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8 Developing a concept

8.1 The six key decisions you need to make simultaneously

Developing a structural design concept is similar in many ways to solving a set of simultaneous equations, except that there is often more than one solution which meets the brief.

We will look at the following six key items to be considered, and decisions to be made, when developing a conceptual design:

1. Influence of ground conditions.
2. Material selection.
3. Structural system — loadbearing, framed or hybrid.
4. Grids and structural layouts.
5. Spans of floor and roof structures.
6. On- or off-site/prefabricated construction.

There are also many other valid considerations e.g. the integration of structure and building services.

While each item is presented separately, these should all be considered at the same time, ideally. This is something that becomes easier with experience, and almost happens subconsciously after several years of practise. Concept design often tends to be an iterative process.

It is also important to note that making one decision, or selecting one parameter e.g. which material to use, will usually have an impact on the choices available in relation to other parameters. For example, if it was decided, possibly for reasons of sustainability, that a timber floor system was to be used in a particular building, this would have implications on the spacing of the supporting walls, beams and columns. Similarly, if loadbearing timber or masonry walls were adopted for the building, this would place limitations on the overall height of the building.

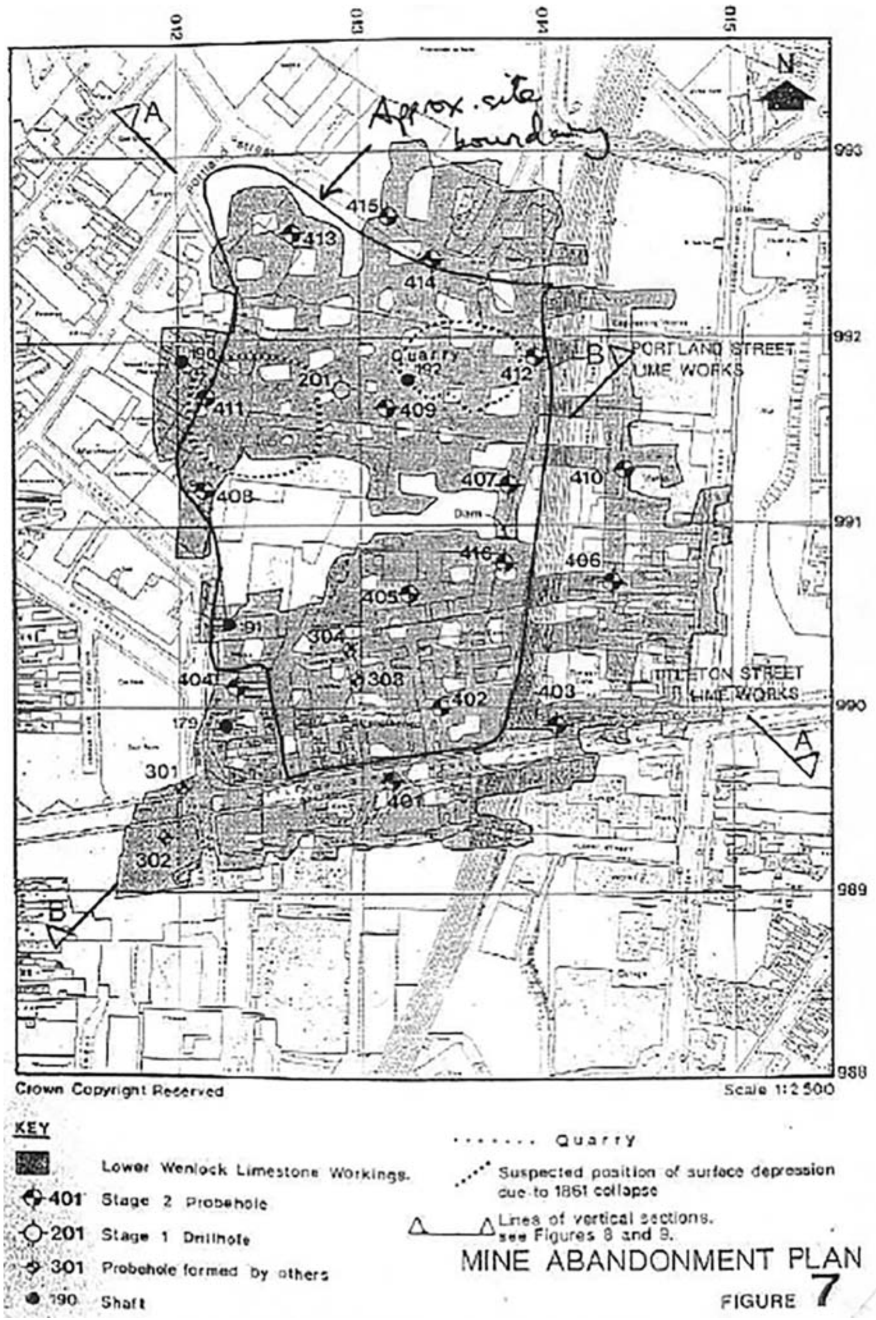
While not listed here as a 'key decision', it is also essential to think about stability and robustness when developing your concept design (Chapter 9).

8.1.1 Decision 1: Influence of ground conditions

It is easy to fall into the trap of carrying out the concept design of the superstructure of a building with little, if any, consideration of the ground conditions. The foundation design is often carried out after that of the superstructure, and is often a '*fait accompli*' i.e. the foundations will be whatever they need to be in order to resist the applied loads. This could however lead to significant issues later in the project, potentially resulting in foundations solutions being adopted which are both impractical and uneconomical. It is good practice to get an understanding of the likely ground conditions as early as possible, by carrying out a desk study (Chapter 7). Indeed, the ground conditions may have significant implications for the superstructure design.

A good example is Walsall College in the West Midlands, which is built over old limestone mine workings, which occur at a depth of approximately 40m local to the proposed building. Figure 8.1 is a plan showing the mine workings (note that the areas shaded in grey are the voids).

Figure 8.1: Mine abandonment plan local to Walsall College



The local authority stipulated that the total dead and imposed load of the building should not exceed 40kN/m^2 at ground level. Given that the proposed building was five storeys high in some areas, and that the imposed floor load was typically either 4.0kN/m^2 or 5.0kN/m^2, this limited the floor dead load to approximately 3.0kN/m^2 at each level. The design team quickly concluded that a steel frame was the only viable solution, which not only complied with this stringent loading requirement, but also provided the flexible space requested in the client's brief. The completed project, which cost £40m, opened in 2009 (Figure 8.2).

Figure 8.2: Walsall College

8.1.2 Decision 2: Material selection

There are four commonly used structural materials to choose from when designing buildings in the UK:

- Steel
- Concrete
- Timber
- Masonry

In other countries, some of these materials may not be as readily available e.g. the steelwork industry in many countries is not as well developed, while other materials, such as lightweight steel framing, and even bamboo and earth may be used, particularly for domestic construction.

In many cases, a hybrid material solution will be appropriate e.g. steel frame buildings often use concrete shear walls or cores, while loadbearing masonry buildings commonly use timber floor construction.

Material selection depends on a wide range of considerations, typically:

- Building height
- Internal layout — open plan or cellular
- Structural form/spans — usually related to internal layout considerations
- Ground conditions and any limitations on the location of foundations e.g. adjacent buildings, underground services or tunnels
- New build, refurbishment or extension e.g. the additional loads are likely to be limited for a refurbishment or extension, whereas the floor-to-floor heights will also be dictated by the need to tie into existing floor levels
- Magnitude and nature of applied loads
- Sustainability/embodied carbon
- Cost, availability and lead-in time
- Fire resistance
- Acoustic properties
- Building physics e.g. lighting, ventilation etc.
- Distribution of building services
- Robustness/disproportionate collapse
- Aesthetics
- Design life, durability and maintenance requirements
- Preconceived ideas/previous experience

Table 8.1 shows indicative values for each of the four most common building materials.

Similarly, each material has its advantages and disadvantages, some of which are listed in Table 8.2.

Table 8.1: Key structural properties of common structural materials

Material	Young's modulus (N/mm^2)	Characteristic compressive strength (N/mm^2)	Characteristic bending strength (N/mm^2)	Characteristic tensile strength (N/mm^2)	Force density (kN/m^3)
Steel	210,000N/mm^2	Typically 275 or 355N/mm^2 (but less if flexural buckling occurs)	Typically 275 or 355N/mm^2 (but less if lateral torsional buckling occurs)	Typically 275 or 355N/mm^2	78kN/m^3
Reinforced concrete	15,000N/mm^2 (long-term)–30,000N/mm^2 (short-term)	Typically 12–90N/mm^2 (but usually use 30–60 N/mm^2 in UK)	Dependent on amount of steel reinforcement provided	Anecdotally is equal to approximately 10% of its compressive strength, but generally assumed to be zero in design	24kN/m^3 (for dry mass concrete). Add 1kN/m^3 for reinforcement plus 1kN/m^3 for wet concrete, as appropriate
Timber (softwoods)	Varies from 8,000 N/mm^2 (mean value for Class C16 timber) to 13,700N/mm^2 (mean value for Class GL32 glulam)	Varies from 17N/mm^2 (for Class C16 timber, parallel to grain) to 29N/mm^2 (for Class GL32 glulam, parallel to grain)	Varies from 16N/mm^2 (for Class C16 timber, parallel to grain) to 32N/mm^2 (for Class GL32 glulam, parallel to grain)	Varies from 10N/mm^2 (for Class C16 timber, parallel to grain) to 22.5N/mm^2 (for Class GL32 glulam, parallel to grain)	Varies from 3.7kN/m^3 (Class C16 timber) to 4.75kN/m^3 for Class GL32 glulam
Masonry	Not applicable since masonry is primarily designed as compression only, and the strength characteristics are based on the masonry/mortar bond	1-10N/mm^2 based on Table 2 of BS 5628-1 (the equivalent ULS values can be found in BS EN 1996-1-1)	0.1–0.2N/mm^2 based on Table NA.6 from NA to BS EN 1996-1-1	Assumed to be zero in design	6kN/m^3 (aerated blockwork) to 22kN/m^3 (brick/stone)

Note: Derived/adapted from BS EN 1992-1-1, BS EN 1993-1-1, BS EN 1995-1-1, BS EN 1996-1-1[64–67] and the corresponding National Annexes[68–71], BS 5268-2[72], BS 5268-1[73] and IStructE manuals[74–77].

Table 8.2: Advantages and disadvantages of common structural materials

Steel	
Advantages	**Potential disadvantages**
High rate of recycling	Low inherent fire resistance — applied fire protection is usually required
Consistent material properties/isotropic	Corrosion if not suitably protected/detailed (depending on exposure/environment)
Good strength-to-weight ratio	Members/elements in compression prone to overall and local buckling effects
Speed of erection	Long lead-in time (typically 12–20 weeks)
Long-span floors achievable	Typically requires a hybrid system e.g. incorporating concrete floors, foundations and potentially shear walls/cores
Connections can transfer very high forces between elements	Stability during construction e.g. often need to provide temporary bracing
Dimensionally stable (not affected by creep or moisture effects, notwithstanding corrosion)	Vibration governs very long spans (≥10m)
Reinforced concrete	
Advantages	**Potential disadvantages**
Very good inherent fire resistance – applied fire protection not normally required	Variable material properties/anisotropic
Flexibility of form	Corrosion if inadequate detailing/construction (depending on exposure/environment)
High thermal mass can be used to reduce, or even obviate, the need for mechanical ventilation	Members in compression prone to overall buckling effects
In situ RC connections can transfer high loads between elements	Not perceived as environmentally friendly compared with other materials, although the use of recycled aggregates and cement replacement materials (e.g. PFA and GGBS) partly addresses this
Dimensionally stable (not affected by moisture effects, notwithstanding corrosion)	Strength-to-weight ratio not as good as steel or timber
Medium- to long-span floors achievable	RC frames heavier than steel or timber frames
Relatively short lead-in time for *in situ* concrete (typically 4–8 weeks)	Speed of erection/need for propping for *in situ* concrete (precast is quicker, although lead-in times are longer)
Strong visual identity	Low tensile and bending resistance if unreinforced
Good acoustic properties due to high mass	Long-term creep effects needs to be considered

Table 8.2: *Continued*

Timber	
Advantages	**Potential disadvantages**
Natural and renewable	Variable material properties/anisotropic
Lightweight	Fire resistance during construction
Good strength-to-weight ratio when loaded along its grain	Movement/creep effects due to shrinkage and moisture (depending on type of timber product specified and moisture content)
Flexible (can be easily cut to length in timber yard or on-site)	Challenging to satisfy robustness/disproportionate collapse requirements for tall buildings i.e. Class 2B upwards
Short- to medium-span floors achievable	Can only transfer modest loads between members
Short lead-in time for sawn timber	Sawn timber products slow to construct on-site
Engineered and prefabricated timber products e.g. CLT, SIPs, are quick to construct on-site	Long lead-in time for engineered and prefabricated timber products e.g. CLT, SIPs
	Vibration governs long spans ($\geq$6m)
Masonry	
Advantages	**Potential disadvantages**
Very good in compression	Variable material properties/anisotropic
Good inherent fire resistance	Thermal expansion and contraction effects e.g. cracking if inadequate allowance for thermal movement
Low maintenance	Poor in flexure/bending
Appearance is generally popular with the public	Not perceived as environmentally friendly compared with other materials, due to use of natural materials (clay, aggregate etc.) and high energy required during production
	Labour intensive to construct
	Availability/cost of suitably skilled labourers
	Challenging to satisfy robustness/disproportionate collapse requirements for Class 2A buildings, and especially challenging for Class 2B upwards
	Can only transfer modest forces between members

One way of quickly shortlisting potential structural materials is to consider building height (Table 8.3).

Steel and concrete are usually suitable for any height of building, although they tend not to be used for low-rise housing with a cellular layout.

Timber is being used for increasingly taller buildings e.g. the ten-storey Dalston Works building in Hackney, London (at the time of construction, the world's largest CLT building)[78] and the 18-storey TallWood House building in Vancouver (at the time of publication, the world's tallest mass timber building)[79], with a concept stage proposal to build as tall as 80-storeys. The vast majority of timber framed buildings in the UK are currently four storeys or less.

Loadbearing masonry buildings up to three storeys are still commonly used in the UK residential sector. While it is possible to build higher in loadbearing masonry, this is now relatively rare in the UK.

For timber and masonry buildings higher than four storeys, it can be very challenging to satisfy the robustness/disproportionate collapse requirements outlined in Building Regulations Approved Document A[80]. For further details, refer to Chapter 9.

Table 8.3: Building height limitations for common structural materials

	One or two storey buildings	Buildings up to four storeys	Buildings with 5–18 storeys	Buildings over 18 storeys
Steel	Y e.g. portals	Y	Y	Y
Concrete	Uncommon	Y	Y	Y
Timber	Y	Y	Y	N
Masonry	Y	Potentially	N	N

8.1.3 Decision 3: Structural system

We essentially have three fundamental options when it comes to the structural system — the system which transfers all the loads down to foundation level:

- Framed
- Loadbearing
- Hybrid of the two

As discussed, the height of the building may well determine which structural system is to be used, with loadbearing systems not currently suitable for buildings over ten storeys (and rarely used for many buildings taller than four storeys, although the introduction of solid wood solutions, such as CLT, has provided structural engineers with more options). For buildings up to ten storeys, the proposed use of the spaces and nature of the architectural floor plans (open plan or cellular) should inform the structural system.

Framed structures

An open-plan floor layout is one with no internal walls to be used as permanent loadbearing elements. It relies on a framed-type structure (beam and column or flat slab), to transfer gravity loads down to the building's foundations (Figures 8.3; a naturally ventilated shallow plan building and 8.4, a mechanically ventilated deep plan building).

Figure 8.3: Indicative column layout/grid arrangement for a shallow-plan/open-plan steel framed office building

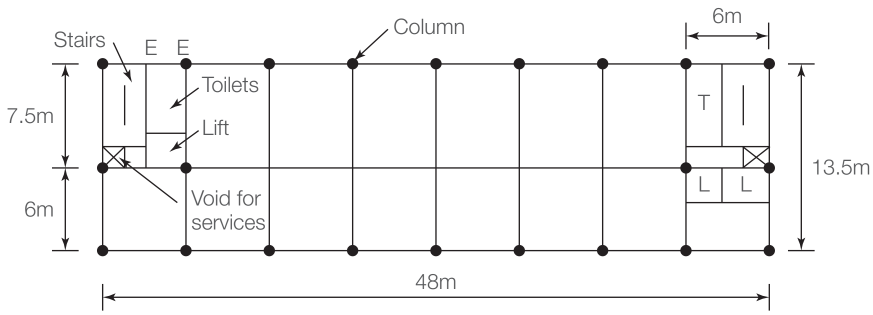
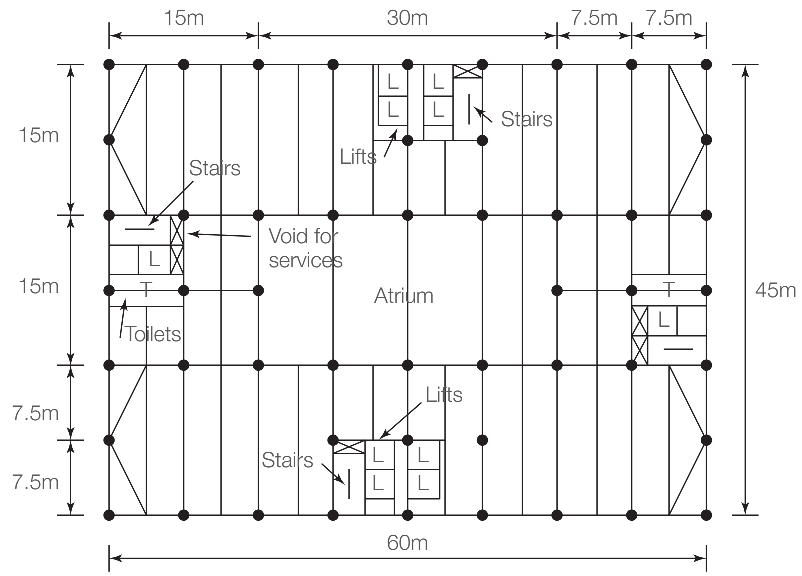


Figure 8.4: Indicative column layout/grid arrangement for a deep-plan/open-plan steel framed office building with a central atrium

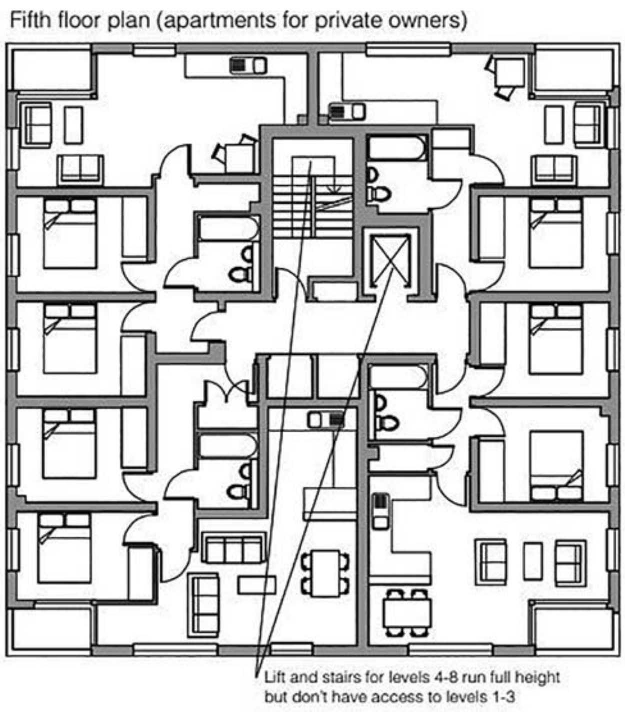


The frames shown in Figs 8.3 and 8.4 could potentially be made from steel, concrete or timber (depending on the height of the building). This form of construction is typically suited to commercial buildings, such as offices, retail and mixed-use buildings, but could also be used for hotels, student accommodation and other types of residential building. There are various ways in which framed structures can resist lateral loads, as discussed in Section 8.4 and Chapter 9.

Loadbearing structures

A cellular layout is one with a sufficient number of suitably located internal loadbearing walls to support the gravity loads from the floors and roof (Figure 8.5). These walls could be in masonry, reinforced concrete, timber or even

Figure 8.5: Typical floor layout for Stadthaus, London, showing CLT wall panel locations



light gauge metal studs (Figures 8.6–8.9) and should ideally be continuous for the full height of the building, to avoid the need for transfer structures/beams. Such walls will often be used to transfer lateral loads to the foundations, although other options are available (Section 8.4 and Chapter 9). This form of construction is probably best suited to residential buildings (apartment blocks), and potentially to hotels, student accommodation and prisons, for example.

Hybrid structures
In some cases e.g. apartment blocks, hotels and student accommodation, where a more open-plan area is required at ground floor than at upper floor levels for example, a hybrid solution could be adopted. The TallWood House student residence building in Vancouver is a good example of this — the bottom storey is a concrete frame with columns at relatively large centres, on top of which is a timber framed structure, with columns at closer centres (Figures 8.10–8.11).

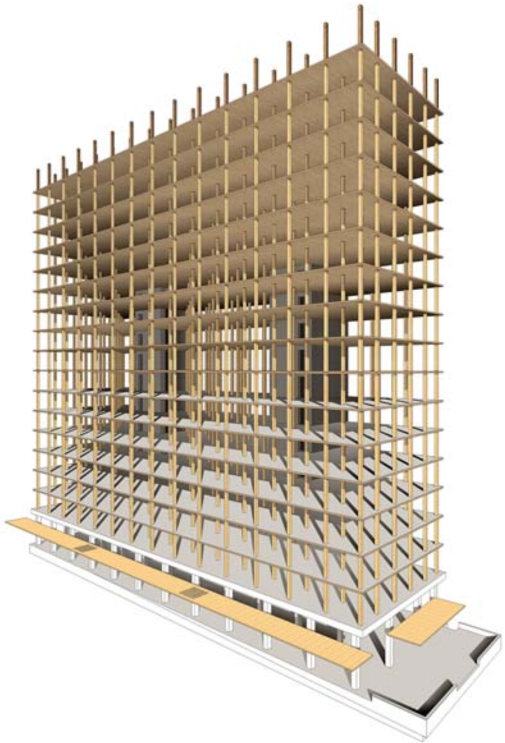
Figure 8.6: Loadbearing masonry walls

Figure 8.7: ‘Tunnel form’ RC walls

Figure 8.8: CLT walls

Figure 8.9: Light gauge steel stud walls

Figures 8.10 and 8.11: Structural frame of TallWood House, Vancouver



8.1.4 Decision 4: Grids and structural layouts

When we talk about grids, we are usually referring to where the floor and roof supports occur, and how far apart they are, and whether these supports take the form of columns or loadbearing walls. The gridlines shown on engineer's and architect's drawings should coincide with column and/or loadbearing wall locations (although changes made during the design development period can result in members being moved off-grid).

Grids should ideally be regular/uniform and perpendicular, to simplify fabrication/construction and maximise economies of scale etc. Gridlines should also be consistent over the full height of the building, in order to avoid the need for transfer structures.

There is often a trade-off between flexibility and economy when determining the structural grid. While placing supports as far apart as possible might seem like a good idea, as it maximises the future flexibility of a building, this comes at a cost. A practical and affordable compromise needs to be reached.

Grid dimensions generally depend on various factors, including:

- Proposed building use/gravity loads
- Proposed room layouts
- Future flexibility requirements
- Presence of car parking under building
- Spanning capability of proposed floor and roof structures
- Spanning capability of proposed cladding solution

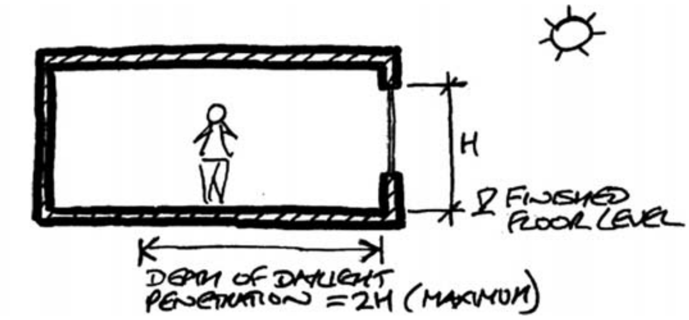
Further guidance regarding optimum grid dimensions is given on:

- Offices
- Residential
- Car parks
- Transfer structures
- Optimum module sizes and construction materials

Offices

The British Council for Offices (BCO)'s *Guide to specification*[81] provides extensive guidance on the preparation of scheme designs. For naturally ventilated offices, a building width of 12–15m is typically used, which can be achieved by two spans of 6–7.5m — with a column placed adjacent to a central corridor, similar to the arrangement shown in Fig. 8.3. Natural lighting can also play an important role in determining the width of floor plate (Figure 8.12). This, and many other helpful rules of thumb relating to sustainable building design, can be found in *101 Rules of thumb for low energy architecture*[82] and *101 Rules of thumb for sustainable buildings and cities*[83].

Figure 8.12: Depth of daylight penetration



In larger buildings, a long-span solution provides a considerable enhancement in flexibility of layout. For air-conditioned offices, a clear span of 15–18m is often used. Fig. 8.4 gives an indicative column layout/grid arrangement for a mechanically ventilated steel framed office building with a central atrium.

Residential (including bedroom floors to hotels and student accommodation)

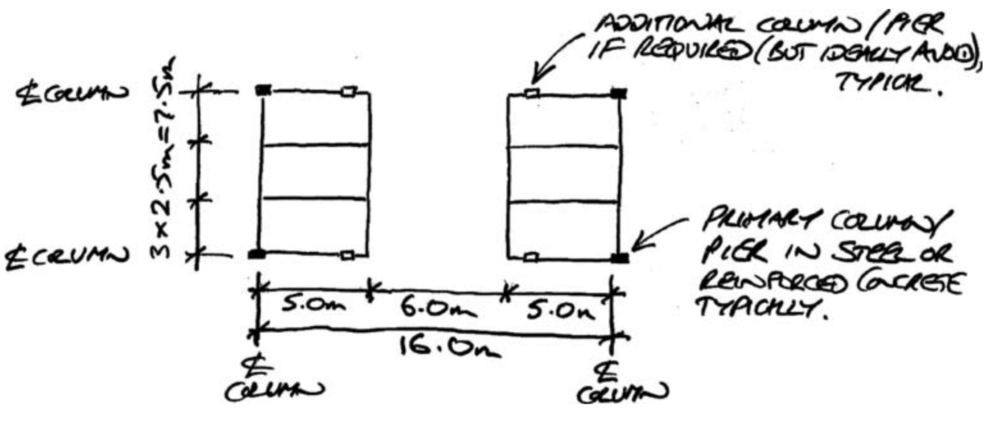
Residential buildings can vary significantly in their size and nature, which complicates giving advice on their associated structural grids/solutions. Large apartment blocks can be designed in a similar way to office blocks, as described, with correspondingly similar column centres/structural grids. Alternatively, the requirement for walls at relatively close centres (to separate rooms/apartments) can be utilised structurally, with loadbearing walls constructed from a range of materials (Figs. 8.6–8.9).

Fig. 8.5 shows a typical floor layout to a multi-storey residential building, in which CLT wall panels have been used. A similar floor layout could easily apply to structures utilising loadbearing masonry, reinforced concrete, or light gauge steel stud walls.

Car parks

The structural grid/column locations to multi-storey car parks, and any buildings containing a car park within their footprint e.g. in the basement will, as a minimum, need to comply with the layout shown in Figure 8.13. However, clear-span construction would be preferable, with columns at 7.5m i.e. 3 × 2.5m centres in one direction and 16.0m i.e. 2 × 5.0m + 6.0m in the other, which should accommodate larger vehicles e.g. SUVs.

Figure 8.13: Indicative column layout to multi-storey car parks

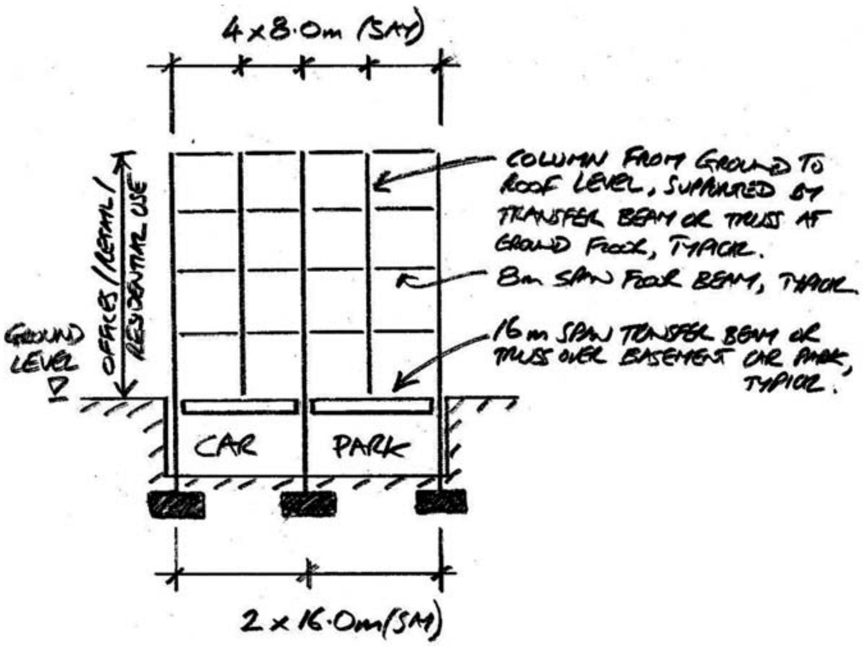


Transfer structures

A common solution is to adopt a transfer structure at ground floor level where an office, retail, residential or mixed-use building is constructed over a basement car park. As an alternative to using a 7.5m × 16.0m column grid at all levels (which would result in relatively deep beams spanning the 16.0m dimension, so relatively high floor-to-floor heights), a 7.5m × 8.0m column grid could be adopted at upper levels, with the additional columns picked up by transfer beams or trusses above the car park (Figure 8.14).

Another good example of a transfer structure is the use of a concrete podium slab at first floor level of the TallWood House student residence building (Figs. 8.10–8.11), in order to create an open plan space at ground floor level.

Figure 8.14: Transfer structure over a basement car park



More elaborate transfer structures include raking columns at ground floor level (Figure 8.15), and systems which use the whole height and width of the building as a transfer structure e.g. when spanning over a road or underground railway lines (Figures 8.16–8.19).

Figure 8.15: Exposed concrete transfer columns in Spinningfields, Manchester

Figure 8.16: Deep truss at roof level spanning over road, Bristol

Figure 8.17: Exchange House, London — four large steel arches to span over train lines adjacent to Liverpool Street station

Figure 8.18: Cannon Place, London — a series of trusses span over a combination of train lines, archaeological remains and a scheduled ancient monument

Optimum module sizes for construction materials

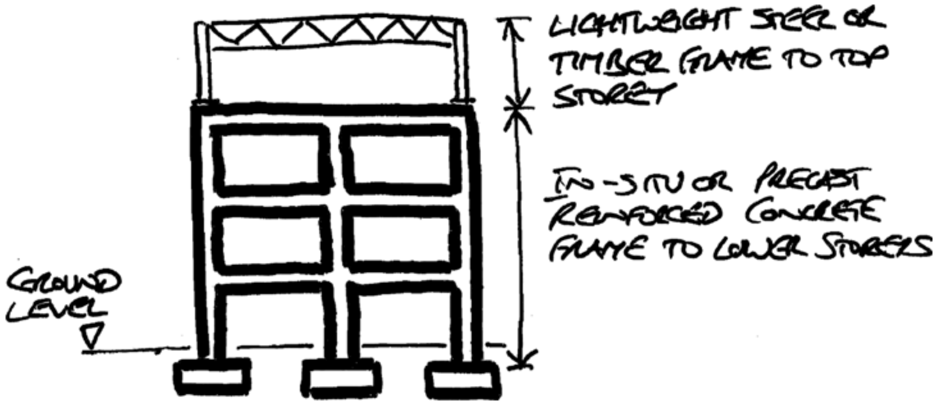
The materials adopted may come in optimum module sizes, which should ideally inform the structural grid e.g. hollow-core precast floor units typically come in 1.2m wide modules, while timber panels typically come in multiples of 0.6m, 1.2m and 2.4m. Buildings with masonry cladding (loadbearing or non loadbearing) should ideally have grids and floor-to-floor heights based on brickwork dimensions i.e. 75mm high × 225mm long, allowing for 10mm mortar joints, and blockwork dimensions i.e. 225mm high × 450mm long, allowing for 10mm mortar, as appropriate. Proprietary cladding and roofing systems may also come in standard size panels.

8.1.5 Decision 5: Spans of floor and roof structures

The spans of floor and roof structures are closely related to the structural grid/supports described in Section 8.1.3. The first question to ask is: Could the floor span the distance between support (whether columns or loadbearing walls) without using any intermediate beams? — which obviously depends on the type of floor being considered. While the comments that follow do not explicitly refer to roof structures, they are also valid for roofs.

Roof structures are generally subject to lower variable loads than floor structures, which provides the option of using lightweight roof structures for many buildings. It is relatively common for concrete frame buildings to have a lightweight steel roof structure, and for some (if not all) internal columns to be omitted at roof level (Figure 8.19).

Figure 8.19: Lightweight roof structure to multi-storey building



Floors

Table 8.4 provides guidance on suitable floor systems, depending on the imposed loads and the span. Where N/A is shown this does not necessarily mean the solution isn't possible, rather that it is not a standard solution. Note that this table is not exhaustive, and only gives an indication of how far typical floor systems used in the UK can span.

In instances where Table 8.4 is not applicable, the span-to-depth ratios given in Table 8.5 can be used to determine an initial size for the floor system. Further details can be obtained from the literature[3–6,74–77,84–89], from where the values in Tables 8.4–8.6 have been derived/adapted.

It is interesting to note from Tables 8.4 and 8.5 the significant increase in allowable span between single and multiple span floor systems e.g. by comparing the allowable spans for one-way spanning, *in situ* RC slabs. It is much more structurally efficient to use slabs/floor systems with two or more spans wherever possible.

Table 8.4: Maximum spans for common types of floor structure (indicative values)

Floor system	Allowance for super-imposed permanent loads due to finishes, services etc. (unfactored)	Maximum clear span, depending on value of unfactored variable floor load					Relevant sources
		1.5kN/m²	2.5kN/m²	3.5kN/m²	5.0kN/m²	7.5kN/m²	
220 × 75 Class C24 timber joists at 400mm c/c	0.25kN/m²	5.55m	N/A	N/A	N/A	N/A	84
220 × 75 Class C24 timber joists at 400mm c/c	1.25kN/m²	5.0m	N/A	N/A	N/A	N/A	84
100 deep CLT floor panels	1.0kN/m²	3.8m	3.4m	3.1m	3.0m	2.7m	4
240 deep CLT floor panels	1.0kN/m²	6.9m (governed by vibration, so a function of dead load and span)				6.4m	4
140mm deep composite metal deck slab (60 mins fire)	Need to consider allowance as part of variable floor load	4.3m	4.3m	4.3m	4.3m	4.15m	86–89
295mm deep composite metal deck slab (60 mins fire)	Need to consider allowance as part of variable floor load	6.0m	6.0m	6.0m	6.0m	5.95m	86–89
150mm deep beam and block floor	1.8kN/m²	6.4m	6.0m	5.5m	5.1m	N/A	86–89
150mm deep non-composite hollow-core precast units (60 mins fire)	1.5kN/m²	7.5m	7.5m	7.1m	6.7m	5.85m	86–89
200mm deep non-composite hollow-core precast units (120 mins fire)	1.5kN/m²	10.0m	9.5m	8.55m	8.05m	7.1m	86–89
300mm deep non-composite hollow-core precast units (120 mins fire)	1.5kN/m²	14.6m	13.7m	12.5m	11.9m	10.7m	86–89
200mm one-way spanning C30/37 *in situ* RC slab (single span)	1.5kN/m²	≥6.0m	6.0m	5.7m	5.4m	5.0m	6
200mm one-way spanning *in situ* C30/37 slab (multiple span)	1.5kN/m²	≥7.0m	7.0m	6.7m	6.4m	6.0m	6

Table 8.4: *Continued*

Floor system	Allowance for super-imposed permanent loads due to finishes, services etc. (unfactored)	Maximum clear span, depending on value of unfactored variable floor load					Relevant sources
		1.5kN/m^2	2.5kN/m^2	3.5kN/m^2	5.0kN/m^2	7.5kN/m^2	
300mm two-way spanning C30/37 *in situ* RC flat slab (multiple span)	1.5kN/m^2	9.2m+	9.2m	8.5m	8.2m	7.0m	6

Note: Values are all based on unpropped construction except for *in situ* RC slabs.

Table 8.5: Guidance on preliminary sizing of common types of floor structure (indicative values)

Floor type	Ideal span-to-depth ratio	Efficient span range	Relevant sources
Softwood timber office floor (softwood joists at 400mm c/c)	L/10–L/15	≤8m	3
One-way spanning RC slab (simply-supported)[a,b]	L/23–L27	4–10m	85
One-way spanning RC slab (multiple span)[a,b]	L/27–L/32	4–10m	85
One-way spanning RC slab (cantilever)[a,b]	L/6	≤4m	85
In situ RC flat slab (multiple span)[a,b]	L/23–L/28	4–10m	85
In situ PT flat slab (multiple span)[a,b]	L/30–L/40	6–13m	85

Notes:
[a] Span-to-depth ratios for RC/PT slabs are based on overall depth.
[b] Span-to-depth ratios for RC/PT slabs are based on imposed loads of 2.5–10.0kN/m^2.
Actual span to depth ratios may significantly differ from the ideal values quoted here, depending on the value of the applied loads, for example.

Beams

The type of floor to be used will inform whether or not any floor beams are required. Floor (and roof) beams will be required in almost all framed structures, the only exception to this being *in situ* RC flat slab structures. Even loadbearing structures may require some beams locally e.g. where more open-plan areas are required, such as at ground floor level.

Due to the significant number of potential variations, including load, beam span and centres, support and propping conditions, it is not practical to produce a version of Table 8.4 for beams. Table 8.6 provides indicative span to depth ratios for a range of timber, steel and concrete beams which are commonly used in the UK. More detailed information can again be obtained from the literature.

Table 8.6: Guidance on preliminary sizing of common types of beam (indicative values)

Beam type	Ideal span to depth ratio	Efficient span range	Max. span	Comments and relevant sources
Sawn timber beams[a,b]	L/10– L/15	≤5m	5m	[3,4,77]
Glulam beams[a,b]	L/10–L/15	≤8m	30m	Consider transport and erection for long-span beams[3,4,77]
Flitch beams (steel/timber)[a,b]	L/10–L/20	≤6m	Potentially 10m, but 6m in practice	Expensive, so ideally used for repairs and alterations. Max. span governed by max. length of timber available[4]
Simply supported rectangular RC beams[a,b,c]	L/12	4–10m	12m	[3,6,74,85]
Simply supported RC T-beams and L-beams[a,b,c]	L/10	5–12m	14m	[3,6,74,85]
Continuous rectangular RC beams[b,c]	L/15	4–10m	≥12m	[3,6,74,85]
Continuous RC T-beams and L-beams[b,c]	L/12	5–14m	≥15m	[3,6,74,85]
Cantilever rectangular RC beams[b,c]	L/6	≤4m	4m	Likely to be governed by deflection[3,6,74,85]
Cantilever RC T-beams and L-beams[b,c]	L/5	≤4m	4m	Likely to be governed by deflection. No benefit in using flanged cantilever beams to floors, since flange is in tension[6,74,85]
Secondary steel floor beams/trusses (subject to UDLs)[a,b]	L/15–L/25	4–20m	≥20m	Consider transport and erection for long-span beams/trusses[3]
Primary steel beams/trusses (subject to heavy point loads)[a,b]	L/10–L/15	4–12m	≥20m	Consider transport and erection for long-span beams/trusses. May need to use plate girders, since standard UB sections may not be adequate[3]
Steel transfer floor beams/trusses[a,b]	L/10	16–30m	≥30m	As above (also note that splicing may be required)[3]
Lightweight steel roof beams[a,b]	L/18–L/30	6–60m	≥60m	As above (also note that splicing may be required)[3]

Notes:
[a] All beams and trusses are considered to be simply supported floor beams unless noted otherwise.
[b] Timber and steel beams are assumed to be unpropped, while *in situ* RC beams are propped.
[c] Span to depth ratios for RC beams are based on overall depth.
Actual span to depth ratios may significantly differ from the ideal values quoted here, depending on the value of the applied loads, for example.

8.1.6 Decision 6: On- or off-site construction

Are there opportunities (particularly on confined city centre sites, but also elsewhere) to prefabricate structural elements off-site? Prefabrication is certainly not a new idea, and was used extensively for post-war construction in the UK, albeit with mixed success. To avoid the baggage associated with the term ‘prefab’, many of the latest systems are generically referred to as ‘modern methods of construction’ (MMC) or ‘off-site manufacture’.

The extent to which pre-fabrication/MMC can be adopted varies from a simple node/connection detail to an entire building (Figure 8.20), from precast floors and walls (Figures 8.21–8.22), to structurally insulated panel systems (SIPs) (Figure 8.23) to complete modular units, as used for accommodation, healthcare and education, in which services, doors, windows and finishes are all installed in the factory (Figure 8.24).

Figure 8.20: ‘Matrix of prefabrication’

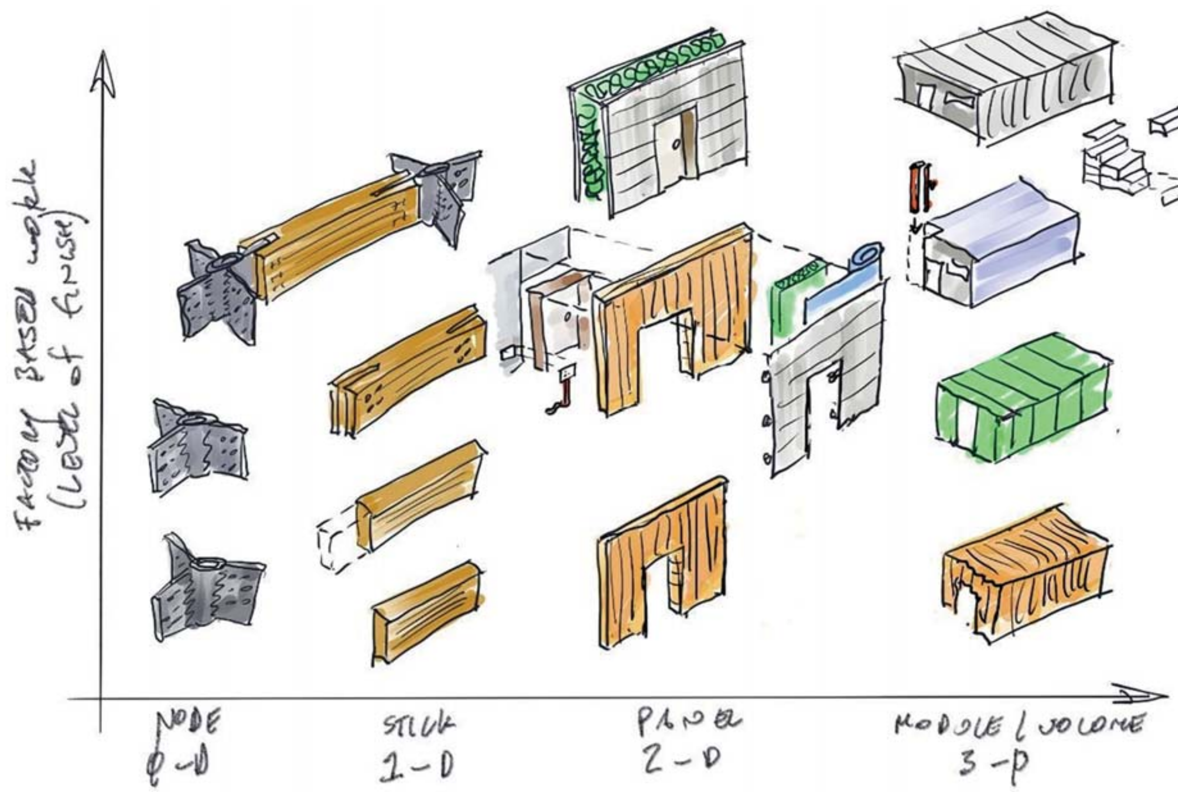


Figure 8.21: Precast concrete floor units

Figure 8.22: Precast concrete walls

Figure 8.23: Structurally insulated panel system (SIPs)

Figure 8.24: Use of modular units/volumetric construction for a school

The key benefits of pre-fabrication/MMC/off-site manufacture include:

Social
- Improved Health and Safety conditions/less accidents
- Improved working conditions

Environmental
- Reduced road traffic movements (congestion and pollution benefits)
- Reduced waste
- Reduced energy use on-site
- Reduced energy use in operation

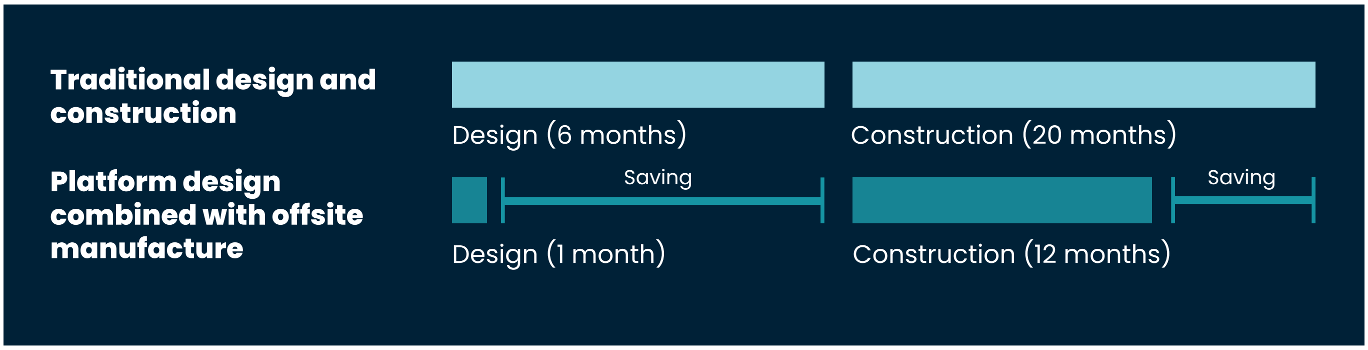
Economic

- Faster construction with up to 60% reduction in on-site construction programme e.g. due to reduced wet trades, and less days lost to inclement weather
- Higher quality construction/finish (e.g. of exposed concrete surfaces)
- More consistent structural properties/performance
- Reduced snagging and defects
- Reduced issues associated with drying shrinkage and creep of concrete and timber
- Higher tolerances

For more information, refer to Buildoffsite[90].

Figure 8.25 shows an indicative example of the programme benefits of pre-fabrication/MMC/off-site manufacture.

Figure 8.25: Indicative programme benefits of pre-fabrication/MMC/off-site manufacture[91]



8.2 Structural layouts

Once you have evaluated the six key decisions discussed in Section 8.1, you can start producing structural layouts, in order to communicate your ideas to the rest of the project team. At concept design stage, it is likely that you will produce a number of options for discussion, and potentially initial costing. Unless there is a very clear preference for a particular solution from the project team, and/or you are very experienced, there is a danger that just considering one option will result in you missing a better one.

The form of the structural layouts can vary at this stage, and options could be drawn up by hand or in CAD. If buildings are very repetitive in nature, it may be sufficient to show just a few typical bays as opposed to the structure of the whole building. Some examples of concept stage structural layouts are presented in Figures 8.26–8.31, as well as in Figs. 8.3–8.5, presented earlier in this chapter.

When we talk about layouts, we don't just mean floor plans, roof plans and foundation layouts, as these do not usually tell the full story of how the structure works — it is a good idea to include at least one full-height cross-section through the building (and more if the cross-sections vary along the length of the building). It would also be helpful to include any non-standard details you are proposing, so that the main contractor and associated subcontractors can make appropriate allowances e.g. for cost and programme.

Information which should ideally be shown on structural layout drawings at concept design stage includes:

- Typical member sizes e.g. beam, column and loadbearing wall sizes
- Floor slab type, and span direction
- Roof construction, and span direction
- Foundation/substructure type(s) and sizes
- Average weights of steel frame members at each floor and roof level
- Reinforcement weights/m^3 of concrete for any RC elements
- Key dimensions (column-to-column dimensions, floor-to-floor heights etc.)
- Locations and sizes of lateral stability systems e.g. shear walls/cores, vertical bracing, plan bracing

- Locations of any movement joints
- Any non-standard details e.g. Figure 8.32
- Strategy for integration of structure and services
- Key assumptions and data e.g. permanent and variable loads assumed for the design
- Information relating to construction sequence, buildability and (residual) design risks which might not be obvious
- Pros and cons of the option(s) shown

Figure 8.26: Don Valley Stadium — isometric sketch of typical bay

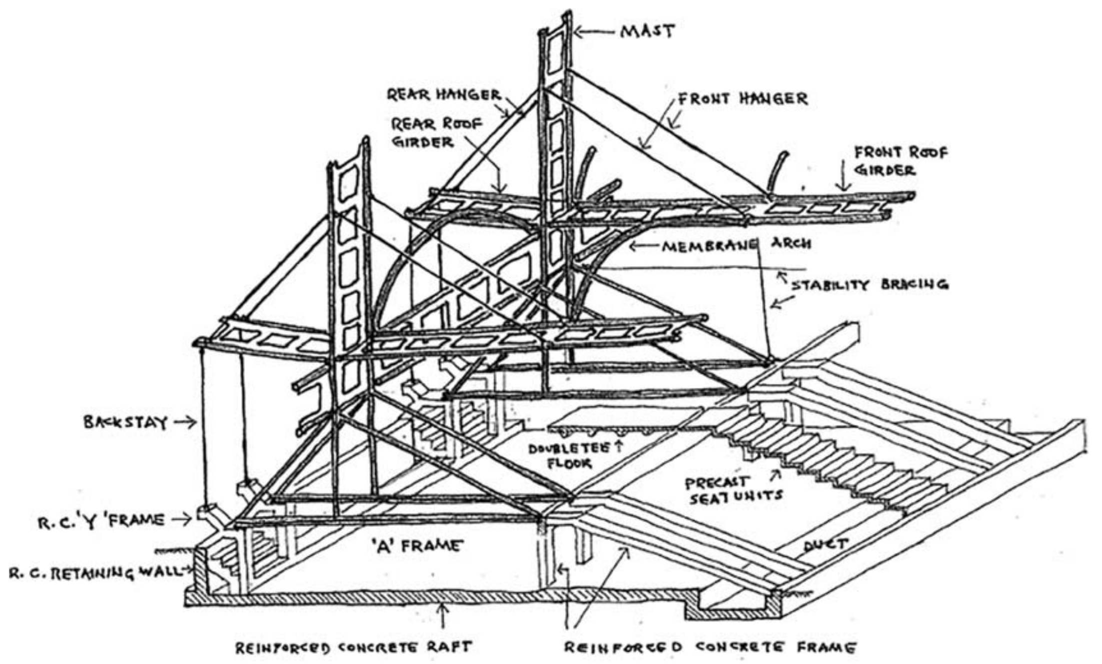


Figure 8.27: Research laboratory — typical floor layout for steel framed option

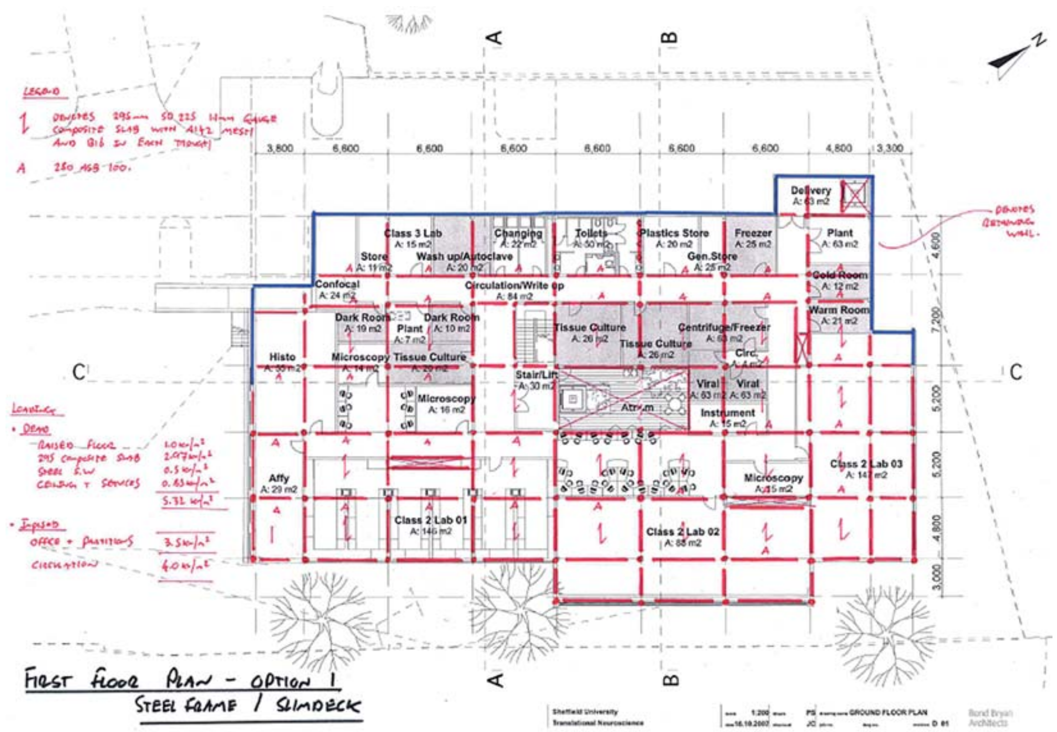


Figure 8.28: Research laboratory — typical floor layout for RC flat slab option

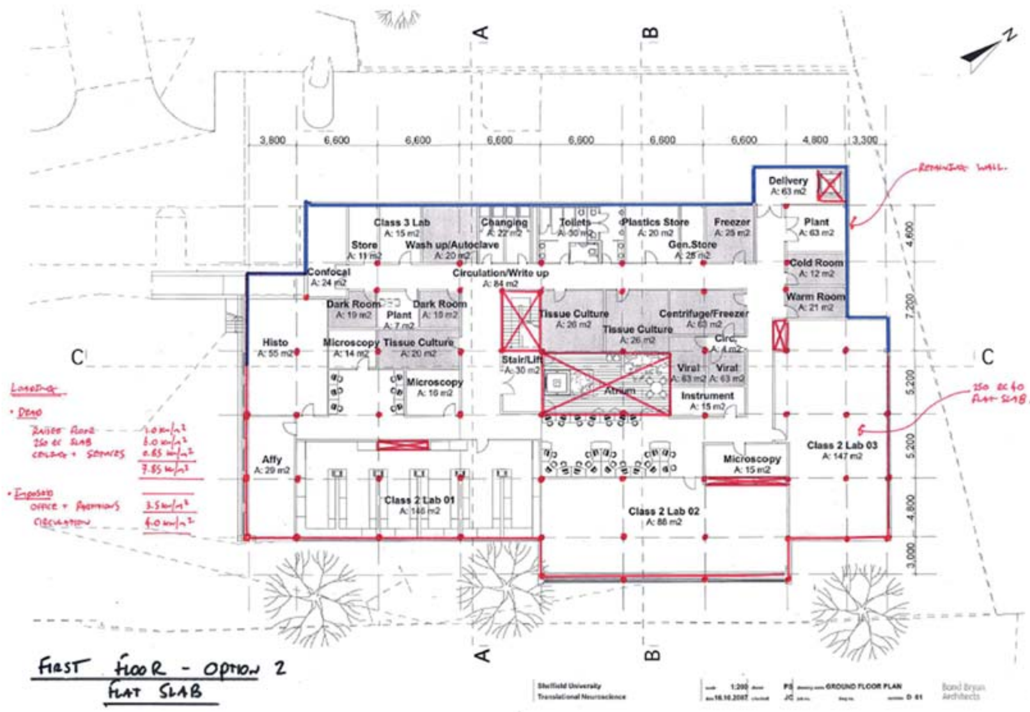


Figure 8.29: Education building — part-floor layout and full-height section for steel frame option

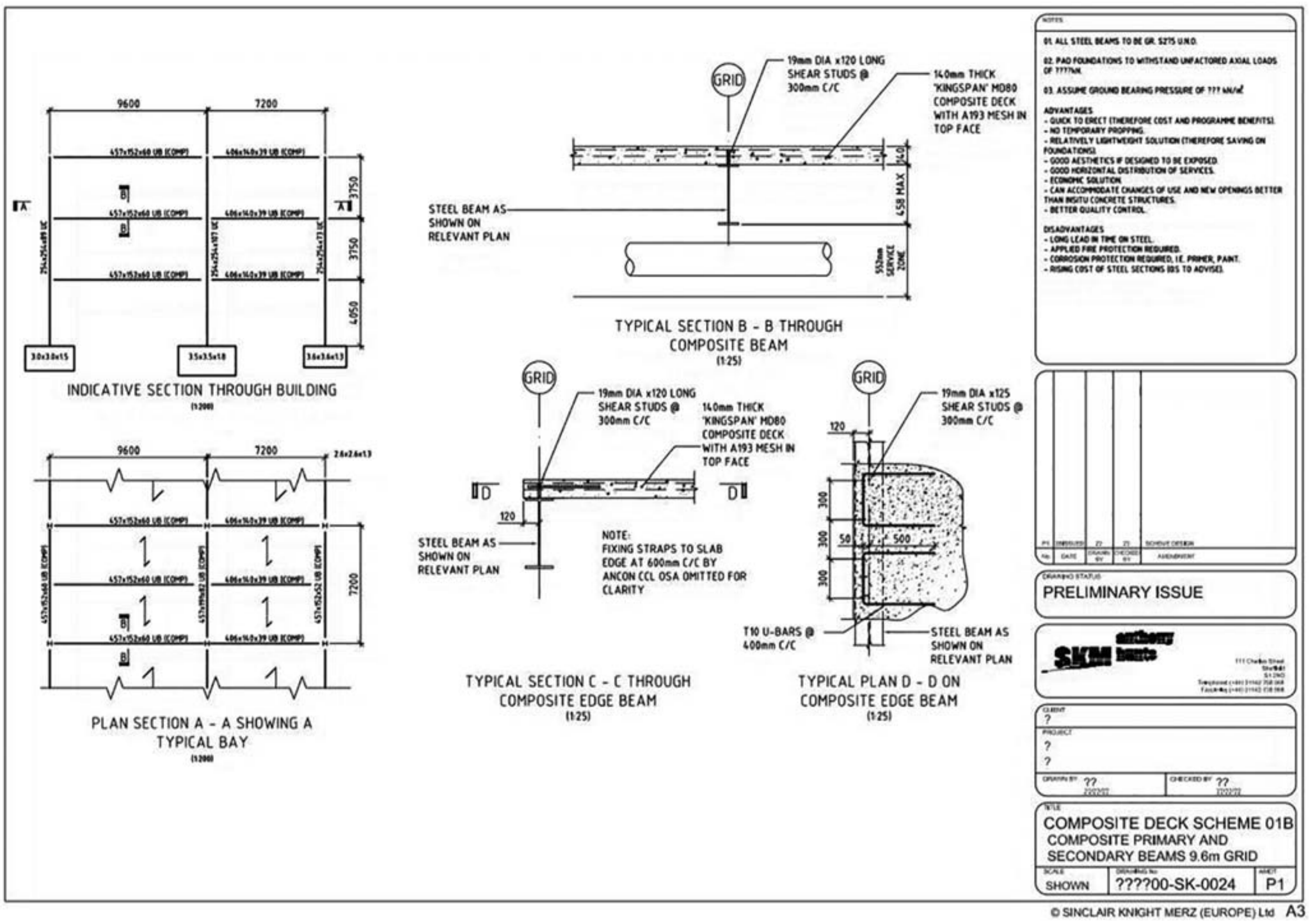


Figure 8.30: Education building — part-floor layout and full-height section for RC frame option

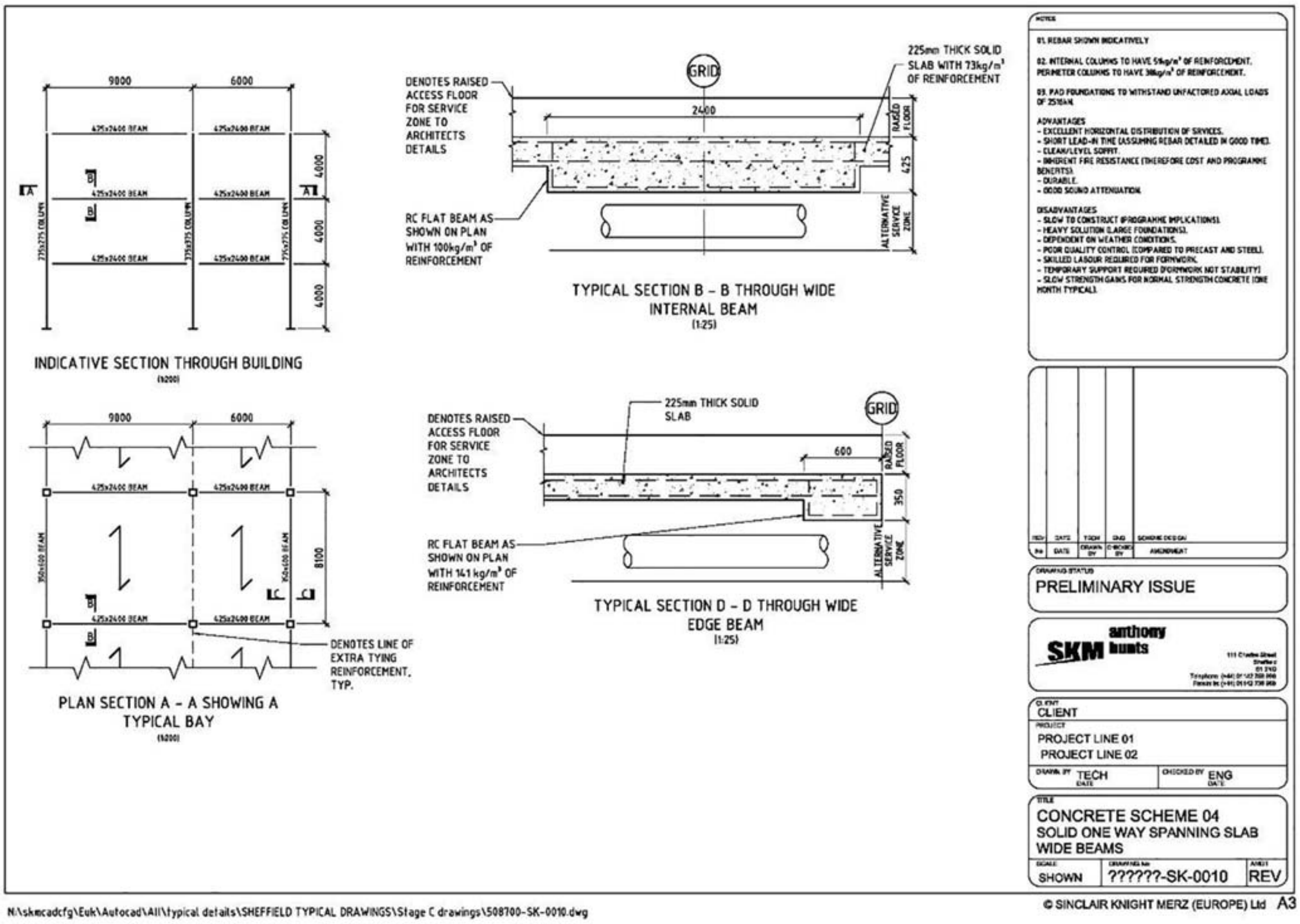


Figure 8.31: Isometric view of new mezzanine floor structure to an existing church

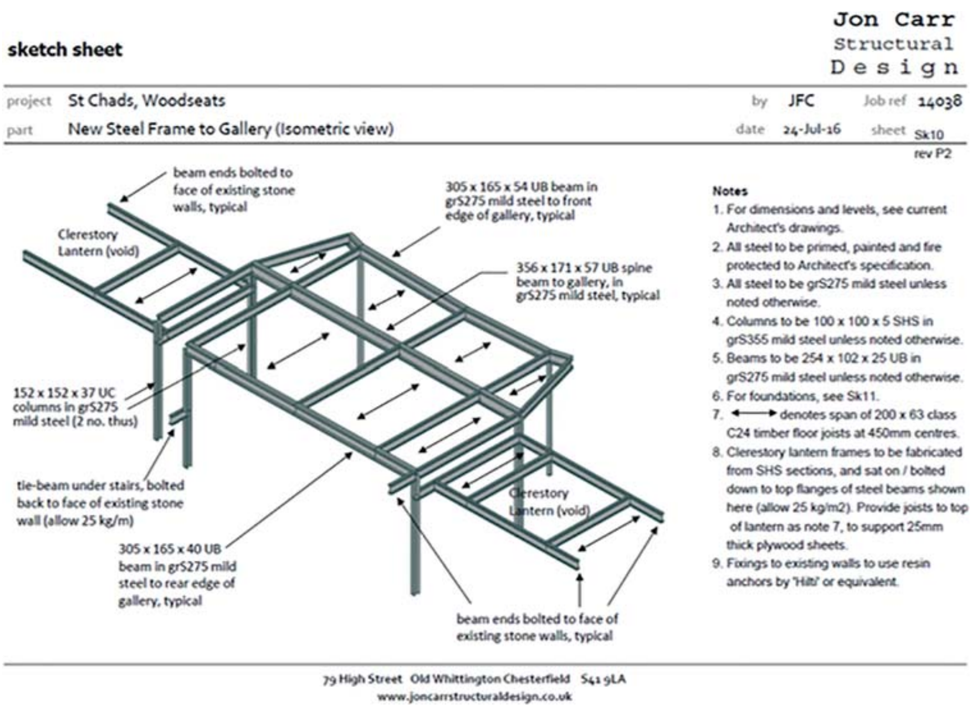
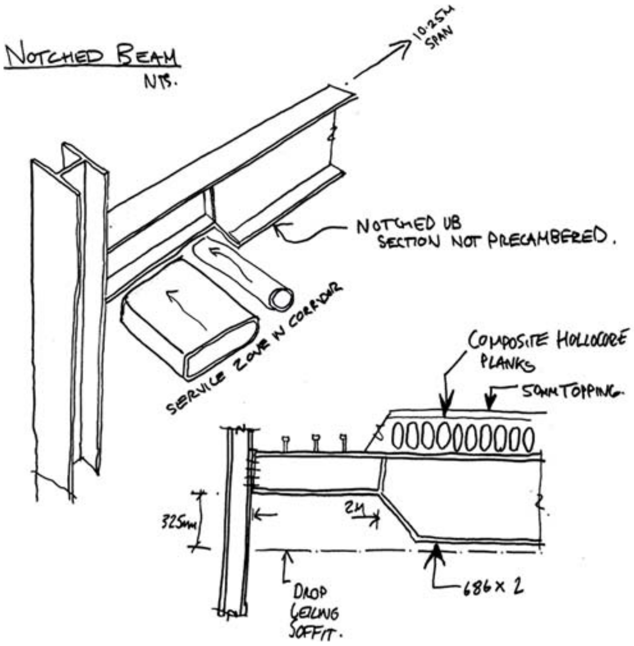


Figure 8.32: Notched steel beam detail to accommodate ducts/services



8.3 Roofs — where structural engineers get to have some fun!

The work carried out by structural engineers is often hidden in the final condition. So when we get the opportunity to show off our creativity and ingenuity, let's make the most of it. Good examples of where we can have some fun include roof structures, atria, entrance canopies, pedestrian bridges/walkways and staircases.

We will focus here on roof structures. Whether a roof to a multi-storey building or a long-span single storey structure, the relatively low variable loads on roofs, and with no requirement for the roof to be flat/level (as is required for a floor), opens up a diverse range of structural solutions to explore. In terms of structural form and materials, options include the following (with some examples in Figures 8.33–8.37):

- Conventional beams (straight, curved or tapered) in steel, timber and reinforced concrete
- Flitch beams (straight, curved or tapered) using a hybrid of steel and timber
- Trusses (straight, curved or tapered) in steel, timber or a hybrid of the two
- Portal frames in steel, timber and reinforced concrete
- Cable stayed roofs in steel, timber or a hybrid of the two
- Arched roofs in steel, timber and reinforced concrete
- Concrete shell roofs (singly- or doubly-curved)
- Timber grid-shell roofs (singly- or doubly-curved)
- Folded-plate structures (typically in either reinforced concrete or timber)
- Membrane/fabric structures (with double/anti-clastic curvature)
- Cable-nets
- Air-supported structures
- Tensegrity structures

Engineers are therefore encouraged to research and collect images and details of inspirational and innovative solutions, which they can potentially use on their own projects at some point in the future.

Figure 8.33: Selection of roof structure options

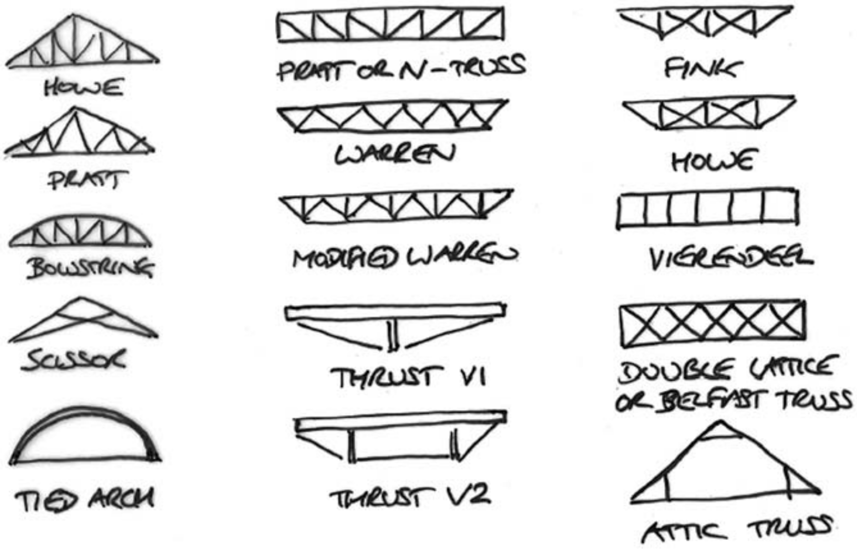


Figure 8.34: Sketch showing roof structure options to Bradford Academy

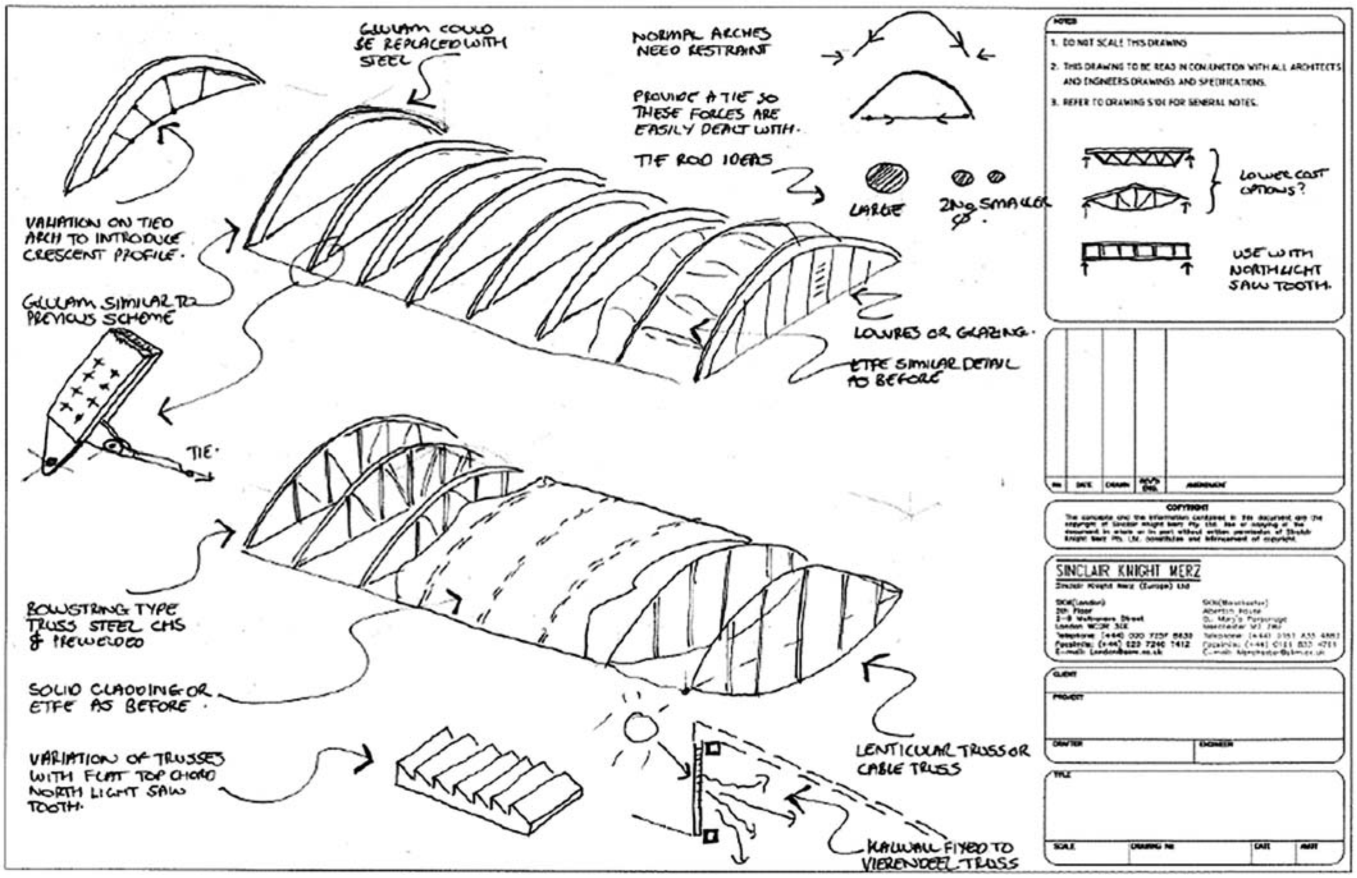


Figure 8.35: Adopted roof structure to Bradford Academy (tied steel arch with ETFE pillows)

Figure 8.36: Exposed concrete roof structure to York College

Figure 8.37: Steel 'trees' supporting steel roof structure to Teesside University

8.4 Movement joints, lateral stability and robustness

Due to their complexity, movement joints, lateral stability and robustness are covered in detail in Chapter 9, but they are fundamental structural issues which need detailed consideration at concept design stage. Making changes later is likely to involve a significant amount of re-design, re-drawing and re-modelling for the design team, and potentially subcontractors, which somebody will have to pay for.

8.5 Foundations

Foundations are covered in detail in Chapter 7. It is important to think about potential foundation solutions at concept design stage, since subsequent changes could prove costly and/or delay the project. In some cases, the foundation/substructure design could have a significant influence on the design of the superstructure being supported. Good examples of this are shown in Figures 8.17–8.18, where the presence of significant constraints below ground (train lines and archaeological remains) informed the structural frame solutions.

8.6 Practical examples

In Chapter 11 we look at three relatively common types of building in the UK — a ten-storey office block, a 30m span single-storey building, and a three-storey residential building. For each building type, two potential structural concepts are presented.

While these solutions cover a range of structural forms and materials, consider that many other solutions are possible. Furthermore the 'best solution' for any given project (if one exists, since in reality there will often be a number of potentially valid solutions) will depend on a diverse range of considerations, many of which will be project-specific.