How to design concrete buildings to satisfy disproportionate collapse requirements

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Introduction

The collapse of Ronan Point in 1968 was a seminal event and resulted in fundamental changes to the design philosophy of building structures in the UK. The disaster highlighted the need for specific consideration of the stability of structures that have been damaged by accidents such as a gas explosion. It was considered that, while localised damage was unavoidable, complete collapse of structures had to be prevented. Thus, the concept of disproportionate collapse was born and structures had to be designed in such a way that they would not be damaged to an extent disproportionate to the initial effect of the accident.

Thus in 1976 the Building Regulations[1] were amended. Buildings of five storeys or more had to satisfy special additional requirements, which were aimed at providing increased robustness. More recently (2004) the Building Regulations for England and Wales[2] were amended again to bring **all** buildings within the scope of the disproportionate collapse requirements.

Approved Document A[3] (AD A) is published by the department for Communities and Local Government (CLG) and provides more detailed guidance on the interpretation of the Building Regulations.

This guide sets out the requirements of the AD A as they relate to buildings constructed with concrete, and includes some practical details to show how to comply with the requirements. Where there is existing, easily accessible guidance this has been referenced rather than being repeated here.

In principle the requirements for Scotland are similar; however, there are some variations and these differences are also explained within this guide.

Current requirements

The Building Regulations in England and Wales were revised in 2004 to make the requirements to avoid disproportionate collapse apply to all buildings. They state: "The building shall be constructed so that in the event of an accident the building will not suffer collapse to an extent disproportionate to the cause". The revised AD A uses a risk-based approach (also followed in Eurocode 1, Part 1–7[4]) to classify buildings according to their height and use. The method allows the risks associated with a building to be considered against the consequences of failure.

Classifying a building

In the AD A there are four building Classes: 1, 2A, 2B and 3. The building type and occupancies for each class are given in Table 1, together with a summary of the requirements of AD A.

At first sight the classification of the building into one of the building classes looks simple; however, further inspection reveals some complications. For instance, buildings with varying numbers of storeys, mixed-use buildings or buildings constructed with basements. To help with this, useful and clear guidance has been published by NHBC[5] with the support of the CLG; this is freely available on the website www.planningportal.gov.uk.

Typically, for a building with varying storey heights, which falls into more than one class, the most onerous class for robustness requirements should be adopted. However, if the building is large in plan area and divided into separate structures to allow for movement, then each structure may be classified separately. This may lead to a lower classification for some of the structures that make up the complete building.

In a mixed-use building the more onerous class should generally be adopted. Where the lower occupancy class is above a higher occupancy class then it may be possible to classify the upper storeys in the lower class. For example two storeys of apartments over one-storey retail premises exceeding 2000 m^2 would require Class 2B for the retail floor, but 2A for the apartments.

Basement storeys may be omitted from the total building storeys provided the basement storeys meet Class 2B or above. There is no further guidance in AD A on how to classify a basement but the NHBC technical guidance notes recommend that a floor must be 1.2 m below external ground level for at least 50% of the plan area of the building to qualify as a basement.

Class 1 buildings

Provided the building has been designed and constructed to the rules given in AD A and/or appropriate codes of practice and in line with general good practice, no additional measures are necessary.

Class 2A buildings

Class 2A buildings require horizontal ties in the floor plates. If dedicated horizontal ties are not provided then there must be 'effective anchorage' of the suspended floors to the walls. In terms of concrete elements, the use of the effective anchorage concept is used when concrete floors are supported on masonry walls, by reference to BS 5628[6].

Class 2A buildings do not require vertical ties.

Class 2B buildings

There are effectively three approaches:

1. Compliance with tying rules
2. Showing that the removal of a wall or column will cause only limited damage
3. Showing that key elements are 'non-removable'.

The simplest approach is to provide horizontal and vertical ties, using tie forces derived from the codes of practice. Alternatively, where ties are not provided, a check should be carried out to show that, upon notional removal of each supporting column and wall, and each beam supporting columns or walls (one at a time in each storey of the building) that the building remains stable. Further, the area of floor at any storey at risk of collapse should not exceed 15% of the floor area of that storey or 70 m^2, whichever is the smaller. The collapse should not extend further than the immediate adjacent storeys (see Figure 1).

Finally, where the removal of an element results in a collapse greater than permitted, then it should be designed as a key element. Further details on the design of key elements is given later in this guide.

Class 3 risk assessment

The Class 3 classification represents a departure from the previous requirements and requires that: "A systematic risk assessment of the building should be undertaken taking into account all normal hazards that may reasonably be foreseen, together with any abnormal hazards. Critical situations or design should be selected to reflect the conditions that can reasonably be foreseen as possible during the life of the building". Unfortunately, this guidance gives the designer little assistance and no references are provided. CLG has acknowledged that there is a paucity of information and is planning to publish more guidance.

Figure 1
Area at risk of collapse in the event of an accident

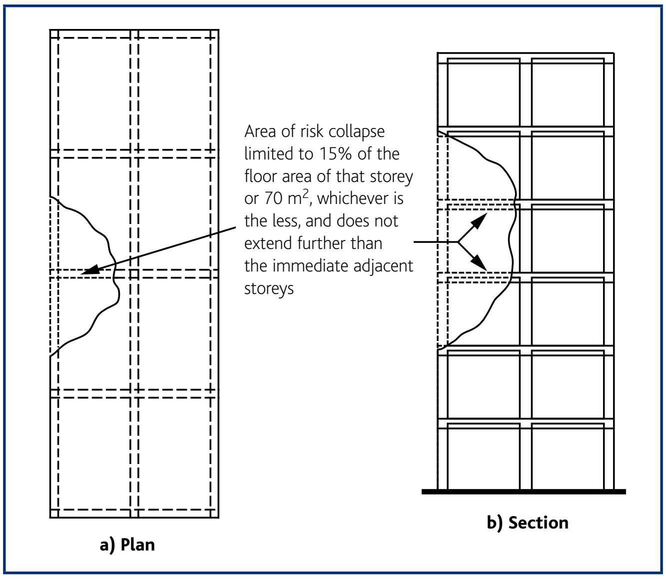


Table 1
Building classes and corresponding tying requirements

Class	Building type and occupancy	Summary requirements
1	• House not exceeding 4 storeys. • Agricultural buildings. • Buildings into which people rarely go.	• No additional measures are likely to be necessary.
2A	• 5 storey single-occupancy houses. • Hotels, apartments and other residential buildings not exceeding 4 storeys. • Offices not exceeding 4 storeys. • Industrial buildings not exceeding 3 storeys. • Retailing premises not exceeding 3 storeys of less than 2000 m^2 floor area in each storey. • Single-storey educational buildings. • All buildings not exceeding 2 storeys to which members of the pubic are admitted and which contain floor areas exceeding 2000 m^2 at each storey.	• Horizontal ties, OR • Effective anchorage of floors to walls, as described in the codes of practice.
2B	• Hotels, apartments and other residential buildings exceeding 4 storeys, but not exceeding 15 storeys. • Educational buildings greater than 1 storey, but not exceeding 15 storeys. • Retail premises greater than 3 storeys but not exceeding 15 storeys. • Hospitals not exceeding 3 storeys. • Offices greater than 4 storeys but not exceeding 15 storeys. • All buildings to which members of the pubic are admitted and which contain floor areas exceeding 2000 m^2 but less than 5000 m^2 at each storey. • Car parking not exceeding 6 storeys.	• Horizontal ties and vertical ties as described in the codes of practice, OR • Show that the removal of a wall or column will cause only limited damage, OR • Design as 'key elements'.
3	• All buildings defined above as Class 2A and 2B that exceed the limits on area and/or number of storeys. • All buildings, containing hazardous substances and/or processes. • Grandstands accommodating more than 5000 spectators.	• Systematic risk assessment.

Note
Basement storeys may be excluded provided they meet Class 2B criteria

There is insufficient space in this guide to discuss fully the approach required for Class 3 buildings. In brief, a risk assessment should be undertaken to identify the hazards and measures that can be taken to prevent or mitigate the risks. Any residual risks or critical situations should be assessed to determine the actions imposed on the structure. Remember the building has to be designed to avoid **disproportionate** collapse; if the hazard is large enough, total collapse may be deemed unavoidable. Further guidance can be found in Eurocode 1, Part 1–7, Annex B and *New approach to disproportionate collapse*[7], which is available online to IStructE members.

Monolithic concrete structures will tend to fair well in such situations because they have redundancy due to their continuity and tying through the reinforcement.

Eurocode 1, Part 1–7

Annex A of Eurocode 1, Part 1–7 gives guidance on designing buildings for the consequences arising from unspecified causes. The guidance in this Annex is similar to that in AD A and Eurocode 2, Cl. 9.10. However, there are subtle differences, which could affect a small number of buildings. Given that Annex A is informative and that the approach to design is the same, it is recommended that the detailed guidance in AD A and Eurocode 2 is adopted.

Design responsibility

BS 8110[8] states: "The engineer responsible for the overall stability of the structure should ensure the compatibility of the design and details of parts and components, even where some or all of the design and details of those parts and components are not made by this engineer". This is particularly important when it comes to the robustness of the structural frame. The Eurocodes are not as specific with regards to a single engineer taking responsibility, but nevertheless it is good practice.

Therefore, it is the responsibility of the designer, before incorporating any proprietary system as part of the structure, to ensure that the assumptions made in the design and construction of such systems are compatible with the design of the whole structure. This should include:

- An adequate specification for that part.
- Where a standard product designed and detailed by the manufacturer is included, it is suitable for the particular structure.
- The design and detailing of any such part is checked by the designer to ensure that it satisfies the design intent and is compatible with the rest of the structure.
- Measures are in place on site to ensure the structure is built as designed.

Concrete design standards

AD A refers to BS 8110 as an appropriate standard for the details of ties and key elements (where required); it is anticipated that AD A will be updated to refer to Eurocode 2[9], which also contains guidance on the design of ties.

Eurocode 2

Eurocode 2, Part 1–1, Cl. 9.10 gives guidance on the design of ties as summarised below; all the expressions are taken from the UK National Annex to Eurocode 2. The tying requirements can be met by using reinforcement provided for other purposes. The partial factors for accidental situations can be reduced to γ_C = 1.2 for concrete and γ_S = 1.0 for reinforcement and prestressing steel.

Peripheral ties in floors (for Class 2A buildings and above)

At each floor and roof level, an effectively continuous tie should be provided within 1.2 m of the floor edge. Structures with internal edges (e.g. atria and courtyards) should also have similar peripheral ties. The peripheral tie should be able to resist a tensile force of:

$$F_{tie,per} = (20 + 4\,n_0) \leq 60 \text{ kN}$$

where

n_0 = number of storeys

Internal ties in floors (for Class 2A buildings and above)

At each floor and roof level, internal ties should be provided in two directions approximately at right angles. The internal ties may be spread evenly in slabs or may be grouped at walls or other positions. If located in walls, the reinforcement should be within 0.5 m of the top or bottom of the floor slabs.

In each direction the tie needs to be able to resist a force, which should be taken as:

$$F_{tie,int} = (1/7.5)(g_k + q_k)(l_r/5)F_t \geq F_t$$

where

$(g_k + q_k)$ = average permanent and variable floor actions (kN/m^2)
l_r = greater of the distances (in m) between centres of the columns, frames or walls supporting any two adjacent floor spans in the direction of the tie under consideration
F_t = $(20 + 4n_0) \leq 60$ kN (n_0 is the number of storeys)

The maximum spacing of internal ties should be $1.5l_r$.

Horizontal ties to columns and walls (for Class 2A buildings and above)

Vertical elements at the edge and corner of the structure should be tied to each floor and roof. In corner columns ties should be provided in two directions. The tie should be able to resist a force of:

$$F_{tie,fac} = F_{tie,col} = \text{Maximum (Minimum } (2F_t\,;\, l_s\,F_t/2.5)\,;\, 0.03\,N_{Ed})$$

where

$F_{tie,fac}$ = peripheral tie force (kN/m run of wall)
$F_{tie,col}$ = column tie force (kN per column)
F_t = $(20 + 4n_0) \leq 60$ kN (n_0 is the number of storeys)
l_s = floor to ceiling height (in metres)
N_{Ed} = total design ultimate vertical load in wall or column at the level considered

Tying of external walls is required only if the peripheral tie is not located within the wall.

Vertical ties to columns and walls (for Class 2B buildings and above)

Eurocode 2, Part 1–1, Cl. 9.10.2.5(2) states: "Normally, continuous vertical ties should be provided from the lowest to the highest level, capable of carrying the load in the accidental design situation, acting on the floor above the column/wall accidentally lost". The accidental design situation is less than the ultimate limit state combination, and can be determined from table NA A.1.3 of the NA to Eurocode[10], which states:

$$E_d = G_k + A_d + \psi_{1,1}Q_{k,1} + \Sigma\psi_{2,i}Q_{k,i}$$

where

G_k = characteristic value of a permanent action
A_d = design value of accidental action
ψ_1 = frequent value of a variable action
Q_k = characteristic value of a variable action
ψ_2 = quasi-permanent value of a variable action

It should be noted that Clause 9.10.2.5(1) limits the requirement for vertical ties to buildings of five storeys and above, but the requirements of AD A override as stated in the background document to the UK National Annex, PD 6687[11] Cl. 2.20, and vertical ties should be provided for all buildings in Class 2B and above.

Anchorage of precast members

Eurocode 2, Part 1–1 does not cover anchorage of precast floor and roof units and stair members, therefore PD 6687 advises that the same requirements as given in BS 8110 are used. In Class 2B and 3 buildings, all precast floor, roof and stair members should be effectively anchored, whether or not such members are used to provide other ties required in Eurocode 2, Part 1–1, Cl. 9.10.2. The anchorage should be capable of carrying the dead weight of the member to that part of the structure that contains the ties.

BS 8110

In May 2008 British Standards Institution announced that BS 8110 was made obsolete from that date and that the relevant BSI technical committee, B/525/2 – Structural Use of Concrete would no longer support it. However, it is recognised that BS 8110 is still cited in AD A. The tie forces given in the section above for Eurocode 2 are all based on the UK National Annex, and are aligned with the tie forces given in BS 8110 with the exception of the vertical tie force. In this case the design force will vary between the two codes depending on the ratio of permanent to variable actions and the type of variable action.

Key elements

Where a building has key elements, each element and its connections should be capable of withstanding a design load of 34 kN/m^2 at ultimate limit state. This should be applied from any direction to the projected area of the member together with the reaction from the attached components, which should also be assumed to be subject to a loading of 34 kN/m^2. The load from the attached components may be reduced to the maximum reaction that can be transmitted by the attached components and their connections. This advice is given in BS 8110: Part 2, Cl. 2.6 and in PD 6687, Cl. 20.2 b) for use with Eurocode 2.

Application to typical buildings

The previous Section outlines the requirements in the codes and standards to provide a robust design. This Section outlines the typical details used for generic concrete element and building types.

In-situ reinforced concrete

Reinforcement provided for other purposes may be used as the reinforcement acting as ties in in-situ concrete. Therefore, it will generally be found that no additional reinforcement is required to ensure a robust structure. Indeed, normal detailing of reinforcement ensures that the ties are adequately anchored. It is worth noting that Amendment 3 of BS 8110:1997 introduced a requirement for horizontal ties to interact 'directly and robustly' with the vertical structure, and notes that this is generally achieved by ensuring that two bottom bars in each direction pass directly between the column reinforcement (see Cl. 3.12.3.8 for further details). Eurocode 2, Part 1–1 has a similar requirement in Clause 9.4.1 (3), but this is specifically applied only to flat slabs.

Post-tensioned concrete

Clause 4.1.6 of BS 8110 implicitly directs the designer to the requirements of Cl. 3.12.3.8 for tying arrangements appropriate for prestressed concrete, and these rules should also be applied to post-tensioned concrete. This includes the requirement to ensure that the horizontal ties interact 'directly and robustly' with the vertical structure. Similarly Eurocode 2 does not differentiate between prestressed and reinforced concrete and the same rules apply, including the requirement for two bottom bars to pass through the column in flat slabs. If the tendons themselves are not passed between the column longitudinal reinforcement, then sufficient tie bars should be provided at the bottom of the slab and be anchored adequately to ensure that the tie forces are carried into tendons which will act as the horizontal ties across the structure.

Precast framed structures

The location of floor ties are shown in Figure 2. The ties will usually have to be detailed specifically for robustness using the design forces given above and can be either reinforcement (e.g. H12) or helical prestressing strand (design strength 1580 N/mm^2), which is laid taught but not prestressed. The bars or strand should be adequately lapped and embedded in in-situ concrete which has a minimum dimension of at least $\phi + 2H_{agg}$ + 10 mm (i.e. usually at least 50 mm) where ϕ is the bar diameter and H_{agg} is the maximum aggregate size. 10 mm aggregate is often used to minimise the size of the concrete infill.

Typical horizontal tie details are shown in Figures 3 to 10. The following should be noted:

- The opening up of adjacent cores at the end supports of hollowcore units should be avoided.
- The recommended maximum length of an open core in a hollowcore unit is 600 mm.

Vertical ties for Class 2B buildings and above should be designed to resist the accidental load combination, E_d

Figure 2
Floor ties for a concrete frame

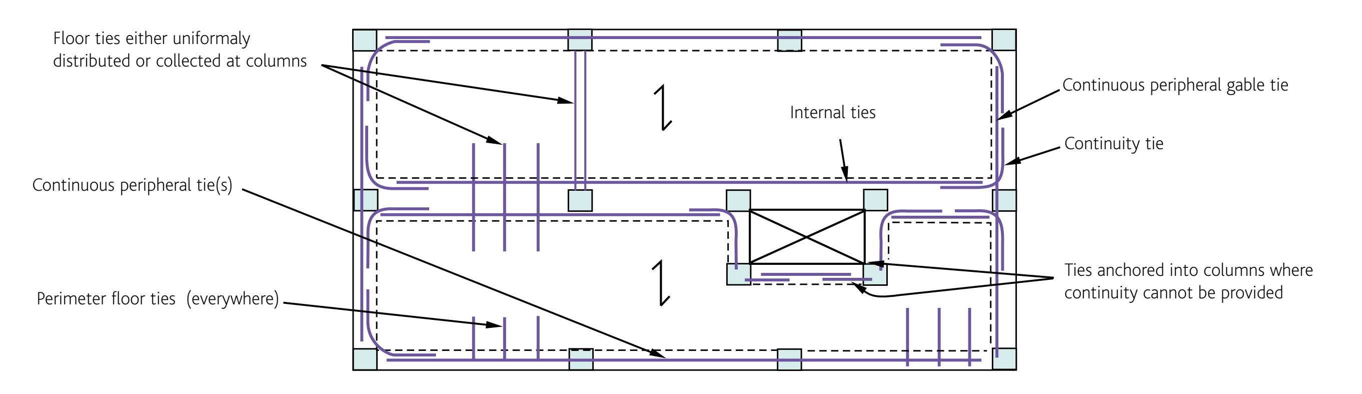
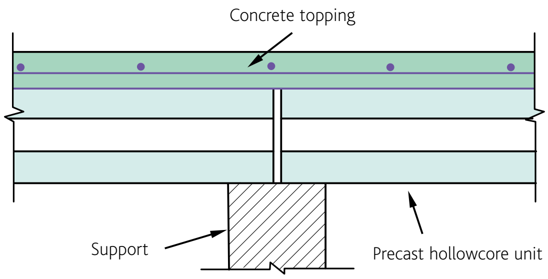


Figure 3
Internal floor ties within bonded concrete topping



Note
Not suitable for Class 2B and Class 3 buildings in accordance with Approved Document A

Figure 4
Internal floor ties within hollowcore units

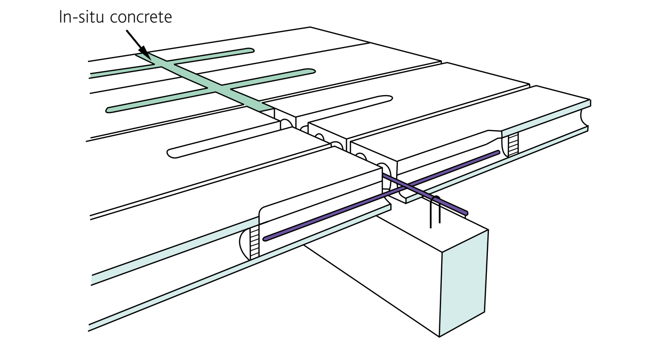


Figure 5
Position of floor tie for hollowcore units

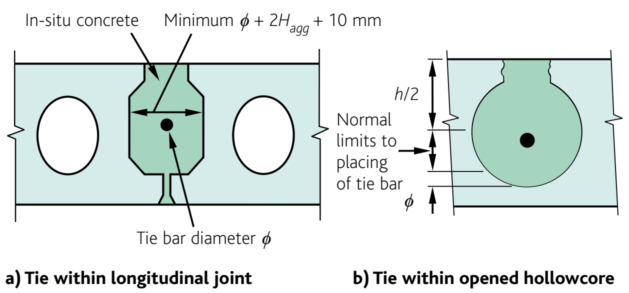


Figure 6
Perimeter floor ties within hollowcore units

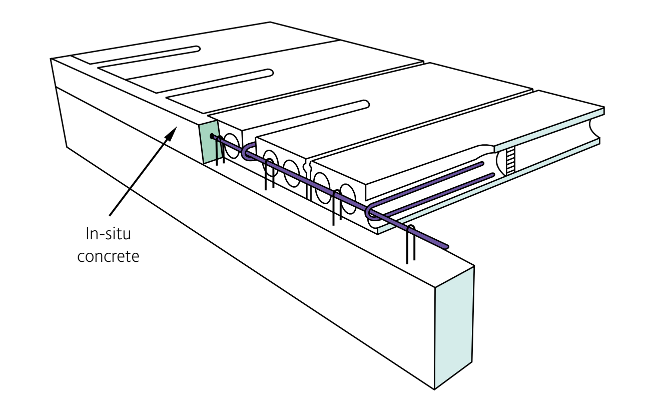


Figure 7
Perimeter ties where hollowcore units span parallel to edge beam

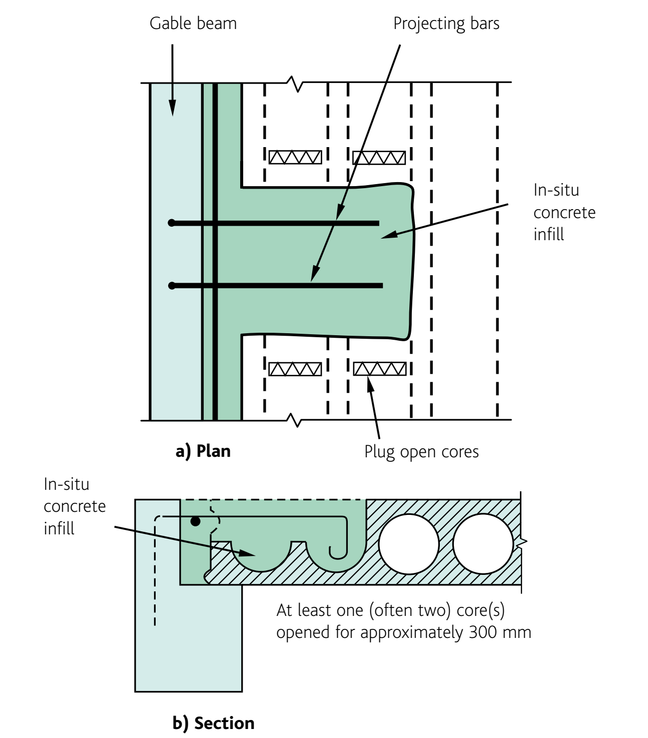


Figure 8
Detailing at corner columns

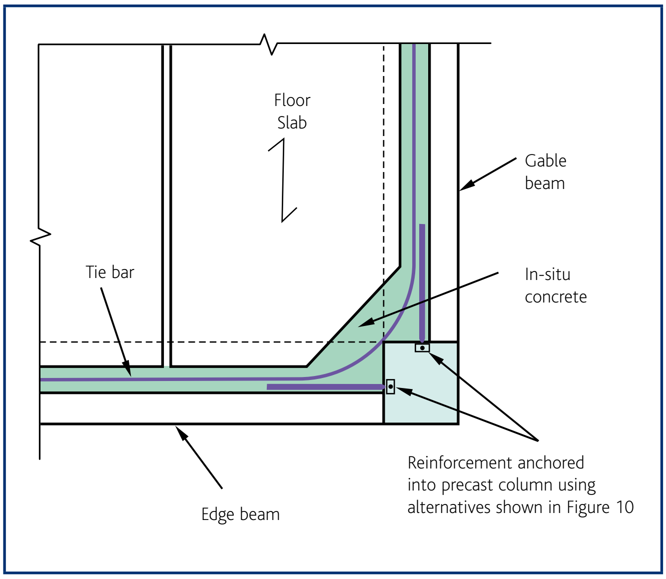


Figure 9
Internal ties taken through precast column

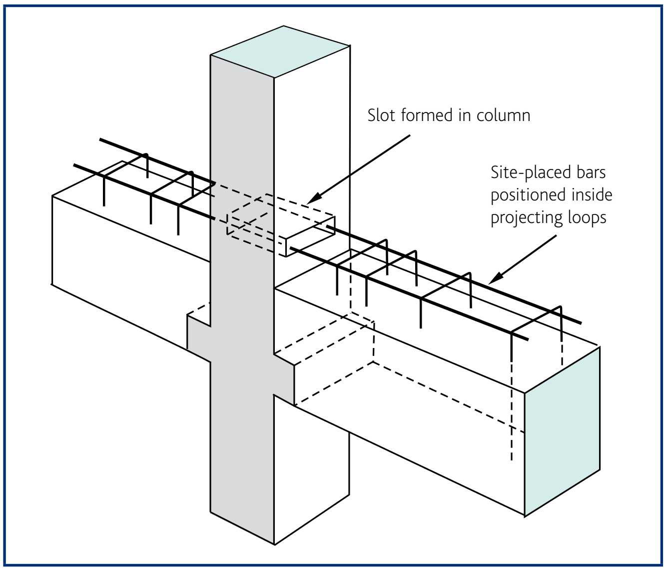
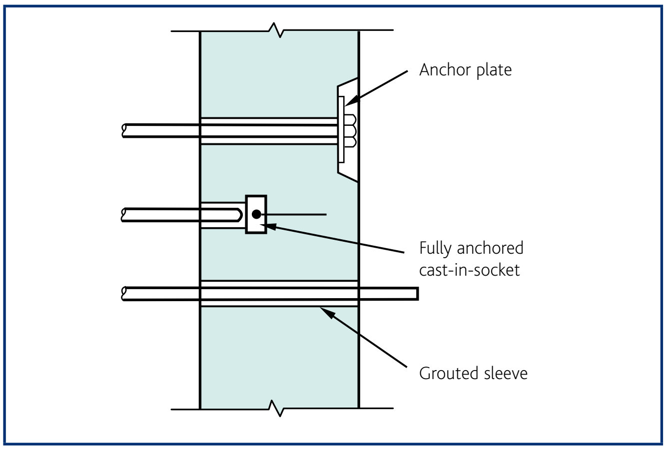


Figure 10
Alternative positions for internal ties at precast column position



Hybrid concrete structures

Hybrid concrete structures use both precast and in-situ concrete to create economic structures. Generally, the use of in-situ concrete makes the frame monolithic and therefore, as with in-situ frames, the tying requirements are met without the need to provide additional reinforcement. However, for hybrid structures, it is important not to assume this will be the case and to carry out specific checks. The details will vary from project to project and will depend on the relative balance between in-situ and precast concrete. Further guidance on the design of hybrid concrete structures can be found in *Design of hybrid concrete buildings*[12].

Crosswall construction

Crosswall construction is often used to refer to precast concrete walls supporting precast concrete floors, and is used mainly for residential type structures. The types of tie required for a Class 2B building are shown in Figure 11 and can be summarised as:

- Floor ties – connecting floors over an internal wall.
- Horizontal perimeter ties – connecting floors to perimeter walls.
- Internal ties – running parallel to the internal walls.
- Peripheral ties – arranged around the perimeter of the floor.
- Vertical ties – connecting vertical walls to provide continuity.

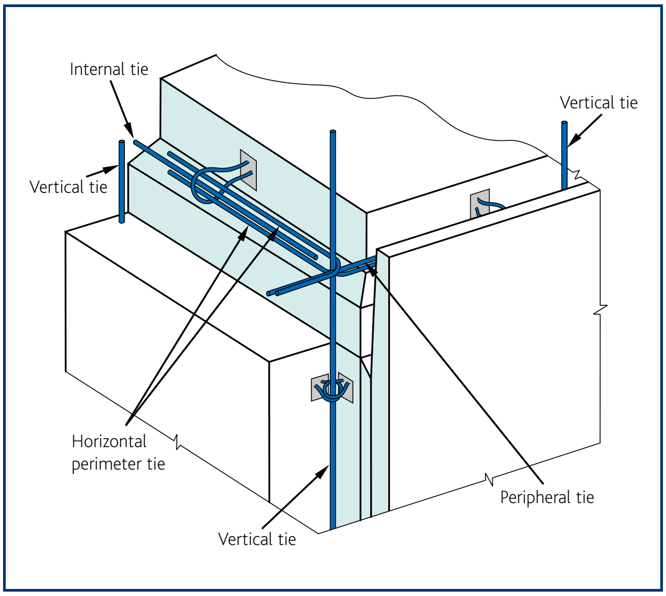
Figures 7 and 8 can be referred to where hollowcore floor units are used.

The tying requirements for a Class 2A building are similar, except the vertical ties can be omitted.

Steel-framed structures supporting precast concrete floors

The detailing of precast concrete floors supported by steel frames is covered in detail in the publication *Precast concrete floors in steel framed buildings*[13], which should be referred to.

Figure 11
Ties for crosswall construction



Load-bearing masonry structures supporting precast floors

This Section focuses on the robustness of the precast flooring system and does not cover the requirements for the robustness of the masonry (for example vertical ties), which is clearly set out in BS 5628 Part 1[6], section 5 and should be included in the *Background Document to the National Annex of Eurocode 6*[14] when it is published. The approach to the provisions of ties will depend on whether the building is Class 1, 2A or 2B and above. Class 1 buildings require no specific measures. Class 2A buildings require horizontal ties to be provided or the provision of effective anchorage of floors to supports.

The definition of 'effective anchorage' can be deduced from Cl. 33.4 and figure D.6 of BS 5628 as 90 mm or half the leaf thickness, whichever is greater (see Figure 12). Where this effective anchorage is not provided the internal ties are required as for Class 2B buildings.

Figure 12
'Effective anchorage' for Class 2A buildings with precast floor construction supported on load-bearing masonry

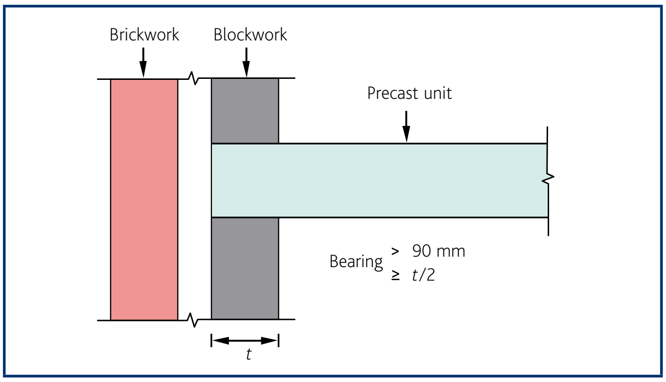
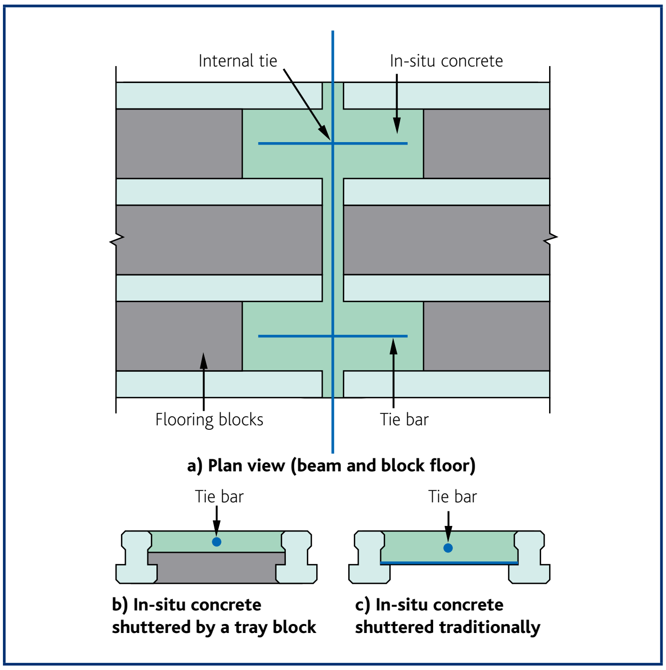


Figure 14
Ties for beam and block construction supported on load-bearing masonry



The tying requirements for Class 2B buildings or above can be achieved by placing horizontal ties within the depth of the floor. Figures 13 and 14 show typical details for hollowcore (also see Section titled Precast framed structures) and beam and block floors.

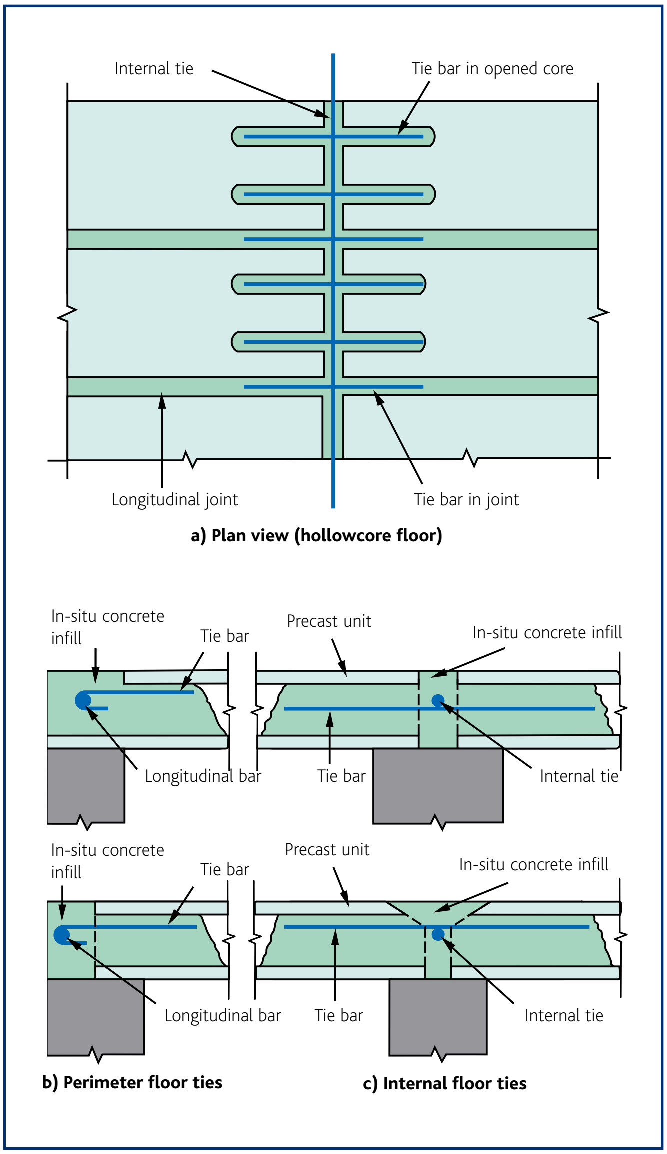
Requirements in Scotland

In Scotland the *Building (Scotland) Regulations*[15] have also been amended and the Technical Handbooks (TH) have been updated[16].

The TH generally have the same requirements as AD A; however, there are some variations and these are explained below.

The categorisation of buildings given in Table 1 is generally the same as that given in the TH. However, rather than referring to classes, the TH refer to Risk Groups (1, 2A, 2B and 3).

Figure 13
Ties for Class 2B buildings with hollowcore floor construction supported on load-bearing masonry



Also some of the descriptions of building type are different. The most noticeable is the reference to factories rather than industrial buildings and that Class 1 storage and factory buildings are in Risk Group 3.

Unlike AD A, the TH clearly defines what can be considered a basement storey – it has to be wholly below the lowest ground level around the building. It should be noted that the TH requirements override the guidance in the NHBC technical guidance note (referred to by the TH) which has a less onerous definition for a basement.

With regard to the use of Eurocodes, the TH acknowledges that they will be introduced and that British Standards will be withdrawn from 2010 onwards. In the meantime Eurocodes can be used, provided the accompanying National Annex is also available, which it is in the case of Eurocode 2.

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