Multi-storey Precast Concrete Framed Structures

2nd Edition

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Preface

Of all the major forms of multi-storey building construction, structural precast concrete is perhaps understood by the fewest practitioners. This is a significant 'blind spot' in that part of the building profession associated with the design and construction of large or small multi-storey precast and prestressed concrete frames. This is due mainly to two particular factors:

- The notion of using a modular form of construction, such as precast concrete, is not widely taught at undergraduate level because it is thought of as being too restrictive in the wider application of theory and design instruction.
- Precast concrete design is usually carried out in-house by the small number of specialist engineers employed by the precast manufacturing companies.

Consequently, the trainee structural designer is rarely exposed to the virtues of using precast concrete in this way. Opportunities to study the basic concepts adopted in the design, manufacturing and site erection stages are not often made available to the vast majority of trainees.

Even where precast concrete is accepted as a viable alternative form of construction to e.g. steelwork for medium to high-rise structures, or to insitu concrete for some of the more complex shaped buildings, or to masonry for low-rise work, it is often considered only at a late stage in the planning process. In these situations, precast concrete is then often restricted to the substitution of components carrying their own locally-induced stresses. The economic advantage of the precast components also carrying global stresses is lost in the urgency to commence construction. Indeed, precast component design has long been considered as having a secondary role to the main structural work. Only more recently have precast designers been challenged to validate the fundamental principles they are using, and to give clients confidence in precast concrete design solutions for entire structures.

To meet ever-increasing building specifications, precast manufacturing companies have considerably refined the design of their product. They have formed highly effective product associations dealing with not only the marketing and manufacturing of the product, but also with technical matters. These include common design solutions, research initiatives, education, unified design approaches, and, importantly, the encouragement of a wider appreciation of precast structures in the professional design office. Even so, the structural and architectural complexity of some of the more recent precast frames has widened the gap between precast designers and the rest of the profession. The latter have limited sources for guidance on how the former are working. Satisfying codes of practice and the building regulations plays only a minor role in the total package; there is so much more, as this book shows.

Nowadays, the use of precast reinforced and prestressed concrete for multi-storey framed buildings is widely regarded as an economic, structurally sound and architecturally versatile building method. Design concepts have evolved to satisfy a wide range of commercial and industrial building needs. 'Precast concrete frames' is a term which is now synonymous with high quality, strength, stability, durability and robustness. Design is carried out to the highest standard of exactness within the concrete industry and yet the knowhow, for the reasons given above, remains essentially within the precast industry itself.

Precast concrete buildings do not behave in the same way as cast-in situ ones. The components which make up the completed precast structure are subjected to different forces and movements from the concrete in the monolithic structure. It is necessary to understand where these physical effects come from, where they go to, and how they are transferred through the structure.

Consequently, this book aims to disseminate understanding of the disparate procedures involved in precast structural design, from drawing office practice to explaining the reasons for some of the more intricate operations performed by precast contractors on site. The principal focus is upon on skeletal-frame type structures, the most extensively used form of precast structural concrete. They are defined as frameworks consisting essentially of beams, columns, slabs and a small number of shear walls.

From the structural and architectural viewpoints, skeletal frames are the most demanding of all precast structures. They contain the smallest quantity of structural concrete per unit volume. The precast components can be coordinated into the architectural façade, both internally and externally, to meet the social, economic and ecological demands that are now required. Ever greater accuracy, quality control, and on-site construction efficiency are being demanded and achieved. The construction industry is turning to high-specification prefabricated concrete for its advancement, using 'factory engineered' precasting techniques.

The chapters in this book have been arranged so that different parts of the design process can be either isolated (for example in the cases of precast flooring, or of connections), without the reader necessarily referring to the overall frame design, or read sequentially to realise the entire design. Chapters 1 to 3 present an overview of the subject in a non-technical way. Chapters 4 to 9 describe, in detail, the design procedures that would be carried out in a precast manufacturing company's design office. Chapter 10 describes the relevant site construction methods. Numerous examples have been used to demonstrate the application of design rules, many of which are not code-dependent.

There are many aspects to the design of precast skeletal frames that have evolved through the natural development of precast frame design since the 1950s. One aim of this book is to update and coordinate this information for the future. Historically, the precast concrete industry considered many of its design techniques commercially sensitive, particularly those for connector design, and was consequently criticised by developers and consultants. More information is now freely available since the expiry of many patents of ideas. One of the main purposes of the first edition was to bring together in a coherent manner, for the benefit of everyone, the widely varied design methods used in the industry. The second edition aims to extend that process in the context of continually developing technology and the introduction of Europe-wide design requirements embodied in the Eurocodes. It also demonstrates the trend towards greater, often fully serviced, spatial precast components.

Precast concrete designs are not entirely code-dependent, but the primary recommendations are in accordance with Eurocode 2 (BS EN 1992-1-1) and its predecessor BS 8110. Where the design procedures from the two codes differ, they are explained. Where major differences occur, or accumulate in design examples, the text is presented in two parallel columns with the Eurocode version in the left column and the BS 8110 text in the right column. When minor textual differences occur for the application of the two codes, Eurocode 2 forms the basic text, with the alternative BS text within braces or curly brackets thus: {to BS 8110}. It may help the reader to know that the authors have retained braces exclusively for this purpose, leaving the use of round brackets for the two contextually differentiable functions of parenthesis or mathematical grouping, and square brackets for references.

The combination of a broad overview, background research, and detailed analysis, the references to the familiar British Standards and the new Eurocodes, and an extensive range of illustrations together combine to offer a valuable resource for both undergraduate and practising engineers in the field of precast concrete.

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Notation

Latin upper-case letters

A	Accidental action
A	Cross-sectional area
A_b	Cross-sectional area of bolts
A_{bst}	Area of bursting reinforcement
A_c	Cross-sectional area of concrete
A_c'	Gross cross-sectional area of hollow-core slabs
$A_c'{}_{(net)}$	Net cross-sectional area of hollow-core slabs
A_d	Area of diagonal reinforcement
A_f	Cross-sectional area of flange
A_{hd}	Area of diaphragm reinforcement
A_k	Contact area in castellated joint
A_p, A_{ps}	Area of a prestressing tendon or tendons
A_s	Cross-sectional area of tension reinforcement
A_s'	Area of compression reinforcement
A_s''	Area of longitudinal reinforcement in top of boot of beam
A_{sc}	Total area of reinforcement in column
A_{sh}	Area of horizontal reinforcement
A_{shv}	Area of horizontal punching shear reinforcement
$A_{s,min}$	Minimum cross-sectional area of reinforcement
A_{sv}	Area of shear reinforcement
A_{sw}	Cross-sectional area of shear reinforcement; area of reinforcing bars welded to plate
B	Breadth of void in slab; breadth of building; breadth of foundation
C	Compressive force
D	Diameter of mandrel; depth of pocket in foundation; depth of floor diaphragm; depth of hcu
D_{Ed}	Fatigue damage factor
E	Effect of action; Young's modulus of elasticity
E'	Equivalent Young's modulus in precast *in situ* joint
E_c	Tangent modulus of elasticity of normal weight concrete at a stress of $\sigma_c = 0$
E_c'	Young's modulus of *in situ* concrete
$E_{c(28)}$	Tangent modulus of elasticity of normal weight concrete at 28 days
$E_{c,eff}$	Effective modulus of elasticity of concrete
E_{cd}	Design value of modulus of elasticity of concrete
E_{ci}	Young's modulus of concrete at transfer
E_{cm}	Secant modulus of elasticity of concrete
$E_{c(0)}$	Tangent modulus of elasticity of normal weight concrete at a stress of $\sigma_c = 0$
$E_{c(t)}$	Tangent modulus of elasticity of normal weight concrete at time t

E_i	Young's modulus of infill concrete
E_p	Design value of modulus of elasticity of prestressing steel
E_s	Design value of modulus of elasticity of reinforcing steel
EI	Bending stiffness
EQU	Static equilibrium
F	Action; force
F_{bt}	Ultimate tensile force in bars at start of bends
F_c	Compressive force in concrete
F_{cR}	Ultimate compressive resistance force
F_d	Design value of an action; tensile force in diagonal reinforcing bars
F_h	Tensile force in horizontal reinforcing bars
F_k	Characteristic value of an action
F_s	Tensile force in reinforcing bars
F_t	Notional tensile force in stability ties
F_t'	Tensile force in stability ties
F_{tR}	Ultimate tensile resistance force
F_v	Shear force to one side of interface (composite construction)
G	Shear modulus
G_k	Characteristic permanent action
H	Total height of building; length of foundation; horizontal force
H_{bst}	Bursting force
H_v	Horizontal resistance of infill wall
I	Second moment of area of concrete section
I_c	Transformed second moment of area of composite section
I_{co}	Compound second moment of area
K	Stress factor $M/f_{ck}\ b\ d^2$ $\{M/f_{cu}\ b\ d^2\}$; shrinkage factor
K_b	Flexural stiffness of connections between members
K_s	Shear stiffness of connections between members
K_t	Bond length parameter
L	Length; span; length of void in slab; length of building base plate overhang distance
L'	Clear opening between columns; length of wall
L_e	Effective length
L_s	Clamping length
L_{sb}	Bond length
L_1	Distance from face of column to load
L_2, L_3	Length of stress block (insert design)
L_4	Length of embedment of insert
M	Bending moment
M'	Moment of resistance based on strength of concrete = $0.206\ f_{ck}\ b\ d^2$ $\{0.156\ f_{cu}\ b\ d^2\}$
M_{add}	Additional bending moment due to deflection = Na_u
M_b	Bending moment due to shrinkage
M_c	Balancing bending moment due to shrinkage
M_{Ed}	Design value of the applied internal bending moment
M_h	Bending moment in floor diaphragm
M_{max}, M_{min}	Maximum and minimum bending moment

M_{net}	M_{max}-M_{min}
M_o	Decompression bending moment
M_R	Moment of resistance
M_{sr}	Serviceability moment of resistance
M_{Rd} $\{M_{ur}\}$	Ultimate moment of resistance
M_1, M_2, M_3	Strength of connections in frames
N	Axial force; number of strands/wires/bolts
N_{Ed}	Design value of the applied axial force (tension or compression)
P	Prestressing force
P_0	Initial force at the active end of the tendon immediately after stressing
P_{po} $\{P_f\}$	Prestressing force after all losses
P_{pi} $\{P_i\}$	Initial prestressing force
P_{pmi}	Prestressing force at installation
P_{pm0} $\{P_t\}$	Prestressing force at transfer
P_r	Prestressing force after initial relaxation
P_t	Prestressing force at transfer
Q_k	Characteristic variable action
Q_{fat}	Characteristic fatigue load
R	Resistance; prop force
R_a	Roughness factor
R_y	Diagonal resistance of infill wall
S	Internal forces and moments; first moment of area; plastic section modulus
S_c	First moment of area to one side of interface
SLS	Serviceability limit state
T	Torsional moment; tension force
T_{Ed}	Design value of the applied torsional moment
ULS	Ultimate limit state
V	Shear force; reaction force
V_{co}	Shear resistance in flexurally uncracked prestressed section
V_{cr}	Shear resistance in flexurally cracked prestressed section
V_d	Shear force in dowel
V_{Ed}	Design value of the applied shear force
V_h	Horizontal shear force
V_r	Increased shear capacity due to additional reinforcement (insert design)
$V_{Rd,c}$ $\{V_{co}\}$	Shear resistance in flexurally uncracked prestressed section
$V_{Rd,cr}$ $\{V_{cr}\}$	Shear resistance in flexurally cracked prestressed section
$V_{Rd,CF}$	Ultimate shear capacity (compression field theory)
V_{uh}	Ultimate horizontal shear force
W	Self weight of column
W_k	Characteristic wind load
W_u	Ultimate wind load
X	Distance to neutral axis; stress block depth factor

Z	Elastic section modulus
Z_b, Z_t	Elastic section modulus at extreme bottom and top fibres
$Z_{b,co}$ $Z_{t,co}$	Compound elastic section modulus at extreme bottom and top fibres
Z_c	Elastic cracked concrete section modulus
Z_u	Elastic uncracked concrete section modulus

Latin lower-case letters

a	Distance; lever arm distance; distance to wall from shear centre; geometrical data
Δa	Deviation for geometrical data
a'	Distance from compression face to point where crack width is calculated
a_b	Clear distance between bars; cover to inside face of bars
a_{cr}	Distance from nearest bar to point where crack width is calculated
a_{eff}	Effective bearing length at corbel
a_f	Tangent of coefficient of friction, i.e. $\mu = \tan \alpha_f$
a_u	Sway deflection
a_v	Lever arm distance to shear force
b	Overall width of a cross-section, or actual flange width in a T- or L-beam
b_e, b_{eff}	Effective breadth
b_l	Length of bearing
b_p	Breadth of bearing
b_t	Breadth of section at centroid of steel in tension
b_v	Breadth of shear section or shear web
b_w	Width of the web on T-, I- or L-beams
c	Cover distance; distance to centre of bar
c_{min}	Minimum distance to bar in tension
c_w	Crack width
d	Diameter; depth; effective depth of a cross-section to tension steel; depth of web in steel sections
d'	Effective depth to compression steel
d''	Effective depth to tension steel in boot of beam
d_f	Effective depth to edge of foundation pocket
d_g	Largest nominal maximum aggregate size
d_h	Effective depth of half joint
d_n	Depth to centroid of compression zone
e	Eccentricity
e'	Effective eccentricity; lack of verticality
e_i $\{e_{add}\}$	Second order eccentricity
e_{net}	Net eccentricity
e_x	Minimum eccentricity (infill wall)
f_b	Ultimate bearing stress; limiting flexural compressive stress in concrete
f_{bc}	Bottom fibre stress due to prestress after losses
f_{bci}	Bottom fibre stress due to prestress at transfer
f_{bd}	Ultimate bond stress
f_{bpd}	Ultimate bond stress within the anchorage length
f_{bpt}	Bond stress within the transmission length
f_c	Compressive strength of bearing material

f_c'	Effective compressive strength of precast *in situ* concrete joint
f_{cc}	Prestress at centroid of tendons after losses
f_{cci}	Prestress at centroid of tendons at transfer
f_{cd}	Design value of concrete compressive strength
f_{ci}	Characteristic compressive cube strength of concrete at transfer
f_{ck}	Characteristic compressive cylinder strength of concrete at 28 days
f_{cm}	Mean value of concrete cylinder compressive strength
f_{cp}	Prestress at centroidal axis (taken as positive)
f_{cpx}	Prestress at centroidal axis at distance x from end of section
f_{ct}	Limiting flexural tensile stress in concrete
f_{ctk}	Characteristic axial tensile strength of concrete
f_{ctm}	Mean value of axial tensile strength of concrete
f_{cu}	Characteristic compressive cube strength of concrete
f_{cu}'	Characteristic compressive cube strength of infill concrete, ditto at lifting
f_{cyl}	Characteristic compressive cylinder strength of concrete
f_k	Characteristic compressive strength of brickwork
f_p	Tensile strength of prestressing steel
f_{pb}	Design tensile stress in tendons/wires
f_{pe}	Final prestress in tendons/wires after losses
f_{pi} $\{f_i\}$	Initial prestress in tendons
f_{pk}	Characteristic tensile strength of prestressing steel
f_{pm0} s_{pm0}	Prestress at transfer
f_{po} s_{po} $s_{pm\infty}$ $\{f_{pe}\}$	Final prestress in tendons/wires after losses
$f_{p0,1}$	0.1% proof-stress of prestressing steel
$f_{p0,1k}$	Characteristic 0.1% proof-stress of prestressing steel
$f_{0,2k}$	Characteristic 0.2% proof-stress of reinforcement
f_{pu}	Characteristic strength of prestressing tendons/wires
f_{Rd}	Ultimate bearing stress
f_s	Stress in reinforcing steel bars
f_t	Tensile strength of reinforcement; limiting direct (splitting) tensile stress in concrete
f_{tc}	Top fibre stress due to prestress after losses
f_{ti}	Top fibre stress due to prestress at transfer
f_{tk}	Characteristic tensile strength of reinforcement
f_v	Characteristic shear strength of brickwork
f_y	Yield strength of reinforcement
f_{yb}	Characteristic strength of bolts
f_{yd}	Design yield strength of reinforcement
f_{yk}	Characteristic yield strength of reinforcement
f_{ykw} $\{p_{weld}\}$	Strength of weld material
f_{yv}	Characteristic strength of reinforcing steel links/stirrups
f_{ywd}	Design yield of shear reinforcement
f_{ywk} $\{f_{yv}\}$	Characteristic strength of reinforcing steel links/stirrups
g_k	Characteristic uniformly distributed dead load
h	Height; floor-to-floor height; overall depth of section
h'	Clear floor-to-floor height; reduced depth at half joint
h_{agg}	Nominal size of aggregate
h_s	Depth of slab in composite construction
i	Radius of gyration

k	Coefficient; factor; core distance = $I/(0.5\,hA)$
k_s	Shear stiffness in joints
k_b	Flexural stiffness in joints
k_j	Rotational stiffness in joints
l	Length; span; distance between column-to-column centres
l_b	Bearing length
l_{bd}	Design anchorage length
l_e	Effective length
l_0	Clear height between restraints
l_{bpd} $\{l_p\}$	Prestress anchorage {development} length
l_{pt1}	Prestress transmission length, lower bound
l_{pt2} $\{l_t\}$	Prestress transmission length, upper bound
l_r	Distance between columns or walls (stability ties)
l_t	Prestress transmission length
l_w	Length of weldment
l_x	Penetration of starter bar into hole
l_z	Distance between positions of zero bending moment
m	Mass; distance from centre of starter bar to holding down bolt (base plate); modular ratio
m_{add}	Additional bending moment due to deflection = $N_{Ed}e_i$
m_s	Modular ratio (of elastic moduli) at service
m_u	Modular ratio (of strength) at ultimate
n	Number of columns in one plane frame, number of bars in tension zone of wall; number of storeys
p_b	Bearing strength of steel plate
p_{weld}	Strength of weld material
p_{yk} $\{p_y\}$	Strength of steel plate
q	Pressure (key elements)
q_k	Characteristic uniformly distributed live load
r	Radius; radius of gyration; bend radius of reinforcing bar
$1/r$	Curvature at a particular section
s	Spacing of reinforcing bars
t	Thickness; time being considered; temperature range
t_{eff}	Effective thickness
t_0	The age of concrete at the time of loading
u	Perimeter of concrete cross-section, having area A_c; perimeter distance
u, v, w	Components of the displacement of a point
v	Thickness of *in situ* infill; v_{Edi} $\{v\}$ ultimate shear stress
v_{ave}	Average interface shear stress
v_c	Design concrete shear stress
v_h	Design interface shear stress
v_{Rdi} $\{v_u\}$	Ultimate shear stress resistance
v_t	Design torsion stress

w	Length of steel plate; uniformly distributed load; breadth of compressive strut
w'	Diagonal length of infill shear wall
w_k	Characteristic uniformly distributed wind pressure
x	Neutral axis depth; dimension of stirrup in boot of beam; distance to centroid of stabilising system
x, y, z	Coordinates
x_{se}	Average crack spacing
y_{po}	Half bearing breadth ($b_p/2$)
y_0	Half section breadth ($b/2$)
z	Lever arm of internal forces

Greek upper-case letters

Δ	Second order deflection; deformation; construction tolerance distance
Φ	Reinforcing bar or dowel diameter; ductility factor

Greek lower-case letters

α	Angle; ratio; ratio Z_r/Z_b; coefficient of thermal expansion; characteristic contact length in infill wall
α_c	Ratio of sum of column stiffness to beam stiffness
α_{cmin}	Minimum value of α_{ca}
α_1	Ratio of distance to shear plane/transmission length l_x/l_{pt2}
β	Angle; ratio; coefficient
γ	Partial factor
γ_A	Partial factor for accidental actions, A
γ_C	Partial factor for concrete
γ_F	Partial factor for actions, F
$\gamma_{F,fat}$	Partial factor for fatigue actions
$\gamma_{C,fat}$	Partial factor for fatigue of concrete
γ_G	Partial factor for permanent actions, G
γ_M	Partial factor for a material property, taking account of uncertainties in the material property itself, in geometric deviation and in the design model used
γ_P	Partial factor for actions associated with prestressing, P
γ_Q	Partial factor for variable actions, Q
γ_S	Partial factor for reinforcing or prestressing steel
$\gamma_{S,fat}$	Partial factor for reinforcing or prestressing steel under fatigue loading
γ_f	Partial factor for actions without taking account of model uncertainties
γ_g	Partial factor for permanent actions without taking account of model uncertainties
γ_m	Partial factors for a material property, taking account only of uncertainties in the material property
δ	Increment/redistribution ratio; deflection; shear slip
ε	Strain
ε_b	Free shrinkage strain in precast beam or slab
ε_{bb}	Free shrinkage strain in bottom of precast beam or slab
ε_{bt}	Free shrinkage strain in top of precast beam or slab
ε_c	Compressive strain in the concrete

ε_{c1}	Compressive strain in the concrete at the peak stress f_c
ε_{cu}	Ultimate compressive strain in the concrete
ε_f	Strain of reinforcement or prestressing steel at maximum load
ε_m	Free shrinkage strain in *in situ* concrete flange or topping
ε_s	Average strain at level where crack width is calculated
ε_{sh}	Steel strain; relative shrinkage strain $\varepsilon_f – \varepsilon_{bt}$
ε_u	Shrinkage strain
ε_u	Strain at the level where crack width is calculated
ε_{uk}	Characteristic strain of reinforcement or prestressing steel at maximum load
ζ	Reduction factor/distribution coefficient
η	Total losses in prestressing force; force reduction factors
θ	Angle; slope of infill wall
λ	Slenderness ratio; relative stiffness parameter; joint deformability
μ	Coefficient of friction; degree of prestress force P_i/P
ν	Poisson's ratio; strength reduction factor for concrete cracked in shear
ξ	Ratio of bond strength of prestressing and reinforcing steel; bursting coefficient; prestress loss due to elastic shortening
ρ	Stress; reinforcement ratio = A/bd; oven-dry density of concrete in kg/m^3
ρ_{1000}	Value of relaxation loss (in %), at 1000 hours after tensioning and at a mean temperature of 20°C
ρ_l	Reinforcement ratio for longitudinal reinforcement
ρ_w	Reinforcement ratio for shear reinforcement
σ_c	Compressive stress in the concrete
σ_{cp}	Compressive stress in the concrete from axial load or prestressing
σ_{cp}	Spalling stress
σ_{cu}	Compressive stress in the concrete at the ultimate compressive strain, ε_{cu}
τ	Torsional shear stress; shear stress
ϕ	Diameter of a reinforcing bar or of a prestressing duct; rotation; diameter
ϕ_n	Equivalent diameter of a bundle of reinforcing bars
$\phi_{(t,t0)}$	Creep coefficient, defining creep between times t and t_0, related to elastic deformation at 28 days
$\phi_{(\infty,t0)}$	Final value of creep coefficient
ψ	Factor defining representative values of variable actions
ψ_0	Factor for combination values
ψ_1	Factor for frequent values
ψ_2	Factor for quasi-permanent values

CHAPTER 1

Precast Concepts, History and Design Philosophy

The background to the relevance of precast concrete as a modern construction method for multi-storey buildings is described. The design method is summarised.

1.1 A Historical Note on the Development of Precast Frames

Precast concrete is not a new idea. William H. Lascelles (1832–85) of Exeter, England devised a system of precasting concrete wall panels, 3 ft × 2 ft × 1 inch thick, strengthened by forged, ⅛ inch-square iron bars. The cost was 3d (£0.01) per ft^2. Afterwards, the notion of 'pre-casting' concrete for major structural purposes began in the late nineteenth century, when its most obvious application – to span over areas with difficult access – began with the use of flooring joists. François Hennebique (1842–1921) first introduced precast concrete into a cast-*in situ* flour mill in France, where the self-weight of the prefabricated units was limited to the lifting capacity of two strong men! White [1.1] and Morris [1.2] give good historical accounts of these early developments.

The first precast and reinforced concrete (rc) frame in Britain was Weaver's Mill in Swansea. In referring to the photograph of the building, shown in Figure 1.1, a historical note states: . . . *the large building was part of the flour mill complex of Weaver and Co. The firm established themselves at the North Dock basin in 1895–6, and caused the large ferro-concrete mill to be built in 1897–98. It was constructed on the system devised by a Frenchman, F. Hennebique, the local architect being H. C. Portsmouth* . . . At this time Louis Gustave Mouchel (1852–1908, founder of the Mouchel Group) was chosen to be Hennebique's UK agent. Mouchel used a mix of cast-*in situ* and prefabricated concrete for a range of concrete framed structures, building at the rate of 10 per year for the next 12 years.

The structure was a beam-and-column skeletal frame, generally of seven storeys in height, with floor and beams spans of about 20 feet. The building has since been demolished owing to changes in land utilisation, but as a major precast and reinforced concrete construction it pre-dates the majority of early precast frames by about 40 years.

Bachmann and Steinle [1.3] note that the first trials in structural precast components took place around 1900, for example at Coignet's casino building in Biarritz in 1891, and Hennebique and Züblin's signalman's lodge in 1896, a complete three-dimensional cellular structure weighing about 11 tons [1.3].

During the First World War storehouses for various military purposes were prefabricated using rc walls and shells. Later, the 1930s saw expansions by companies such as Bison, Trent Concrete and

Multi-storey Precast Concrete Framed Structures, Second Edition. Kim S. Elliott and Colin K. Jolly.

Figure 1.1 Weaver's Mill, Swansea – the first precast concrete skeletal frame in the United Kingdom, constructed in 1897–98 (courtesy of Swansea City Archives).

Girling, with establishments positioned close to aggregate reserves in the Thames and Trent Valley basins. The reason why precast concrete came into being in the first place varies from country to country. One of the main reasons was that availability of structural timber became more limited. Some countries, notably the Soviet Union, Scandinavia and others in northern Continental Europe, which together possess more than one-third of the world's timber resources but experience long and cold winters, regarded its development as a major part of their indigenous national economy. Structural steelwork was not a major competitor at the time outside the United States, since it was batch-processed and thus relatively more expensive.

During the next 25 years developments in precast frame systems, prestressed concrete (psc) long-span rafters (up to 70 feet), and precast cladding increased the precasters' market share to around 15 per cent in the industrial, commercial and domestic sectors. Influential articles in such journals as the *Engineering News Record* encouraged some companies to begin producing prestressed floor slabs, and in order to provide a comprehensive service by which to market the floors these companies diversified into frames. In 1960 the number of precast companies manufacturing major structural components in Britain was around thirty. Today it is about eight.

Early structural systems were rather cumbersome compared with the slim-line components used in modern construction. Structural zones of up to 36 inches, giving rise to span/depth ratios of less than 9, were used in favour of more optimised precasting techniques and designs. This could have been called the 'heavy' period, as shown in C. Glover's now classic handbook *Structural Precast Concrete* [1.4]. Some of the concepts shown by Glover are still practised today and one cannot resist the thought that the new generation of precast concrete designers should take heed of books such as this. It is also difficult to avoid making comparisons with the 'lighter' precast period that was to follow in the 1980s, when the saving on total building height could, in some instances, be as much as 100 to 150 mm per floor.

Attempts to standardise precast building systems in Britain led to the development of the National Building Frame (NBF) and, later, the Public Building Frame (PBF). The real initiative in developing these systems was entrenched more in central policy from the then Ministry of Public Building and Works than by the precasting engineers of the building industry. The NBF was designed to provide: . . . *a flexible and economical system of standardised concrete framing for buildings up to six* *storeys in height. It comprises a small number of different precast components produced from a few standard moulds* [1.5].

The consumer for the PBF was the Department of Environment, for use within the public sector's expanding building programme of the 1960s. Unlike the NBF, which was controlled by licence, the PBF was available without patent restrictions to any designer. The structural models were simple and economical: simply supported, long-span, prestressed concrete slabs up to 20 inches deep were half recessed into beams of equal depth. By controlling the main variables, such as loading (3+1 kN/m^2 superimposed was used throughout), concrete strength and reinforcement quantities, limiting spans were computed against structural floor depths. Figures 1.2 and 1.3 show some of the details of these frames. Diamant [1.6] records the international development of industrialised buildings between the early 1950s and 1964. During this period the authoritative Eastern European work by Mokk [1.7] was translated into English, and with it the documentation of precast concrete had begun.

Unfortunately, the modular design philosophy was reflected in the façade architecture. The results were predictable, exemplified at Highbury Technical College in Portsmouth (now a part of the University of Portsmouth) shown in Figure 1.4. The precast industry has found it difficult to dispel the legacy of such architectural brutalism.

Following the demise of the NBF and PBF, precast frame design evolved towards more of a client-based concept. Standard frame systems gave way to the incorporation of standardised components into bespoke solutions. The result, shown in Figure 1.5 of Western House (1990), Surrey Docks (1990) and Merchant's House (1991), established the route to the versatile precast concrete concepts of the present day.

In the mid-1980s, the enormous demands on the British construction industry led developers to look elsewhere for building products, as the demands on the British precast industry far exceeded its capacity. Individual frame and cladding companies (with annual turnovers of between £1 m and £3 m) were being asked to tender for projects that were singularly equal to or greater in value than their annual turnovers. Programmes were unreasonably tight and it seemed that the lessons learned from mass-market-led production techniques of the 1960s had gone unheeded. One solution was to turn to Northern Europe, where the larger structural concrete prefabricators were able to cope with these demands. Concrete prefabricated in Belgium was duly transported to the London Docklands project, shown in Figure 1.6.

In making a comparison of developments in Europe and North America, Nilson [1.8] states: *Over the past 30 years, developments of prestressed concrete in Europe and in the United States have taken place along quite different lines. In Europe, where the ratio of labor cost to material cost has been relatively low, innovative one-of-a-kind projects were economically feasible. . . . In the U.S. the demand for skilled on-site building labor often exceeded the supply, so economic conditions favored the greatest possible standardisation of construction . . .*

North America's production capabilities are an order of magnitude greater than those of Europe. Figure 1.7 shows the construction of a 30-storey, 5000-room hotel and leisure complex in Las Vegas. The conditions to which Nilson refers are changing. The gap between labour and material costs in Europe is now closer to that of North America. At the same time, progressively lower oil and transportation costs into the early twenty-first century made it feasible to manufacture components virtually anywhere in the world and transport them to regions of high construction demand. Recent indications are that increasingly scarce energy resources and narrowing pay differentials will reverse this trend.

While the market share for complete precast concrete frames has remained constant in the UK, the development of high-strength concrete for columns and the use of innovative shallow prestressed concrete beams, together with speed of construction to rival that of steelwork, has led to successful tower buildings in Northern Europe, particularly in Belgium and Holland. The twin-tower building 'galaxy' in Brussels, Figure 1.8, is such an example. With column sizes of 600 mm diameter (cast in two-storey heights using 95 N/mm^2 concrete strength) and beam and floor spans up to 9.2 m × 405 mm depth, construction rates achieved 2 storeys in 8 working days [1.9].

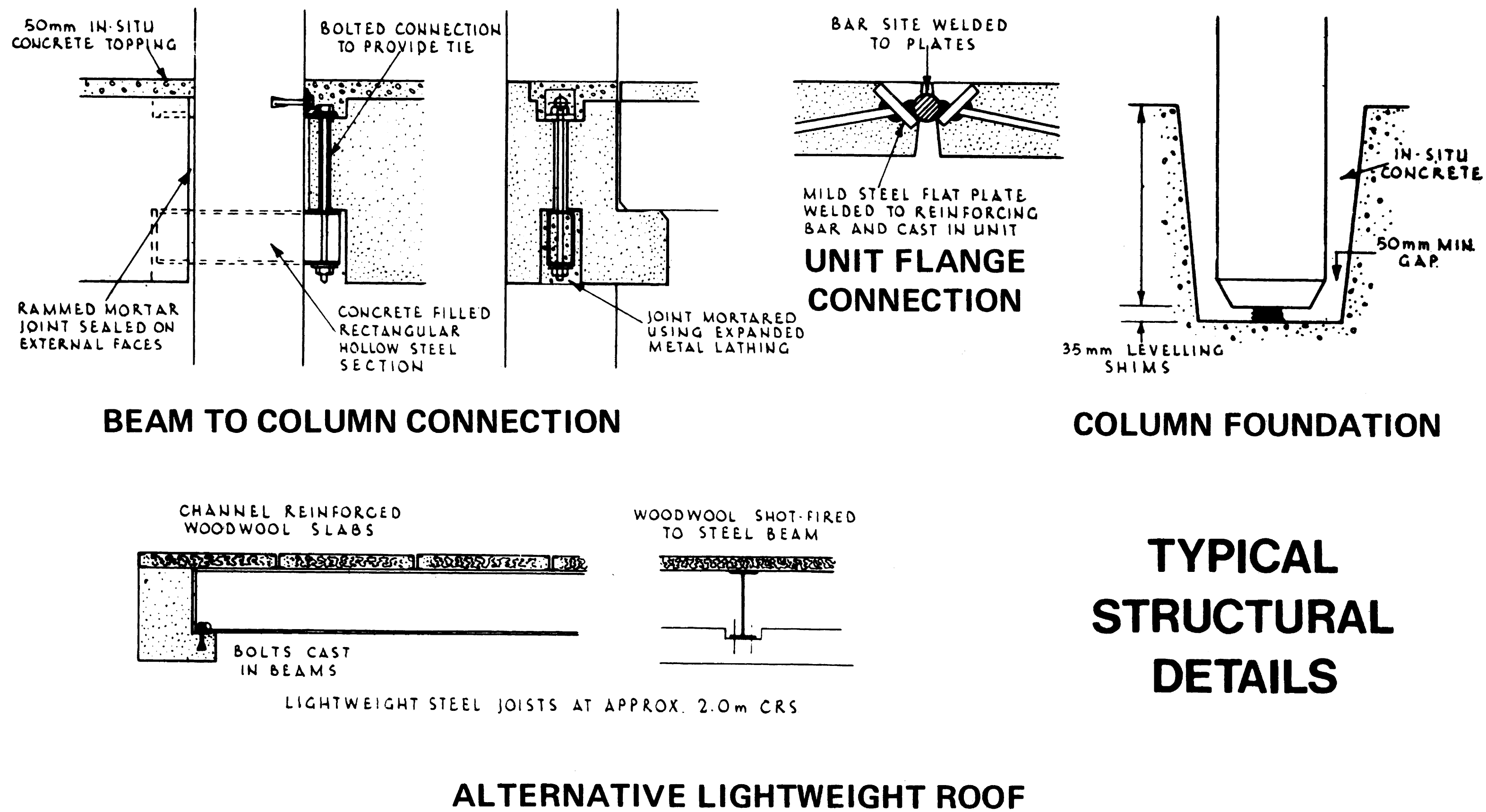


Figure 1.2 Typical structural details for the National Building Frame [1.4].

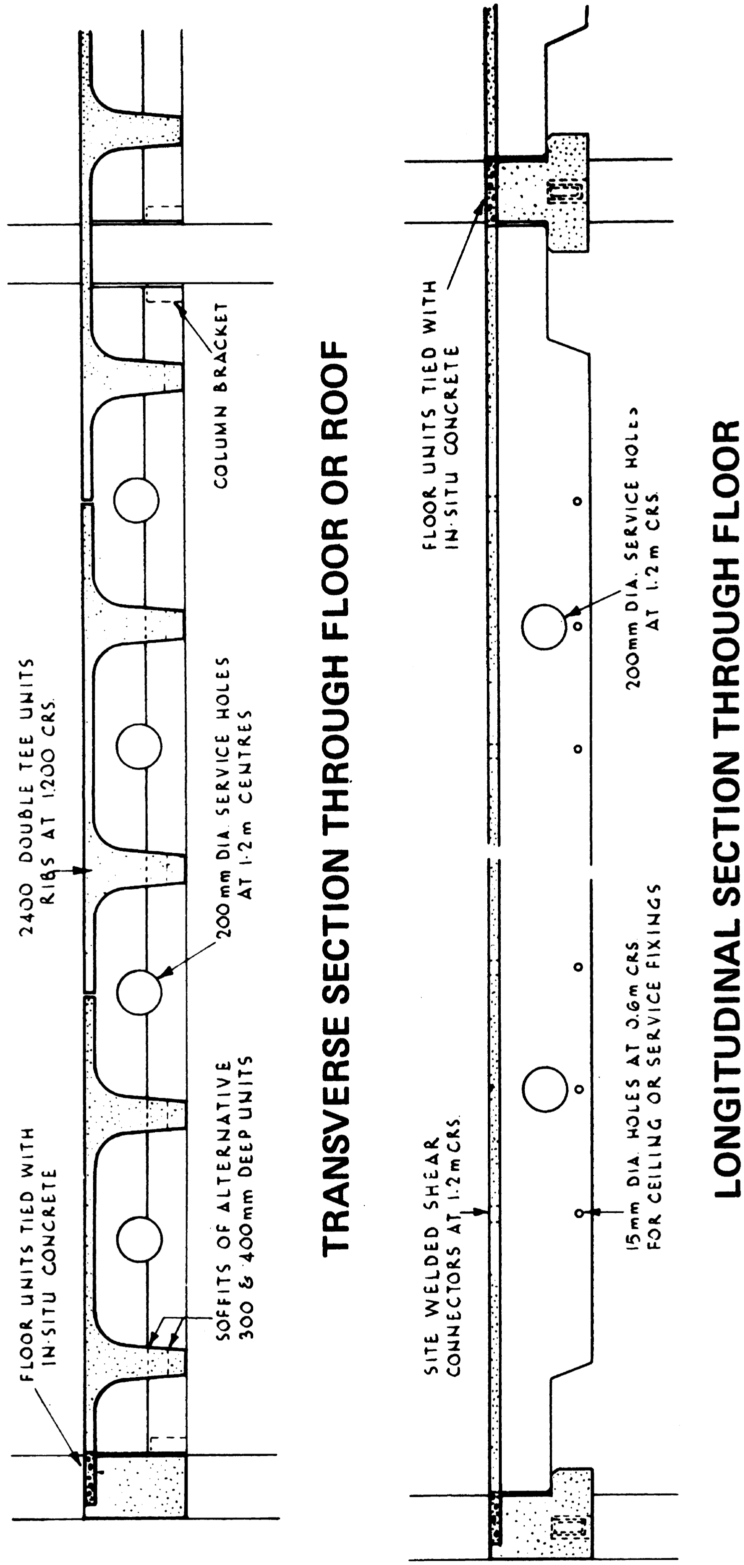


Figure 1.3 Floors used in the National Building Frame [1.4].

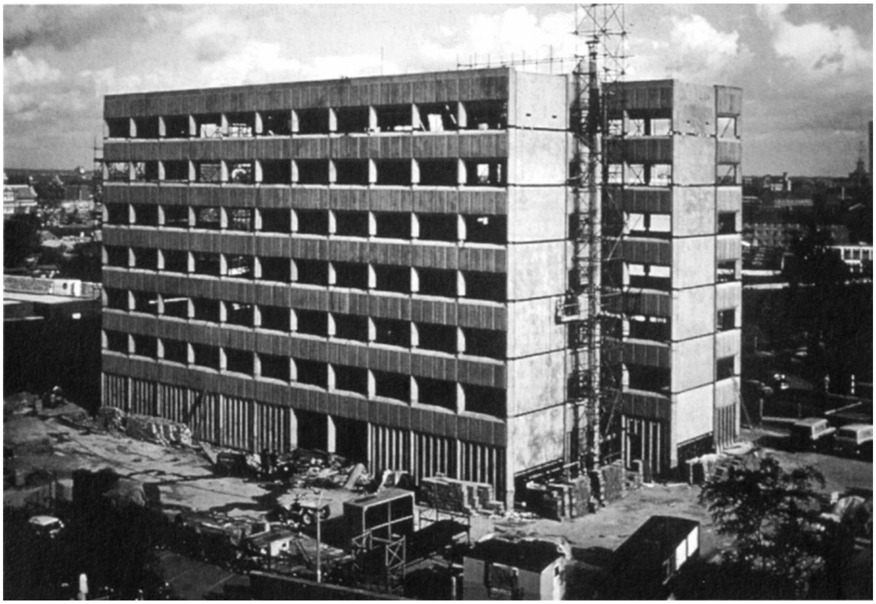
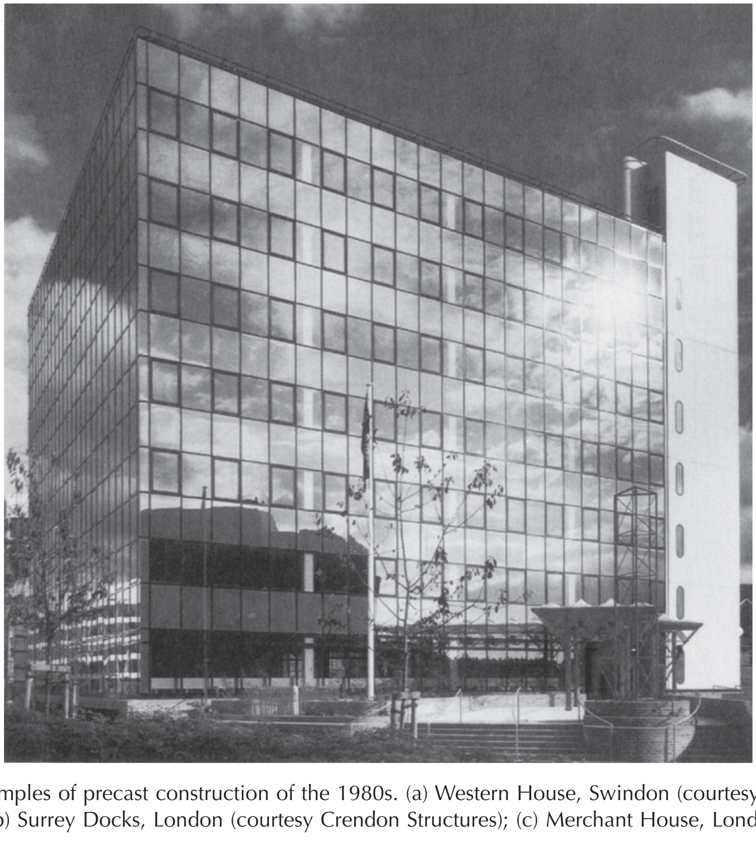


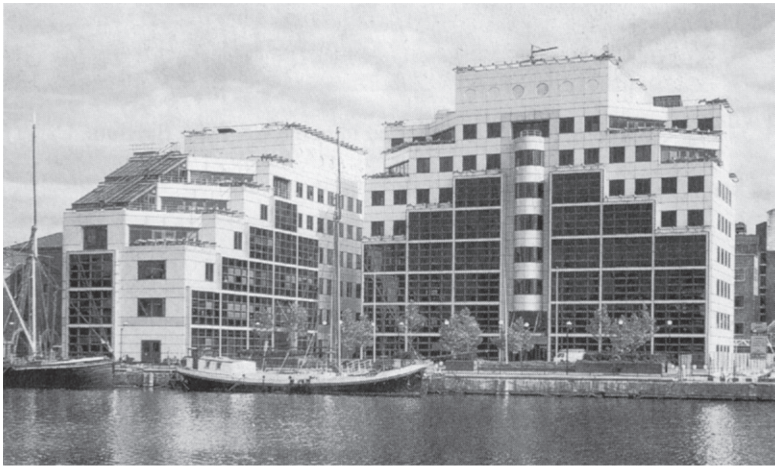
Figure 1.4 Precast construction of the 1960s using the National Building Frame, The building is Highbury College, now part of the University of Portsmouth (courtesy of Costain Building Products).



(a)

Figure 1.5 Examples of precast construction of the 1980s. (a) Western House, Swindon (courtesy Trent Concrete Ltd); (b) Surrey Docks, London (courtesy Crendon Structures); (c) Merchant House, London [1.10].

(b)



(c)

Figure 1.5 (*Continued*)

Changes to the way in which the construction industry should operate in a 'zero-waste and zero-defects' environment were given in the 1998 Egan Report [1.11]. The report called for sustained improvement targets: 10 per cent in capital construction costs; 10 per cent in construction time; 20 per cent of defects, and a 20 per cent increase in predictability. Further, the report goes on: . . . *The industry must design projects for ease of construction, making maximum use of standard components and processes.* Although the reports did not use the term 'prefabrication', to many people that is what 'predictability' and 'standard components' mean. The precast concrete industry is ideally placed to accommodate these higher demands by using experienced design teams and skilled labour in a quality-controlled environment to produce high-specification components. Figure 1.9 illustrates this in the repetitive use of granite cast spandrel beams and columns to form a building in the convoluted shape of a shell. Since 2000, high-quality architectural finishes have been more widely adopted for the exposed structural components, as illustrated in the integrated structure in Figure 1.10. The requirement for off-site fabrication will continue to increase as the rapid growth in management contracting, with its desire for reduced on-site processes and high-quality workmanship, will favour controlled prefabrication methods. The past five years have witnessed extensive developments in student accommodation – for example in Figure 1.11, where some 600 rooms were constructed using precast wall and floor systems in just over eight months, and were completed for occupancy within 18 months of site possession in 2009.

(a)

(b)

Figure 1.6 An early example of quality architecturally detailed precast concrete imported from Belgium. (a) Overall impression. (b) Architectural detail. (Courtesy of A. Van Acker, TU Ghent.)

Figure 1.7 MGM Hotel and Casino at Las Vegas, US constructed in 1992 (courtesy of A. T. Curd).

Figure 1.8 36-storey precast skeletal tower buildings in Brussels (courtesy of Ergon, Belgium).

Figure 1.9 Granite aggregates in spandrel beams and columns, polished to reflect the Australian sunshine at No. 1 Spring Street, Melbourne, 1990.

(a)

(b)

Figure 1.10 Asticus Building, London, 2010. Precast cruciforms form (a) the exterior structure, and (b) architectural finish.