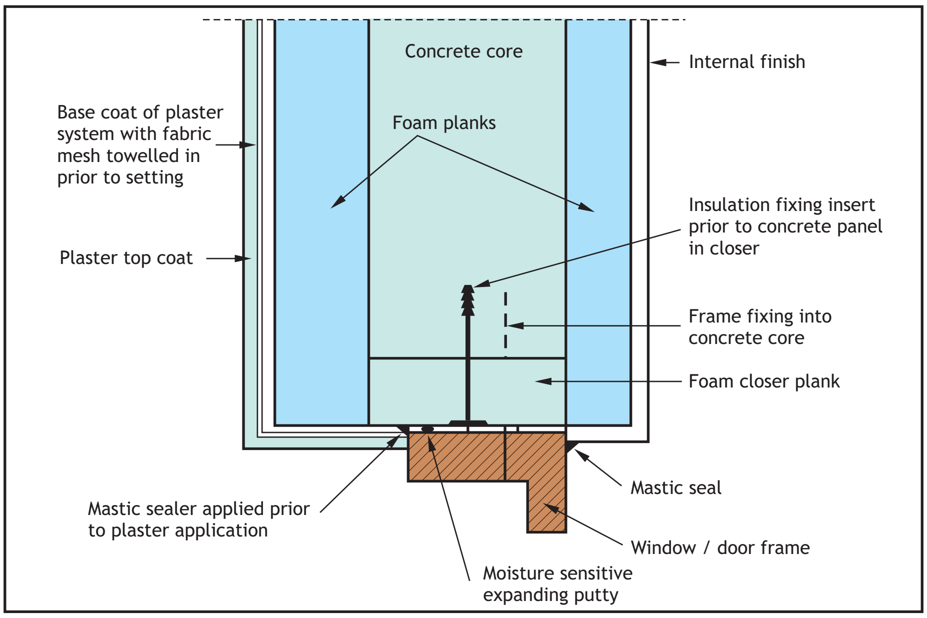


8.3 Door and window openings

Some block systems feature special inserts that stop-off the concrete core to form the openings. These have the benefit of avoiding cold bridging. Where wooden forms need to be used, the forms should be lined with polystyrene off-cuts and left in situ to act as insulating cavity closures (see Figure 8.10). Although it is clearly not necessary to install any blocks within the openings themselves, it is recommended that the bottom run of blocks be continued across all openings. This helps to maintain the dimensional grid, reducing the possibility of creep, which could otherwise create problems when the grid is recommenced at lintel height.

Careful attention to the weather stripping of all openings is very important. ICF structures can be expected to have a useful life far into the future, when weather conditions are expected to become more extreme. Timber components in doors and windows will always be susceptible to movements caused by seasonal moisture changes. This means shrinkage cracks around the openings, forming pathways for draughts and ingress of water. Flexible mastic seals should be installed around the openings, both internally and externally, but mastic should not be relied on as the only means of achieving the seal. Mastic seals should be supplemented by expanding hydrophilic tapes or putty in the centre of the contact area (see Figure 10).

Figure 8.10
Typical weather protection and stripping arrangement.



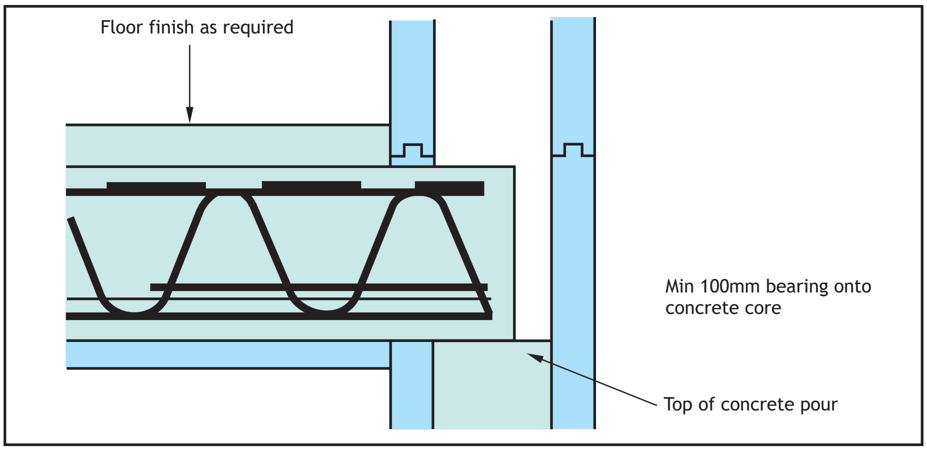
8.4 Intermediate floors

Intermediate floors, whether concrete, timber or steel, can be fixed using a number of alternative methods. On small projects, the floors can conveniently be constructed at the same time as the lower-storey walls; on larger and more complex projects, it is almost certainly better to separate the two operations, as this will give greater control.

8.4.1 Concrete

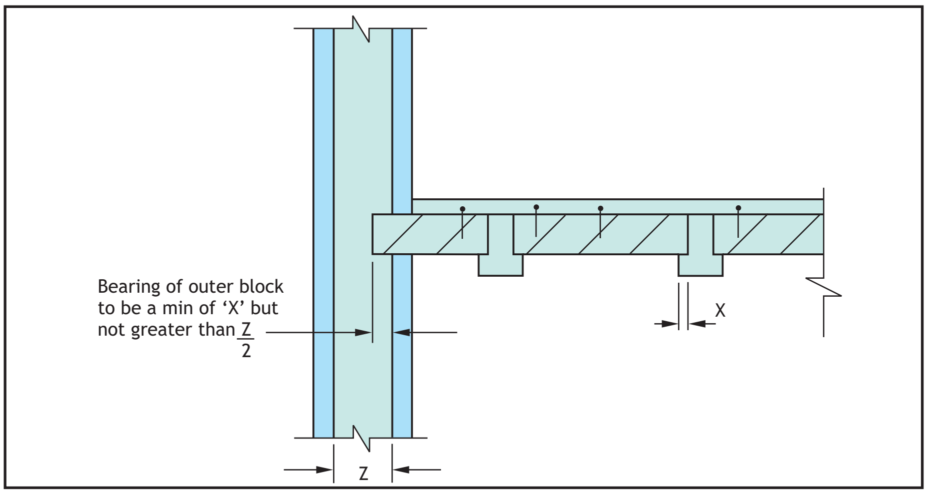
Precast beams can be conveniently cast-in, and the deck concreted and power–finished, Figure 8.11.

Figure 8.11
Precast/in-situ plank floor cast into an ICF wall.



Support must be given to the edges of the infill blocks or pots, the support being provided by the core and not the polystyrene formwork. The bearing provided by the concrete core should not be less than the bearing provided by the flooring system support beams (see Figure 8.12).

Figure 8.12
Precast beam and block floor to an ICF wall.

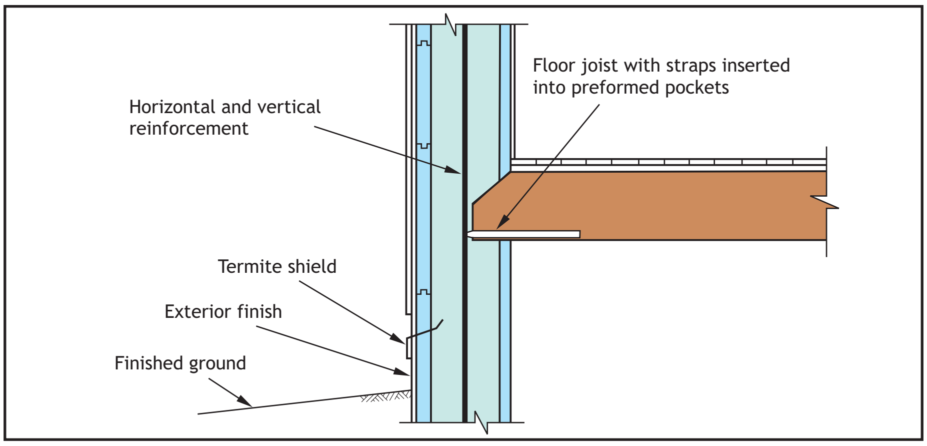


8.4.2 Timber

Timber joisted floors are most easily fixed by simply cutting slots in the formwork, into which the joists are directly inserted, and the joists cast in during the pour. The joists should have a minimum bearing of 50mm, or reach halfway across the core, whichever is the greater (see Figure 8.13).

If there are joists on both sides of the wall, they should be staggered to ensure the joist ends are not in contact, and any cut ends specified as treated with preservative. Irregular-shaped composite joists and concrete beams can also be installed in this manner, but extra time and care will be needed to make good around the more complicated cut-outs.

Figure 8.13
Section through wall with embedded timber floor.



8.4.3 General

The ICF method is well-suited for casting in the floors as part of a continuous pouring sequence. The pour can be stopped temporarily just below the level of the underside of the joists, to be continued after any final adjustments to the floor. In such cases, the lift should be terminated 50–75mm below the joist-bearing level. If the floor is propped, this will allow the continuation concrete pour to flow beneath the joists, giving a full bearing and solid fixing. Alternatively, the joists can be levelled and bedded onto mortar packs before the next lift is resumed.

If the floors are not to be cast in with the walls, or if the floors are required to be separated from the walls, e.g. to improve acoustic performance, a timber stringer can be used to support the joists. The timber stringer is fixed to the walls by cast-in J- or L-bolts, which then supports the floor. This provides a true simply supported floor structure (see Figure 8.14). Because the stringer is supporting the floor, it is essential that it is connected directly to the concrete and not fixed through the polystyrene formwork. This is to avoid any possibility of movement caused by compression creep of the polystyrene over time. The direct bearing to the concrete is achieved by cutting out pockets from the inner formwork face behind the ledger before the core is concreted. The stringer is fitted with the J-bolts, aligned with the cut-outs and positioned against the formwork. The pockets fill with concrete when the wall is poured, casting in the fixing bolts, and ensuring solid support to the back of the stringer as shown in Figure 7.6.

An alternative method, which is ideally suited for taller structures where the wall section is reduced for the upper storeys, is shown in Figure 8.15. A similar effect, useful where the wall section is not reduced, can be achieved by the use of corbel sections, referred to previously in Figure 8.5, which showed its use for supporting external brickwork.

Figure 8.14
Section through ledger support.

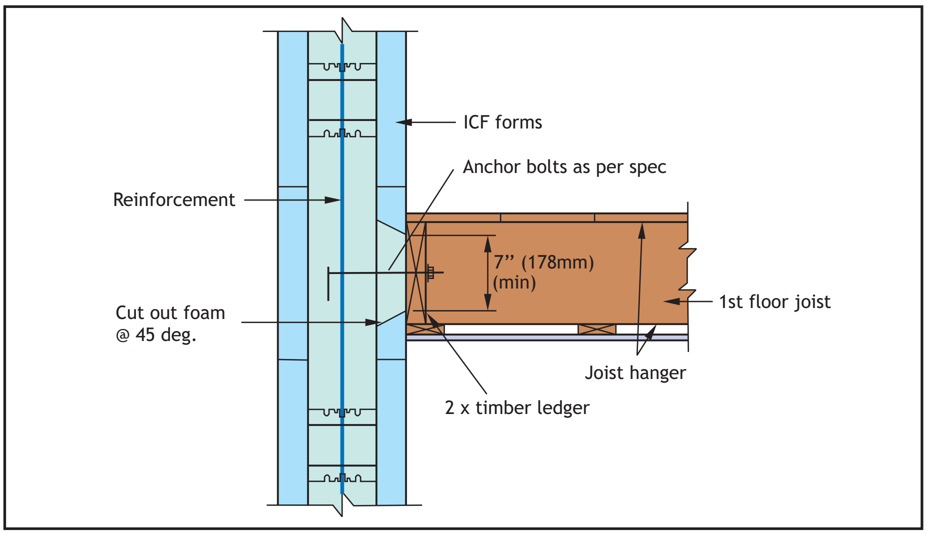
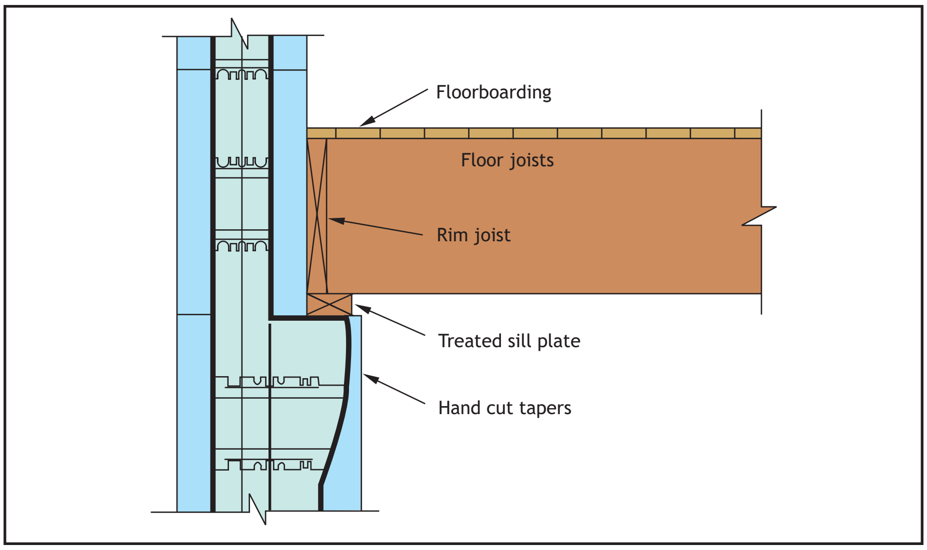


Figure 8.15
Floor support by internal corbel system.

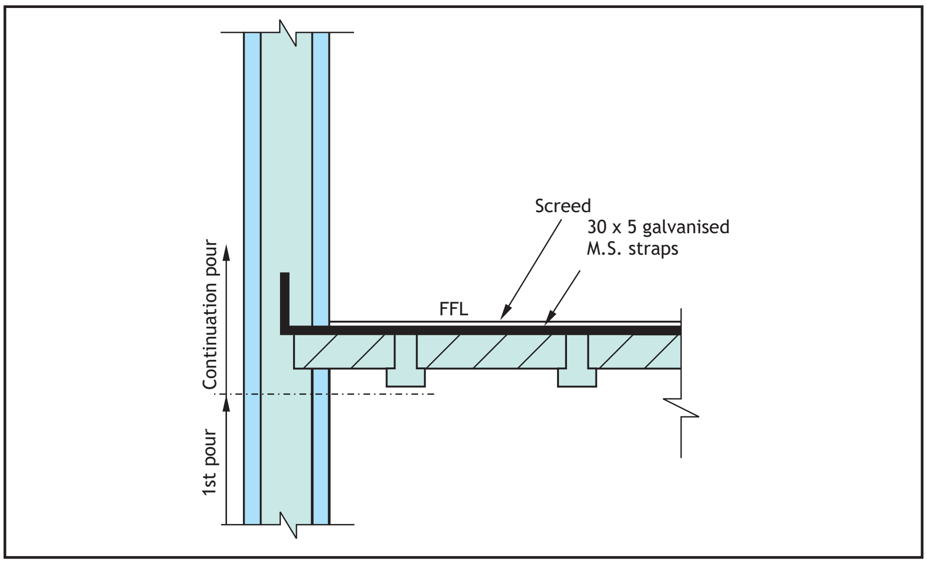


8.4.4 Lateral restraints

Where the joists run parallel to the wall, restraints to prevent lateral movement must be provided. In masonry construction, this is usually achieved by retro-fixing L-shaped steel straps to the underside of the joists, and screw-fixing them to the face of the wall below. In ICF construction, retro-fixing to obtain a direct connection to the concrete core would involve stripping away part of the formwork.

A more convenient method, when floors are not constructed at the same time as the supporting walls are cast, is to fix the straps to the upper surface of the joists/concrete beams during the installation of the floor, and locate the vertical leg upwards into the centre of the concrete core above the joist level, to be cast in with the next pour (see Figure 8.16).

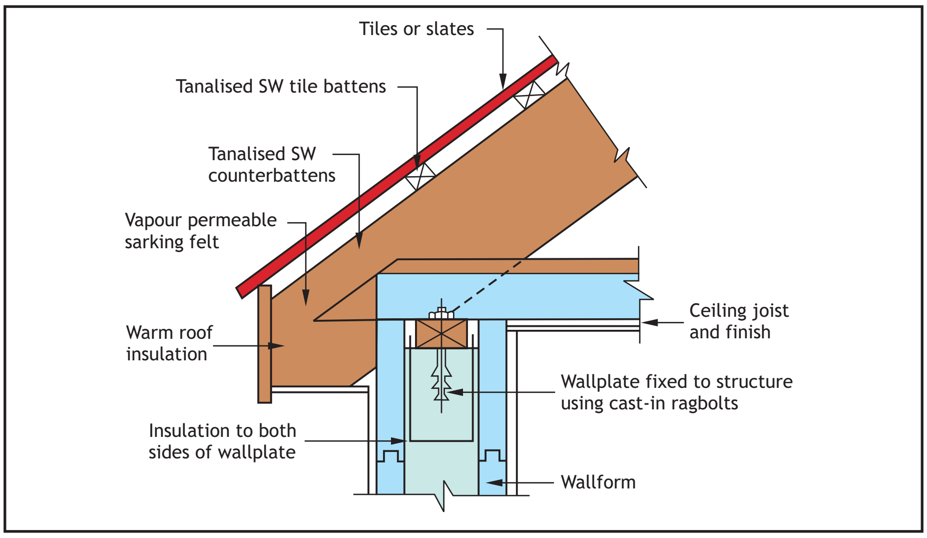
Figure 8.16
Example of a lateral support tie.



8.5 Roofing details

A robust fixing is provided by drilling the wall plate to take rag, J- or L-bolts. After fitting the washers and bolts, the wall plate and bolt assembly is located at the top of the form immediately the pour is completed, ensuring the bolts are fully immersed and the plate is solidly bedded onto the fluid concrete – see Figure 8.17. The locations of the holding-down bolts should be specified so as not to interfere with the rafters and joists. This method of fixing the roof structure to the walls dispenses with the need for the holding-down straps used in masonry construction.

Figure 8.17
Typical wall/roof detail.



Restraint straps will be required for the roof gable structure but, unlike floor restraints, the gable restraints are best cast in during the concreting of the supporting wall. If not, retro-fitting will be necessary. This is quicker and more practical than post-installation of strapping.

Depending on the roof type, a variation of the wall plate holding down detail can also be used for the gable restraint.

8.6 Wall junctions

External wall junctions, and internal junctions where the ICF wall construction is required to be maintained, are all easily accommodated with any ICF system, and are not discussed further.

Junctions with existing non-ICF walls are easily achieved. ICF formwork can readily be scribed to closely butt-up to an existing wall, any gaps being filled with expanding foam. Structural continuity is achieved by fixing conventional masonry ties to the existing wall and casting in with the ICF pour.

Internal non-ICF walls must be secured directly to the concrete core, which entails casting in ties when concreting and then stripping away that part of the formwork abutting the internal wall once the concrete has cured. Alternatively, timber studs or masonry ties may be post-fixed as required.

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Appendix A. Detailed design of plain ICF to Eurocode 2

The design of plain concrete structures is covered by Section 12 of Eurocode 2[A1], which also applies to situations where the reinforcement provided is less than the minimum required for reinforced concrete. This chapter examines this with respect to the design of plain ICF construction.

A1 Reinforcement requirements

Eurocode 2 clause 12.1(4) does not give any specific values for reinforcement in plain walls and simply says members using plain concrete do not preclude the provision of steel reinforcement needed to satisfy serviceability and/or durability requirements nor reinforcement in certain parts of the members. It continues by saying that this reinforcement may be taken into account for the verification of local ultimate limit states as well as for checks of the serviceability limit states.

It is considered that the comments given within the BS 8110 design section with respect to the matter of reinforcement to control cracking (see Section 4.2.9) may equally be applied to a design to Eurocode 2.

A2 Compressive strength and design factors

The characteristic compressive strength used for Eurocode 2 designs is based on the cylinder strength rather than cube strength used for BS 8110. This means that equations between the two codes cannot be directly compared but similar results will be obtained. While Eurocode 2 tends to produce more economic designs than BS 8110, in some instances this is not necessarily the case with plain walls.

Eurocode 2 is in line with BS 8110 in that it indicates that due to the less-ductile properties of plain concrete, lower design factors should be used. Eurocode 2 utilises specific subscripts to define different elements/factors of design. For example, α_{cc} is the factor used in the equations for the design compressive strength of reinforced concrete and amends to $\alpha_{cc,pi}$ for plain concrete. Eurocode 2 indicates that α_{cc} should lie between 0.8 and 1.0 (1.0 is the recommended value), and for $\alpha_{cc,pi}$ a value of 0.8 is recommended *but* the value to be used in each country is set by its National Annex.

The UK National Annex sets α_{cc} as 0.85 for compression in flexure and axial loading and 1.0 for other situations and $\alpha_{cc,pl}$ is given a value of 0.6. Now the partial safety factor for materials for ultimate limit state γ_c is 1.5 for persistent and transient design situations.

Allowing for the change in the a_{cc} to $a_{cc,pl}$ for plain concrete gives an effective partial safety for materials for plain concrete of:

$$\frac{1.5}{0.6} = 2.5$$

Which is somewhat greater than the value of 2.25 used in BS 8110 (see Appendix B).

A3 Tensile strength

When tensile stresses are considered for the design resistance of plain concrete members, the stress strain diagrams may be extended up to the design tensile strength using the expression given in 3.16 of Eurocode 2 or a linear relationship.

The tensile strength f_{ctd} is given by the expression:

Eurocode 2 12.1

$$f_{ctd} = \frac{a_{ct,pl} f_{ctk,0.5}}{\gamma_c}$$

where f_{ctk} is the characteristic tensile strength, which may be taken from Table 3.1 in Eurocode 2 or from the following given expression:

$f_{ctk,0.05} = 0.7 \times f_{ctm}$ 5% fractile

Where $f_{ctm} = 0.3 \times f_{ck}{}^{(2/3)} \leq C50/60$

Combining these together for the normal range of concrete ≤ C50/60:

$$f_{ctk,0.05} = 0.7 \times 0.3 \times f_{ck}{}^{(2/3)} = 0.21 \times f_{ck}{}^{(2/3)}$$

and for a 20/25 grade concrete:

$$f_{ctk} = 0.21 \times 20^{(2/3)} = 1.547\text{N/mm}^2$$

The recommended value of $a_{ct,pl}$ is 0.8, but this is reduced to 0.6 in the UK National Annex.

Thus the UK design tensile strength is obtained from:

$$f_{ctk} = \frac{0.6 \times 0.21 \times f_{ck}{}^{(2/3)}}{1.5} = 0.084 \times f_{ck}{}^{(2/3)}$$

and for a 20/25 grade concrete:

$$f_{ctd} = 0.084 \times 20^{(2/3)} = 0.62\text{N/mm}^2$$

The small benefit of using the above expressions is shown by the values given in Table A1 which may be compared with those derived from Eurocode 2 Table 3.1 which, for example, results in a value of:

$0.6 \times f_{ctk}/\gamma_c = 0.6 \times 1.5/1.5 = 0.6$ for strength class 20/25.

Table A1
Tensile strength of plain concrete (N/mm^2).

1.0	12/15	16/20	20/25	25/30	30/37	35/45	40/45	45/50	50/60
f_{ctd}	0.44	0.53	0.62	0.72	0.81	0.90	0.98	1.06	1.14

The above relates to members subject to axial tension, and the design tensile strength for members in flexure may be take as:

f_{ctd} or $(1.6 - h/1000)\, f_{ctd}$, whichever is the lesser

The second expression reduces the flexural tensile strength for members exceeding 1.6m in depth, which allows the value of f_{ctd} (Table A1) to be used when assessing the lateral resistance of an ICF wall (see Section 4.2), as the depth will be typically only 140–300mm.

A4 Structural stability

The design axial resistance N_{Rd} of a rectangular cross-section with a uniaxial eccentricity, e, in the direction of h_w may be taken as:

Eurocode 2 12.2

$$N_{Rd} = \eta f_{cd} \times b \times h_w \times \left(1 - \frac{2e}{h_w}\right)$$

Where:

ηf_{cd} is the design effective compressive strength (Eurocode 2 3.1.7(3)).

b is the overall width of the cross-section.

h_w is the overall depth of the cross-section.

e is the eccentricity of N_{Ed} in the direction h_w.

Now, as given above for plain concrete $f_{cd} = \alpha_{cc.pl} f_{ck}/\gamma_c$
Thus:

$$N_{Rd} = \frac{\alpha_{cc.pl}}{\gamma_c} \times b \times h_w \left(1 - \frac{2e}{h_w}\right) \times f_{ck}$$

$$= \frac{\alpha_{cc.pl}}{\gamma_c} \times b \times (h_w - 2e) \times f_{ck}$$

$$= \frac{0.6}{1.5} \times b \times (h_w - 2e) \times f_{ck}$$

$$= 0.4\, b\, (h_w - 2e)\, f_{ck}$$

The cylinder strength is typically taken as 0.8 of the cube strength and thus, in terms of the cube strength, with b taken as unity:

$$\begin{aligned} N_{Rd} &= 0.4 \times 0.8\ (h_w - 2e)\ f_{ck,\,cube} \\ &= 0.32\ (h_w - 2e)\ f_{ck,\,cube} \end{aligned}$$

Which shows that Eurocode 2 is approximately equal to that given by BS 8110 for a stocky braced wall ($n_w \leq 0.3\ (\mathrm{h} - 2\mathrm{e}_x)\ f_{cu}$, BS 8110, equation (43)). See also Section B6.1.

A5 Slender wall

Eurocode 2 12.8

Eurocode 2 gives the slenderness of a column or wall as:

1 $\lambda = l_o/i$

Where:

i is the minimum radius of gyration

l_o is the effective length of the member, which can be assumed to be:

Eurocode 2 12.9

$l_o = \beta \times l_w$

and where:

l_w is the clear height of the member.

β is a coefficient, which depends on the support conditions:

- for columns $\beta = 1$ should in general be assumed
- for cantilever columns or walls $\beta = 2$;
- for other walls β values are obtained from Eurocode 2 (Table 12.1).

Which gives for walls supported on three edges:

$$\beta = \frac{1}{1 + \left(\frac{l_w}{3b}\right)^2}$$

And for wall supported on four edges:

$$\beta = \frac{1}{1 + \left(\frac{l_w}{b}\right)^2} \quad \text{when } b \geq l_w \text{, and } \beta = \frac{b}{2\,l_w} \quad \text{when } b < l_w$$

The above equations can give a range for β from 0.2 to 1.0 and offer notable benefits. It is likely that most ICF design, particularly for housing, would use β = 1.0 since this will still provide more than adequate strength, and wall strength is not affected if one or more of the edge restraints are removed (either during the design stage or subsequently), e.g. the introduction of a window or door.

In addition to the above:

2. The β - values should be increased appropriately if the transverse bearing capacity is affected by chases or recesses.
3. A transverse wall may be considered as a bracing wall if:
   - Its total length is not less than $0.5h_w$ where h_w is the overall depth of the braced wall.
   - It has the same height as l_w as the braced wall under consideration.
   - Its length as l_{nt} is at least equal to $l_w/5$, where l_w is the clear height of the braced wall.
4. In the case of a wall connected along the top and bottom in a flexurally rigid manner by in-situ concrete and reinforcement, so that the edge moments can be fully resisted, the values given for β may be factored by 0.85.

Note: This is not quite the same wording as BS 8110, which takes in-situ or precast floors as enhancing slenderness by 0.75 and has no specific requirement for reinforcement. Thus it currently cannot be assumed that the use of precast floors will enable 0.85 to be used when designing to Eurocode 2. However, the requirement for reinforcement in (4) is questionable since no matter how much reinforcement is used the resistance to edge moments can never be greater than the cracking moment or forces on a plain wall.

5. The slenderness of walls in plain concrete cast in situ should generally not exceed $\lambda = 86$ (i.e. $l_o/h_w = 25$) (note: 30 for BS 8110).

A6 Simplified design method for walls and columns

Eurocode 2 12.10

In the absence of a more rigorous approach, the design resistance in terms of axial force for a slender wall in plain concrete may be calculated from:

$$N_{Rd} = b \text{ x } h_w \text{ x } f_{cd} \text{ x } \Phi$$

Where:

N_{Rd} is the axial resistance.

b is the overall width of the cross-section.

h_w is the overall depth of the cross-section.

Φ is the factor taking into account eccentricity, including second-order effects and normal effects of creep.

f_{cd} is the design value of concrete compressive strength.

Note: the minimum thickness for a plain wall should not be smaller than 120mm.

For braced members (walls or column), the factor Φ may be taken as:

Eurocode 2 12.11

$$\Phi = \left(1.14 \text{ x } \left(1 - \frac{2e_{tot}}{h_w} \right) - 0.02 \text{ x } \frac{l_o}{h_w} \right) \leq \left(1 - \frac{2e_{tot}}{h_w} \right)$$

where $e_{tot} = e_o + e_i$ and where:

e_o is the first-order eccentricity including, where relevant, the effects of floors (e.g. possible clamping moments transmitted to the wall from a slab) and horizontal actions.

e_i is the additional eccentricity covering the effects of geometric imperfections, which for a braced member may be taken as:

$$e_i = \frac{l_e}{400}$$

Using the simplification for e_i then Φ may be determined from:

$$\Phi = 1.14 \times \left(1 - 0.0225\frac{l_o}{h_w} - 2\frac{e_o}{h_w}\right) \le \left(1 - 0.005\frac{l_o}{h_w} - 2\frac{e_o}{h_w}\right)$$

which is used to give the values in Table A2 below (limited for practical reasons to $l_o/h_w \geq 15$).

Table A2

Eurocode 2 design eccentricity factors Φ.

l_o/h_w	Eccentricity at top of wall, e_o/h_w						
	0	**0.05**	**0.1**	**0.15**	**0.2**	**0.25**	**0.3**
10	0.88	0.77	0.66	0.54	0.43	0.31	0.20
11	0.86	0.74	0.63	0.52	0.40	0.29	0.17
12	0.83	0.72	0.60	0.49	0.38	0.26	0.15
13	0.81	0.69	0.58	0.46	0.35	0.24	0.12
14	0.78	0.67	0.55	0.44	0.32	0.21	0.10
15	0.76	0.64	0.53	0.41	0.30	0.19	0.07
16	0.73	0.62	0.50	0.39	0.27	0.16	0.05
17	0.70	0.59	0.48	0.36	0.25	0.13	0.02
18	0.68	0.56	0.45	0.34	0.22	0.11	–
19	0.65	0.54	0.42	0.31	0.20	0.08	–
20	0.63	0.51	0.40	0.29	0.17	0.06	–
21	0.60	0.49	0.37	0.26	0.15	0.03	–
22	0.58	0.46	0.35	0.23	0.12	0.01	–
23	0.55	0.44	0.32	0.21	0.09	–	–
24	0.52	0.41	0.30	0.18	0.07	–	–
25	0.50	0.38	0.27	0.16	0.04	–	–

Note

Values of Φ for l_o/h_w below 10 may be determined but will seldom be required.

Taking a wall thickness of 140mm, a storey height 2.80, and concrete floors providing lateral support and resistance to rotation will enable a comparison to be made with the example used for BS 8110 later.

In this situation, the coefficient β for support conditions may be factored by 0.85. However, it should be noted that, unlike BS 8110, Eurocode 2 stipulates the use of reinforcement from the floor into the wall in order carry the restraint moment.

Assuming resistance to rotation:

Then $l_0 = 2{,}800 \times 0.85$ and $\frac{l_o}{h_w} = \frac{280 \times 0.85}{140} = 17$

Then, using Table A2, the capacity factor $\Phi = 0.70$

As given above, $N_{Rd} = 0.4 \times b \times h_w \times f_{cd} \times \Phi$

Then design load capacity for a 20/25 concrete is:

$0.4 \times 1000 \times 140 \times 20 \times 0.70 \times 10^{-3} = 784$kN/m

This is slightly lower than that derived for a the same wall designed to BS 8110 which gave 945kN/m (see Section B6.2).

With a timber floor or concrete floor providing lateral resistance but not resistance to rotation:

$l_0 = 2{,}800$ and $\frac{l_0}{h_w} = \frac{2800}{140} = 20$ giving a capacity factor of 0.63 (see Table A2).

This gives a design load capacity of:

$0.4 \times 1000 \times 140 \times 20 \times 0.63 \times 10^{-3} = 706$kN/m

This is slightly better than BS 8110 (651kN/m), but BS 8110 assumes a minimum eccentricity of 0.05t whereas Eurocode 2 appears to have no minimum for eccentricity e_o.

A7 Laterally loaded walls

There will be some situations where ICF walls will be subjected to predominately lateral loads (wind loads). This might occur in a tall single-storey structure, a cantilever feature or, for example, if used as an infill wall to a frame.

In this situation, consideration can be given to it being designed as a laterally loaded panel using elastic or yield line analysis. Eurocode 2 does not give a direct method, but analysis of laterally loaded walls is covered in detail in BS 5628. Although BS 5628 is not directly applicable for ICF, as indicated in Chapter 3, the method of analysis using a yield line is a recognised method for reinforced concrete floors, where attainment of moment along a yield line can occur. This is not the case for an un-reinforced panel, but use of yield-line analysis has been shown to be an appropriate method for masonry walls and, as a concrete wall will be generally more predictable, it would seem valid to use the same approach for an un-reinforced and ICF panels and, indeed, more so where it is reinforced.

BS 5628 gives bending moment coefficients for various configurations of wall panels with three- or four-side support of pinned or fixed edges. The coefficients related to an orthogonal ration $\mu = 1.0$ would be appropriate for a plain concrete ICF wall. Account could also be taken of the change in orthogonal ratio due to the self-weight or additional vertical load. This method of analysis is given considerable coverage in *The Concrete Masonry Designers' Handbook*[A2], which also contains the full yield-line equations to enable further variations to be made, the effect of openings, and comment on vertically spanning walls.

In essence, the flexural tensile strength obtained in Section A3 above could be used with the coefficients given in BS 5628 or reference 2 ($\mu = 1.0$, or as modified by wall loads) to analyse an ICF wall taken as spanning either vertically or in two directions as the structure supports dictate.

This method would be appropriate for ICF systems with continuous concrete section in both directions (e.g. Figures 2.2–2.4).

Insulation cavity bridged systems (Figure 2.1) do not readily fit this method of analysis and instead would normally be assessed as vertically spanning column sections. The effect of these bridges will be to reduced vertical and lateral capacity in the region of 30% compared with continuous core systems (e.g. those containing thin plastic or steel ties). This may require the use of reinforcement (Chapter 5) to enhance strength, which can be difficult, and a change to the use of an ICF that has a continuous inner core can regain the loss in strength, thus reducing or possibly eliminating the need for reinforcement bars or steel fibres.

Eurocode 2 indicates walls of plain concrete cast in situ should generally not exceed $\lambda = 86$ (i.e. $l_o/h_w = 25$). However, this is intended for vertically loaded walls and the 'generally' might allow some relaxation where the wall is predominantly laterally loaded, as permitted in other codes[A3, A4].

Even limiting the slenderness ratio to 25 will still enable considerable lateral strength to be obtained and, indeed, the use of flexural tensile strength is used to determine the sizing of plain basement retaining walls in the pending addendum[A5] to *Approved Document – Basements for Dwellings*[A6].

An example of lateral capacity of a vertical spanning wall can be considered as follows:

The flexural tensile strength f_{ctd} for a C20/25 concrete is 0.62N/mm^2 (see Section A3).
The bending moment coefficient for a simple span is 0.125.
Taking a 140mm wall, height 3.5m (i.e. $l_o/h_w = 3{,}500/140 = 25$).

$$\text{Thus the moment capacity} = \frac{f_{ctd} \times b \times h_w^2}{6 \times 10^6} = \frac{0.62 \times 1000 \times 140^2}{6 \times 10^6} = 2.02\text{kN/m}$$

The applied moment = $W_f \times \gamma_f \times \alpha \times h_w^2 = W_f \times 1.4 \times 0.125 \times 3.5^2$

From which $W_f = \dfrac{2.02}{1.4 \times 0.125 \times 3.5^2} = 0.94\text{kN/m}^2$

This would typically be sufficient for housing and small low-rise buildings within the UK.

Adopting a slenderness factor of 40 (see BS 5628) for the same wall thickness would extend the height (l_o) to 5.6m and still results in $W_f = 0.42\text{kN/m}^2$. Clearly such a panel will have somewhat reduced vertical capacity but it serves to show that walls can be designed to be adequate without recourse to reinforcement, when care is taken of the form of ICF used.

Panels designed with three or four edges for support will enable use of lower bending moment coefficients for two-way span[A3, A4]. This may, depending on wall dimensions, require the use of some horizontal reinforcement to control shrinkage and enable two-way span to be maintained. The walls will typically be free to move vertically (no restraint).

A7.1 Lateral plus vertical loads

Reference A2 also provides design guidance on walls carrying both lateral and vertical loads, which vary depending on the ratio of vertical to lateral load.

The effect of a lateral load acting at the same time as a vertical load will be to effectively increase the total eccentricity on the wall. Eurocode 2 does not give an equation for determining the eccentricity due to a lateral load on plain walls but consideration may be given to that given in Reference A2, which uses a value of:

$$e_a = \frac{q l_o^2}{16N}$$

Where:

q is the lateral load.

l_o is the height.

N is the vertical load.

This may be added to the other eccentricities so that $e_{tot} = e_o + e_i + e_a$. This value of e_{tot} may then be input into expression Eurocode 2 12.11 (see Section A6) to derive a modified value of Φ.

The vertical load is often ignored or may be used to modify the orthogonal ratio for a panel spanning in two directions, as indicated in Section A7.

A8 Bearings

The design stress under bearings (e.g. from beam bearings) on a plain ICF wall should not exceed $0.4f_{cd}$ ($= 0.23f_{ck}$), for dry conditions, which is significantly less than BS 8110 (which is $0.5f_{cu}$) Eurocode 2 gives enhancement for situations where the concrete is confined by use of reinforcement (see Section 3.1.9, Eurocode 2) but this will seldom occur with ICF walls.

A9 Design load capacity

The calculation of the design load of a plain ICF wall may follow that for a plain wall to Eurocode 2. This does appear to give guidance on the design load capacity assessed on the distribution of load along the length of the wall, but use of linear distribution would equate with BS 8110. Eurocode 2 does not specifically indicate whether flexural strength should be used where loads are distributed along a wall but formula for design tensile strength is given (Eurocode 2 3.1.6) and commented on above.

The maximum unit axial load is affected by the slenderness of the wall, and vertical eccentricities but, unlike BS 8110 or BS 5628, there is no which distinction between 'Stocky/Short' or 'Slender' walls. All are subject to first-order and second-order effects, although the latter may be neglected in certain conditions under a rigorous analysis and typically when using the simplified procedures.

It should again be noted that Eurocode 2 gives a minimum thickness for structural members of 120mm and this should also be applied to ICF construction.

A10 Unbraced walls

Eurocode 2 gives no simplified methods for the design of un-braced plain walls. This design could be assessed using a rigorous analysis, although it would be uncommon for a plain wall to be used in this mode, particularly in housing.

A11 Shear strength

Eurocode 2 12.6.3 states that: 'In plain concrete members account may be taken of the tensile strength of the concrete in the ultimate limit state for shear, provided that either by cal-culations or by experience brittle failure can be excluded and adequate resistance can be assured.'

As there is no reinforcement to provide ductility, then in essence a plain element will always have a brittle failure so some interpretation is required. A logical view would be to take 'brittle failure' as meaning an instability failure, for example vertical shear in a wall over an opening whereby failure would create a collapse situation (i.e. a plain beam). Whereas horizontal failure along the base of a wall might result in slip, then resistance due to load/aggregate interlock would occur but not total instability.

Eurocode 2 indicates that in plain concrete members it should be checked that:

Shear stress $\tau_{cp} = k\,\dfrac{V_{Ed}}{A_{cc}} \leq f_{cvd} = 1.5\,\dfrac{V_{Ed}}{A_{cc}} \leq f_{cvd}$ when adopting the value of τ from the National Annex.

Where:

A_{cc} is the cross-sectional area.

V_{Ed} is the shear force.

f_{cvd} is concrete design strength in shear and compression.

Which is dependent on the level of axial stress (see Table A3) obtained from:

$$f_{cvd} = (f_{ctd}{}^{2} + \sigma_{cp}\, f_{ctd})^{0.5} \qquad \text{when } \sigma_{cp} \leq \sigma_{c,\,lim}$$

or

$$f_{cvd} - [f_{ctd}{}^{2} + \sigma_{cp}\, f_{ctd} - 0.25\,(\sigma_{cp} - \sigma_{c,\,lim})^{2}]^{0.5} \qquad \text{when } \sigma_{cp} > \sigma_{c,\,lim}$$

Where:

σ_{cp} $= N_{Ed}/A_{cc}$ when N_{Ed} is the normal force

$\sigma_{c,\,lim}$ $= f_{cd} - 2\,(f_{ctd}\,(f_{ctd} + f_{cd}))^{0.5}$

Where:

f_{cd} is the concrete design strength in compressive.

f_{ctd} is the concrete design strength in tension (see Section 4.1.2).

Table A3

Shear strength f_{ctd} of plain concrete (N/mm^2).

Note

Further values may be obtained from the above equations.

σ_{cp} (N/mm^2)	Characteristic compressive strength f_{ck}								
	12	16	20	25	30	35	40	45	50
0.0	0.44	0.53	0.62	0.72	0.81	0.90	0.98	1.06	1.14
1.0	0.80	0.90	1.00	1,11	1.21	1.31	1.40	1.48	1.56
2.0	1.03	1.16	1.27	1.40	1.51	1.61	1.71	1,80	1.89
3.0	1.06	1.35	1.50	1.63	1.76	1.87	1.98	2.08	2.17
4.0	0.84	1.38	1.66	1.84	1.98	2.10	2.21	2.32	2.42

When reinforcement is introduced, for example at the base of a wall, then Eurocode 2 clause 6.2.2 could be applied, but with a check on the plain wall shear resistance where the reinforcement stops.

In this situation the design value for shear resistance $V_{Rd,\,c}$ is given by:

$$V_{Rd,\,c} = [\, C_{Rd,\,c}\, k\,(1000\,\rho_l\, f_{ck})^{1/3} + k_1\, \sigma_{cp}\,]\, b_w\, d$$

With a minimum value (taken to be the shear strength of plain concrete) of:

$$V_{Rd,\,c} = [\, v_{min} + k_1\, \sigma_{cp}\,]\, b_w\, d$$

$$C_{Rd,\,c} = 0.18/\gamma_c = 0.18/1.5 = 0.12$$

$$k = 1 + \sqrt{\frac{200}{d}} \leq 2.0 \text{ with } d \text{ in mm}$$

$$k_1 = 0.15$$

$$\rho_l = \frac{A_{sl}}{b_w d} \leq 0.02$$

$\sigma_{cp} = N_{Ed}/A_c < 0.2\ f_{cd}$ [N/mm²]

$v_{min} = 0.035k^{1.5}\ f_{ck}^{\ 0.5}$

Where:

f_{ck} is in N/mm²

A_{sl} is the area of the tensile reinforcement, which extends $\geq (l_{bd} + d)$ beyond the section considered (see Figure 6.3 in Eurocode 2)

b_w is the smallest width of the cross section in the tensile area [mm]

d is the effective depth [mm]

N_{Ed} is the axial force in the cross section due to loading or prestress [N] ($N_{Ed} > 0$ for compression). The influence of imposed deformations on N_E may be ignored

A_c is the area of concrete cross section [mm]

$V_{Rd,c}$ is [N]

Note: The values for $C_{Rd,c}$, v_{min} and k_1 given above are those set by the UK National Annex.

A12 Deflection

Again Eurocode 2 does not specifically deal with the deflection of plain walls but, again, it may be reasonable to follow the guidance given in BS 8110 that deflections should be within acceptable limits if the simplified design process is followed. BS 8110 also indicates that this should be so for shear walls where the total height does not exceed ten-times the length of the wall.

A13 ICF-specific design matters

The above design guidance can be applied to all ICF systems that have a fully continuous and uniform cross-section typical with most normal strut tied block and panel systems (see Chapter 2). Where insulation tied block systems are used (Figure 2.1), then the section properties will be reduced. Because of the variations that can occur, it is not possible to give a detailed design procedure.

However, one approach with panels systems with a waffle grid profile (rectangular elliptical cross-section) would be to design on the basis of an equivalent rectangular section having the same moment of inertia.

Insulation tied block systems enabling continuous vertical columns could be designed as above but reducing the load capacity per metre length in proportion to the plan area of concrete carrying the load to that of the total plan area of the wall. However, in addition to structural design for vertical and other loads, it will be necessary to assess fire-resistance, sound insulation and other properties.

Appendix B. Detailed design of plain ICF to BS 8110

The design of plain concrete walls is covered by section 3.9 of BS 8110[B1], which may be applied to un-reinforced ICF construction. Such walls should be designed on the basis that the design ultimate force acting on it is calculated on the assumption that the beams and slabs (floors) transmitting forces into it are simply supported. The sub-clauses to this section of the standard are considered in detail in the following Appendix B subsections:

B1 Structural stability

The stability of structures built with ICF construction employing plain concrete walls should meet the provisions of clause 3.9.2 of BS 8110. This indicates that the elements of construction providing lateral stability to the structure as a whole need not, in any direction, be designed to support the defined forces of clause 3.9.2.3 in addition to the other loads and forces. The defined forces are the simple static horizontal forces acting at the point of lateral support (e.g. wind forces) or 2.5% of the design ultimate vertical load at the point of lateral support.

ICF plain walls, as with conventional plain walls, should not depend on unbraced walls alone. This is seldom an issue, as most structures will have walls in two directions with floors capable of re-transmitting forces to other bracing walls. Following on from this, a 'braced wall' is defined as a wall where the reactions to lateral forces are provided by lateral supports (e.g. appropriate floors). The wall is defined as 'unbraced' when it provides its own stability. Housing, typically, will have walls in both directions to provided stability and robustness, which is also a requirement of the simple rules to the building regulations, and in most constructions the walls will be designed as braced. The strength of a wall will be influenced by whether it is braced or unbraced and other factors as given below.

B2 Partial safety factors

BS 8110 does not directly indicate in its section on design strengths (clause 2.4.4.1) any difference in the partial material factors between reinforced and plain concrete. It just indicates that concrete in flexure or axial load γ_m should be taken as 1.5. However, in the design equations for plain concrete, as given later in this appendix, the stress block on the concrete is taken as $0.3f_{cu}$, and this corresponds to a γ_m partial safety factor of 2.25 (1.5 x 0.45/0.3 = 2.25), instead of 1.5 used for reinforced design.

The reasoning behind the higher safety factor for plain concrete is that, in the case of reinforced concrete, both steel and concrete have to reach their design strength to precipitate failure, whereas with plain concrete only the one material needs to reach its design strength. This has a higher probability of occurring and, hence, logically, plain concrete requires a greater safety factor.

It is expected that most ICF construction will be carried out by specialist contractors employing appropriate specifications, control and supervision to enable a γ_m of 2.25 to be adopted for design. If this is not the case then it may be prudent to allow for other factors with ICF construction than for normal plain concrete cast with removable formwork..

B3 Effective height and slenderness

The effective height of an ICF wall should be taken as defined in BS 8110, clauses 3.9.4.2 or 3.9.4.3. In most cases such walls will be effectively braced and thus the effective height l_e will be either 0.75 times the clear distance between lateral supports where the floors provide both rotation and lateral support; or 1.0 times the clear distance between the centres of lateral support where only lateral support is provided. In other cases, for example walls with a free edge, other provisions prevail, as detailed in BS 8110.

The resistance to rotation of lateral supports is defined in clause 3.9.2.4, which equally applies to ICF walls. There is an unfortunate difference between BS 8110 and BS 5628[B2] in what constitutes a floor capable of providing both resistance to rotation and lateral support. BS 8110 indicates concrete, whereas BS 5628 allows timber floors to provide enhanced support. This might be due to either BS8110 assuming that concrete is the most likely floors material when designing to this code, or that the allowable loads that are permitted with respect to BS 8110 designs are typically far in excess of that permitted by BS 5628. This is not quite correct as it is possible to design masonry to carry very heavy loads but, for such loads to be generated, it is likely that concrete floors would occur in any case. So, although there is a departure on this matter between the two codes, they may in a practical sense meet together as loads increase.

This is a debatable matter and, in the end, this will be the decision by the engineer, but this guide follows the wording in BS 8110 to which this chapter relates. This will not be an issue in most cases since there will typically be more than adequate strength in ICF construction so designed.

The slenderness ratio l_e/h of an ICF wall should not exceed 30 (note: 25 when using Eurocode 2), as with other plain walls. In this expression, h is the wall thickness. When, in a braced wall, the effective height divided by the thickness (l_e/h) is equal or less than 15, the wall is defined as 'stocky'. In the case of an unbraced wall, it is defined as 'stocky' at a lower value of l_e/h of 10. Above these values, they are defined as 'slender'.

The minimum concrete thickness of ICF systems is 100mm, but the minimum thickness for load-bearing walls will typically be 140mm (often 150mm for fire-resistance) and the typical clear storey height in housing is 2.325m. When using concrete floors and assuming a braced wall, this gives a slenderness ratio l_e/h = 2,350 x 0.75 / 140 = 12.59, and thus, by definition, stocky. When used with timber floors, ratio l_e/h = 2,350 x 1.0 / 140 = 16.79, which by definition is slender. Although storey height can vary, it will typically not change significantly in housing, which means that most walls will be or tend towards stocky, enabling significant loads to be carried.

B4 Design eccentricities

The eccentricities as given in BS 8110 for plain concrete walls may be applied to plain ICF walls. For single walls, this means in-plane forces may be calculated by statics alone (3.9.4.6). For two or more walls, the in-plane forces should be shared in proportion to their relative stiffness, unless the resulting eccentricity in a particular wall is greater than one-third of its length, in which case its stiffness should be considered as zero, and the forces should then be proportionally distributed into the remaining walls (3.9.4.7).

Loads from floors may be assumed to act at one-third of the depth of bearing. BS 8110 does not specifically cover the case of floors supported on joist hangers (or ledgers in the case of ICF walls), but a value of 25mm from the face of the wall would equate with that given in BS 5628. In the case of a continuous in-situ floor on either side of the wall, the common bearing area may be assumed to be shared equally on each floor. Reference should be made to BS 8110 clause 3.9.4.11 in the case of unbraced walls, but these will seldom be used with ICF and house construction.

BS 8110 aligns with BS 5628 in that, at any level, the transverse eccentricity in a braced wall with respect to the wall's axial load may be calculated on the assumption that immediately above a lateral support the resultant eccentricity of all vertical loads above that is zero. In simple terms this means any eccentricity in a braced wall (e.g. at its top) is assumed to be axial at its base. Figure 4.1 shows the position of vertical forces acting at the top of a wall, which is followed by an equation for determining the resultant eccentricity at the top of the wall.

B5 Concentrated loads

The design stress under local concentrated loads (e.g. from beam bearings) on a plain ICF wall should not exceed $0.5f_{cu}$, or $0.6f_{cu}$ for concrete C20/25 or above.

B6 Design load capacity

The calculation of the design load of a plain ICF wall may follow that for a plain wall to BS 8110. This indicates that the design load per unit length should be assessed on the basis of a linear distribution of load along the length of the wall, with no allowance for any tensile strength.

The maximum unit axial load is affected by the slenderness of the wall, and which is used to define the wall as 'stocky' or 'slender' as defined above (effective height and slenderness).

B6.1 Stocky braced wall

The maximum design ultimate axial load per unit length due to ultimate loads, n_w for a stocky braced plain wall (BS 8110, clause 3.9.4.15) should satisfy the following:

$$n_w \leq 0.3\ (h - 2e_x)\ f_{cu}$$

Where:

e_x is the resultant eccentricity of load at right angles to top the of the wall (with a minimum value of $h/20$)

B6.2 Slender braced wall

The maximum design ultimate axial load n_w for a slender braced plain wall (BS 8110, clause 3.9.4.16) should satisfy the above and the following:

$$n_w \leq 0.3\ (h - 1.2e_x - 2e_a)\ f_{cu}$$

as well as $n_w \leq 0.3\ (h - 2e_x)\ f_{cu}$

Where:

e_x is as defined above.

e_a is the additional eccentricity due to deflections which may be taken as $l_e^{\,2}/2{,}500h$.

which may be re-written as:

$$e_a = \left(\frac{l_e}{h}\right)^2 \div 2500 \text{ x } h$$

The benefit is that it then enables tables to be produced that are independent of the actual effective height of the wall.

Table B1 gives factors derived from the above equations (for the purpose of this design guide it is given the symbol Φ), which when multiplied by 0.3, the wall thickness h and the characteristic compressive strength f_{cu}, give the design load capacity per metre length of a wall.

Table B1
BS 8110 design eccentricity factors.

l_e/h	**Eccentricity at top of wall, e_x/h**					
	≤0.05	**0.1**	**0.15**	**0.2**	**0.2**	**0.3**
≤15	0.90	0.80	0.70	0.60	0.50	0.40
16	0.74	0.68	0.62	0.56	0.50	0.40
17	0.71	0.65	0.59	0.53	0.47	0.41
18	0.68	0.62	0.56	0.50	0.44	0.38
19	0.65	0.59	0.53	0.47	0.41	0.35
20	0.62	0.56	0.50	0.44	0.38	0.32
21	0.59	0.53	0.47	0.41	0.35	0.29
22	0.55	0.49	0.43	0.37	0.31	0.25
23	0.52	0.46	0.40	0.34	0.28	0.22
24	0.48	0.42	0.36	0.30	0.24	0.18
25	0.44	0.38	0.32	0.26	0.20	0.14
26	0.40	0.34	0.28	0.22	0.16	0.10
27	0.36	0.30	0.24	0.18	0.12	0.06
28	0.31	0.25	0.19	0.13	0.07	0.01
29	0.27	0.21	0.15	0.09	0.03	–
30	0.22	0.16	0.10	0.04	–	–

Note
Φ is used for the purpose of this guide and is not a BS 8110 symbol.

Taking an example using Table A4 and assuming a C20/25 concrete gives an axial design load capacity for a 140mm ICF stocky wall of:

0.3 x 0.9 x 140 x 25 = 945kN/m (assuming an eccentricity of 0.05h).

This would apply to a wall supporting concrete floors (floors providing resistance to rotation and lateral support) of 15 x 0.14/0.75 = 2.8m high or a wall with timber floors 15 x 0.14/1.0 = 2.10m high.

A wall 2.80m high with timber floors would have a slenderness ratio of 2,800/140 = 20 and its capacity would be:

0.3 x 0.620 x 140 x 25 = 651kN/m

This is greater than a 140mm masonry internal wall built with 7.3N/mm^2 blocks (144kN/m) in a two-storey building. But note: BS 5628 allows timber floors to provide enhanced resistance to lateral movement in this instance, whereas a modification factor of 1.0 is applied in the case of the plain wall.

This is also clearly greater than a 190mm masonry wall built with 7N/mm^2 blocks (capacity = 179kN/m), and also a 290mm wall with the same 7N/mm^2 (capacity = 505kN/m), which are the requirement for walls to both Approved Document A and BS 8103. This is used as the basis for the comments given in Chapter 4.

B6.3 Unbraced walls

The maximum design ultimate axial load n_w for an unbraced wall (BS 8110, clause 3.9.4.17) should satisfy:

$$n_w \leq 0.3\,(h - 2e_{x,1})\,f_{cu}$$

$$n_w \leq 0.3\,\{h - 2\,(e_{x,2} + e_a)\}\,f_{cu}$$

Where:

$e_{x,1}$ is the resultant eccentricity calculated at the top of the wall.

$e_{x,2}$ is the resultant eccentricity calculated at the bottom of the wall.

However, although an equation is given, it would be uncommon for a plain wall to be designed as unbraced, particularly in housing, and indeed it should not be used where it provides the sole means of stability for a building.

B6.4 Walls vertically and laterally loaded

BS 8110 does not directly cover the addition of lateral loads, but consideration can be given to the approach indicated under Eurocode 2 (see Section A7). In this case, a value of 2e_a would be added to the equation given in section B6.2.

B7 Predominantly laterally loaded walls

BS 8110 does not give a method for walls subject to lateral loads, but this is examined in section A7, which should equally be appropriate for designs generally to BS 8110. Comment on the necessary tensile strength is given in the following section.

B8 Tensile strength

BS 8110, unlike Eurocode 2, does not provide values for the development of tensile bending stresses in either plain or reinforced concrete. This is not an issue in the design of superstructures since the forces are predominantly vertical in nature. Lateral loads are limited to wind and these are generally small and seldom will be critical in ICF for housing and many other structures. However, tall gable or perimeter walls, for example to a single-storey warehouse development, might be dominated by lateral loads necessitating the development of tensile stresses, which BS 8110 does not permit or, rather, does not include for. Such elements may not possess sufficient self-weight to enable a three-pinned arch design, and in the absence of permitted flexural strength may require reinforcement. Although flexural tensile strength can be used in many situations, it should not be used where it is the only mechanism of failure and where the force exceeds the self-weight resistance, as immediate collapse can occur in the event of tensile failure. A free-standing boundary wall is a classic example in this respect.

However, it is a different matter where tensile strength is used with, or associated with, other capacities and on more stocky construction. Indeed the development of flexural tensile stresses has been adopted for plain concrete propped basement retaining walls in the *Additions to Approved Document – Basements for Dwellings*. But, in this case, the walls, which are subjected to lateral loads from the soil creating flexure, also often carry substantial vertical loads from the superstructure. The walls in the addendum to the basement AD were designed to Eurocode 2, which does contain flexural strength values and thus overcomes the deficiency or limitation of a strict BS 8110 design.

Adopting an equivalent flexural strength for a BS 8110 design to produce the same wall thickness as would be achieved by a design to Eurocode 2 should be permitted, as the resulting walls would effectively be the same. If one is acceptable, then, under the building regulations, so is the other.

B9 Shear strength

The shear strength of plain ICF walls may be taken as that for a normal plain wall and, in accordance with BS 8110, the shear strength need not be checked if either:

- The horizontal shear force is less than one-quarter of the design vertical load, or
- The horizontal design shear force produces an average stress of not more than 0.45N/mm^2 over the whole-wall cross-section. A value of 0.30N/mm^2 applies if the strength is lower than strength class C20/25 or is of lightweight concrete.

Shear strength will seldom be a problem in most ICF constructions.

B10 Deflection

The deflection of ICF walls as with normal plain walls in accordance with BS 8110 should be within acceptable limits if the proceeding design process is followed, and this should also be the case for shear walls where the total height does not exceed ten-times the length of the wall.

B11 Effect of use of EPS bridged ICF blocks

The above design guidance can be applied to all ICF systems that have a fully continuous and uniform cross-section typical with most normal strut tied block and panel systems (see Chapter 2). Where insulation tied block systems are used (Figure 2.1) then the section properties will be reduced. Because of the infinite variations that can occur, it is not possible to give a detailed design procedure.

Insulation tied block systems enabling continuous vertical columns could be designed as above, but reducing the load capacity per metre length in proportion to the plan area of concrete carrying the load to that of the total plan area of the wall. The effect of this will be to reduce capacity by up to around 25–30% (the reduction depending on the size of the bridged sections). The flexural lateral capacity of this type of block configuration will also be lower than continuous core systems, and this will be different in both vertical and horizontal directions (typically a loss of 25% vertically and 50% horizontally). In addition to structural design for vertical and other loads, it will be necessary to assess fire-resistance, sound insulation and other properties.

Although the EPS bridged blocks will typically show a reduced structural capacity, they are still likely to provide sufficient capacity for many housing projects and some other some larger-walled, lightly loaded projects. And, in any case, the manufacturers will be able to supply continuous cored systems where the insulation bridged systems are deemed insufficient.

B12 Reinforcement for control of movements

The design of plain concrete walls is covered by clause 3.4.9 and its sub-clauses of BS 8110.

Clause 3.9.4.19 indicates that reinforcement may be needed in walls to control cracking due to flexure or thermal and hydration shrinkage. This clause indicates further guidance in subsequent clauses and continues that, wherever provided, the quantity of reinforcement should be in each direction at least:

- 0.25% of the concrete cross-sectional area for steel grade 500.
- 0.30% of the concrete cross-sectional area for steel grade 250.

However, it is important to note that BS 8110 does not say that reinforcement must be provided, but only that it needs to be considered to control the effects of stress and movements within the concrete. The following review of subsequent BS 8110 clauses concludes that the text within BS 8110 is not specifically appropriate to ICF construction.

BS 8110 clause 3.9.4.20 deals with 'anticrack' reinforcement in external plain walls. This indicates that, if necessary, in walls exceeding 2m in length and exposed to the weather, reinforcement should be provided in both horizontal and vertical directions. It also says that such reinforcement should consist of small diameter bars, relatively closely spaced, with adequate cover near the exposed surface.

It is again important to note that this is not a specific requirement as it is worded as 'if necessary' and relates to exposed walls.

The concrete surface of an external ICF wall is protected by an insulating layer, which protects the inner concrete from the extremes of weather and this virtually eliminates or significantly minimises temperature movement. The insulation will also have a beneficial effect on strength gain and this, together with the controlled environment, will reduce or elongate the effects of thermal shrinkage that would otherwise affect an exposed element as covered by clause 3.9.4.20. Therefore, it is considered that clause 3.9.4.20 is not specifically appropriate for ICF construction.

Clause 3.9.4.21 deals with 'anticrack' reinforcement in internal plain walls. This indicates that it may be sufficient to provide reinforcement only in that part of the wall where junctions with floors and beams occur. It also indicates that, when reinforcement is provided, it should be dispersed half near each face. Again it is important to note that this is a designer's decision and not a specific requirement. Furthermore, the text, by referring to the disposition of reinforcement near each face, is assuming an exposed wall element or it may be postulated where any subsequent finish might be materially affected.

It is again considered that clause 3.9.4.21 should not be specifically applied to ICF construction.

Clause 3.9.4.22 covers the use of reinforcement around openings in plain walls. This simply states that reinforcement should be considered and, therefore, does not impose a direct requirement for reinforcement. Again, in keeping with the previous clauses, this clause is assuming directly exposed walls or where such cracking might adversely affect perhaps finishes. It is considered that this clause need not be specifically applied to ICF construction. However, it is likely that reinforcement will be introduced to enable the provision of lintels and beams at windows and other openings, and that this will suffice to control integrity at such positions.

Clause 3.9.4.23 concerns itself with the reinforcement of plain walls for flexure. It indicates that if, at any level, a length of wall greater than one-tenth of the total length is subjected to tensile stresses, resulting from in-plane eccentricity of the force, vertical reinforcement to distribute potential cracking may be necessary. It continues by saying that such reinforcement needs to be provided only in the area of wall found to be in tension under the design service loads, and indicates that it should be arranged in two layers and conform to the spacing rules given in 3.12.11. The situation where this might occur is where a heavily loaded beam runs into the wall and the resulting eccentricity of such vertical load creates flexural tensile stresses in the wall. Should this condition arise in an ICF construction, then it would appear appropriate to introduce the requirements of this clause, but this is unlikely to occur much in housing due to the limited loads and spans.

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Design and Construction using Insulating Concrete Formwork

Insulating Concrete Formwork (ICF) is a popular method of construction in many countries. It is a simplistic method of concrete wall construction where the polystyrene 'formwork' is left in place to provide permanent insulation to the wall.

The guide covers ICF wall design to both BS 8110 and Eurocode 2 and demonstrates that in many cases ICF walls do not require main reinforcement.

The guide aims to provide a level of knowledge and confidence in the ICF system, covering specification and workmanship aspects. This guide is not intended for use in deciding the system to be used in a particular case, this decision should be based on information, specific to the particular site, provided by the building contractor.

Alan Tovey as Principal of *Tecnicom Ltd.* provides technical consultancy on concrete and masonry, and administrative and technical support to the Basement Information Centre. Alan has had a long association with the concrete industry and has authored numerous publications on concrete related topics.

John Roberts is Emeritus Professor of Civil Engineering at Kingston University and Principal of the Technical Innovation Consultancy. He has provided specialist consultancy to a number of concrete and masonry related organisations including the preparation of Approved Documents and Design Guides.

Michael Kilcommons is a civil engineer with a background in construction industry documentation and procedures. He provides a consultancy service covering construction and insurance project management, and the assessment of innovative building systems.

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Riverside House, 4 Meadows Business Park,
Station Approach, Blackwater, Camberley, Surrey, GU17 9AB
Tel: +44 (0)1276 606800   **Fax:** +44 (0)1276 606801
www.**concretecentre**.com