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Design of Tall Buildings of Lightweight Superstructure

Projection de bâtiments élevés de construction légère

Entwurf hoher Gebäude im Leichtbau

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Introduction

Generally the floors in tall buildings are repetitive due to the shape of the structures. Table 1 gives an analysis of the estimated weights of the various components within typical floors of several buildings in London.1, 2, 3.

These buildings are approximately 35 storeys high with the exception of Moor House, which is 19 storeys high. It can be seen that the dead weight of the structure is 50 - 60% of the total weight and is thus by far the largest single item. Possible savings in weight on cladding, finishes and partitions are likely to be small in comparison with savings in dead weight of structure.

The average weight of structure of a typical floor including walls and columns is approximately 140 lbs/sq.ft. for a reinforced concrete frame 35 storeys high. The floor slabs vary in weight from 50 lbs/sq.ft. to 110 lbs/sq.ft. for spans up to 30 ft. with superloads of 80 lbs/sq.ft. including demountable partitions.

Those structures with light floors generally have a greater weight of walls and columns which yields a remarkably uniform average weight of structure. For lower structures of 20 storeys with spans up to 20 ft. the overall weight is approximately 120 lbs/sq.ft. and the slab weighs 85 lbs/sq.ft.

Table 1 - Weights of Tall Buildings.

	STAG PLACE		MILLBANK		DRAPERS GDNS		EUSTON CENTRE		MOOR HOUSE	
	weight lbs/ft^2	%	weight lbs/ft^2	%	weight lbs/ft^2	%	weight lbs/ft^2	%	weight lbs/ft^2	%
FLOOR SLAB	75	27.3	76	30.0	105	39.0	101	41.0	85	37.2
WALLS	60	21.8	48	18.7	37	13.8	17	6.8	22	9.6
COLUMNS	13	4.7	21	8.2	6	2.3	3	1.2	9	4.2
EXTERNAL CLADDING	20	7.3	10	3.9	14	5.4	9	3.6	10	4.2
FINISHES FLOORS CEILINGS	27	9.8	23	9.0	27	10.0	34	13.7	27	11.8
PARTITIONS	20	7.3	27	10.6	20	7.5	34	13.7	25	11.0
SUPERLOADS	60	21.8	50	19.6	60	22.0	50	20.0	50	22.0
TOTAL	275	100.0	255	100.0	269	100.0	248	100.0	228	100.0

Methods of reducing the dead weight of superstructure

Reduction in dead weight may be accomplished by the following:-

1. Use of high strength materials, i.e. high grade concrete, high tensile reinforcement or prestressed and/or precast concrete. These invariably cost more than average strength materials in common use, but reduction in weight and size may compensate.

2. The use of deeper structural sections of reduced thickness, i.e. ribbed and waffle slabs or open web joists. The deeper section increases the strength with very little increase in the weight. Increased fabrication costs are normally involved.

3. Use of lightweight materials of comparable strength to conventional materials i.e. lightweight concrete, plastics and aluminium. These usually cost more than their equivalent volume of conventional material, but the saving in weight may enable these costs to be recouped.

4. Reducing the floor spans, thus reducing the thickness of the floor. This technique is obviously limited as present day requirements are for open floor areas without supports.

5. Using the stiffness of the structural frame to withstand the horizontal loads without increasing the size of the members as determined by consideration of the vertical loads i.e. accommodating the stresses due to horizontal loads within the permitted 25% overstress (U.K. Standards).

6. The use of lightweight fire protection to structural steelwork in lieu of solid protection.

7. Special design techniques i.e. suspended structure where hangers may be used in lieu of columns and whole building loads ultimately supported on the core walls.

Factors to be balanced against savings in dead weight

Dead weight savings on structure are always desirable but must be reconciled with the other functions and also letting of the building. The importance of the latter is sometimes lost on engineers concerned primarily with structural design, but is vitally important to the client. The following factors should be balanced against the reduction in weight:-

a. Site Cost.
b. Building Cost.
c. Area of space available for letting.
d. Amenity values which may increase the prospect of letting.
e. Serviceability of the building.
f. Speed of construction.
g. Sound insulation and vibration.

TYPES OF STRUCTURE SUITABLE FOR LIGHTWEIGHT CONSTRUCTION AND EXAMPLES

a. Flat Plate Construction. In this type of construction the floors are designed as solid plates which act with columns to form a multi-storey rigid frame. The height for which this type of building is suitable is limited by the stresses within the plate floor and the deflections of the frame horizontally. Buildings up to 20 storeys can be constructed in this way, but the thickness of floors and the quantities of reinforcement required tend to make flat plate frame construction uneconomic above this limit.

The design imposes certain restrictions and advantages namely:- the external columns should be preferably inset from the face of the building; floor openings adjacent to the columns should be restricted; lightweight cladding should be used; the building should be preferably at least three bays wide to develop adequate lateral stiffness; the bay sizes should be approximately square. The compensations are that the elevators and staircases may be placed in any position; the shape of the building is not restricted; the construction is extremely simple, no shear walls are necessary, and it provides a flat soffite to the floors which may be plastered direct without false ceilings. It also reduces floor thickness to a minimum.

The trend today is to construct these buildings with lightweight concrete with a density of approximately 100 lbs/cu.ft. which reduces floor and column loadings, resulting in more economic design. In the U.K. buildings are often restricted in height and cubic content and therefore this form of construction, which takes up as little floor depth as possible, is often essential to obtain the maximum number of floors and therefore lettable area.

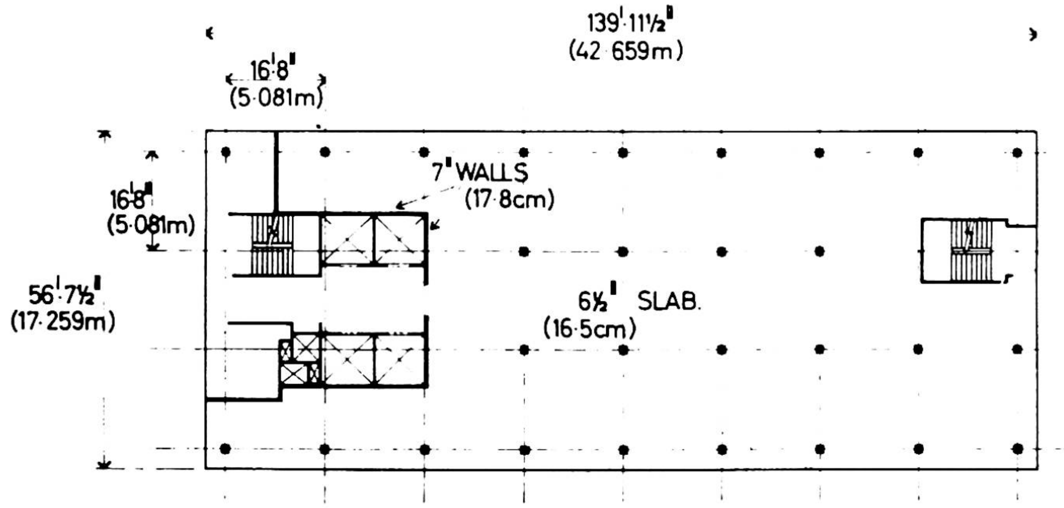


Fig. 1. MOOR HOUSE – TYPICAL FLOOR PLAN

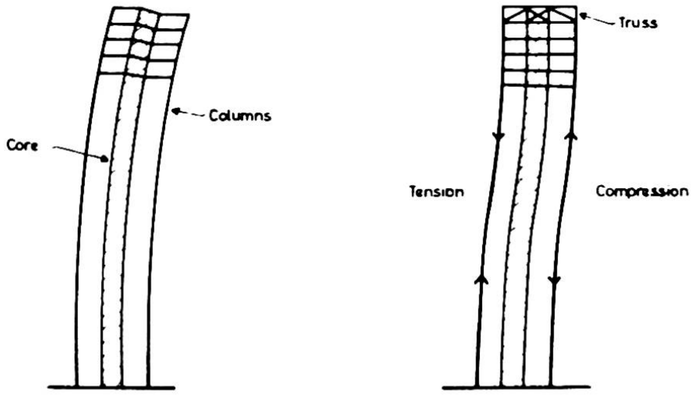


Fig. 2 FREE CANTILEVER

Fig. 3 TIED CANTILEVER COLUMN – CORE INTERACTION

Figure 1 shows the floor construction of Moor House, London, 228 ft. high, and illustrates the principles outlined above. The floors are of normal gravel aggregate concrete and are only 6½ ins. thick. No column heads are provided.

b. Central Core Construction, with External Edges of Floor supported on either columns or hangers. The utilisation of the central core to withstand all lateral loads is becoming standard technique in buildings constructed in the U.K. up to 450 ft. high. Above this height the cores are rarely large enough to limit the lateral deflection of the building without increasing the thickness of the walls and columns as designed for vertical loading. The core supports a high proportion of the vertical loads of the

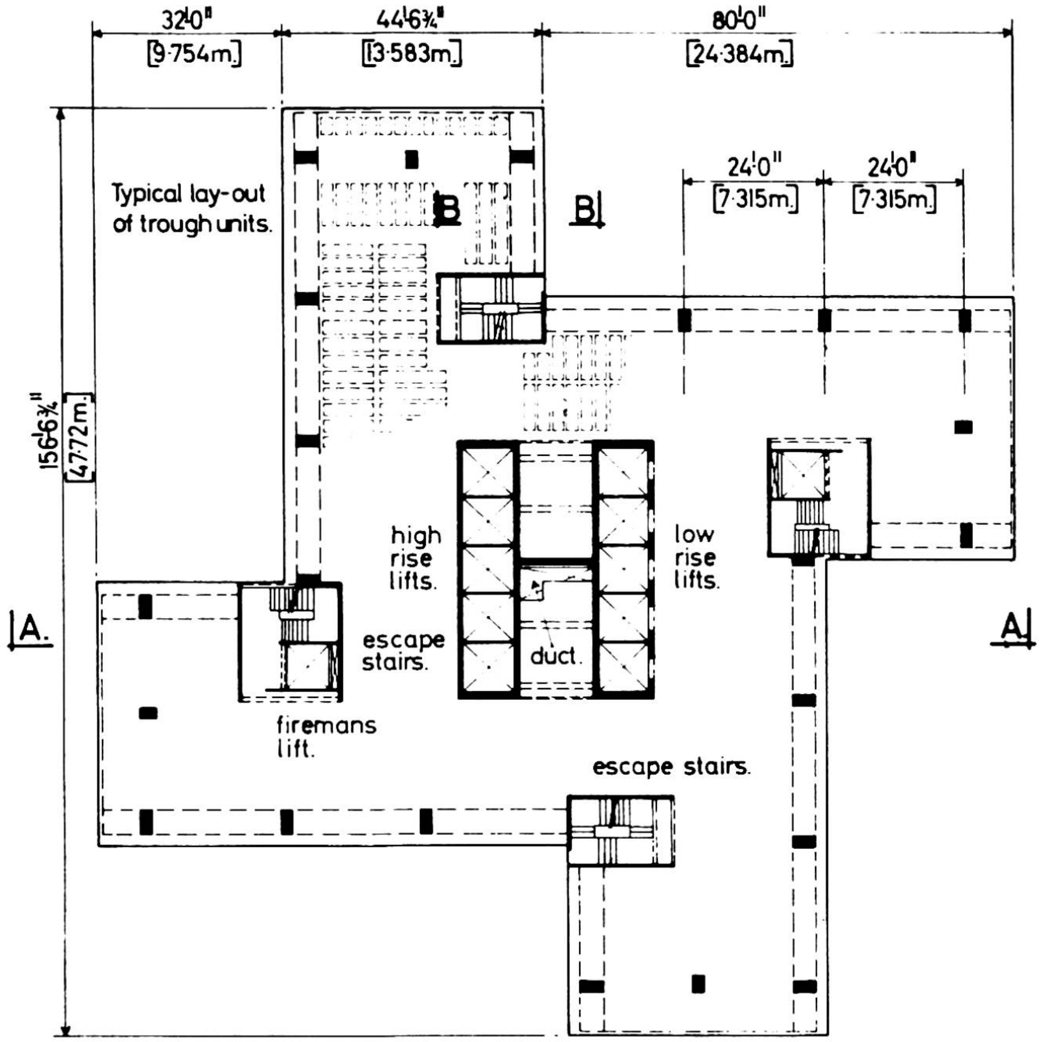
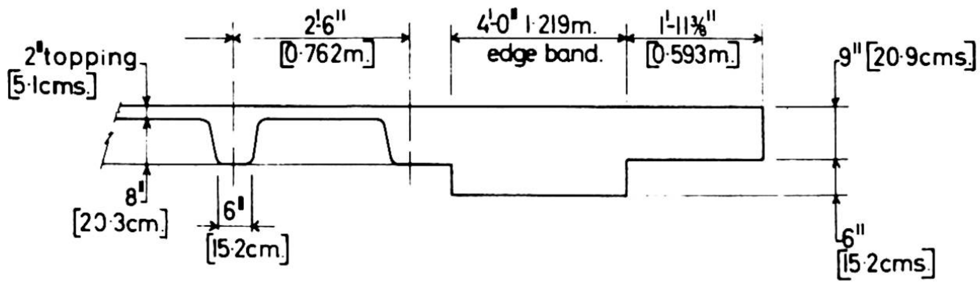


Fig. 4. – EUSTON CENTRE
TYPICAL FLOOR PLAN.



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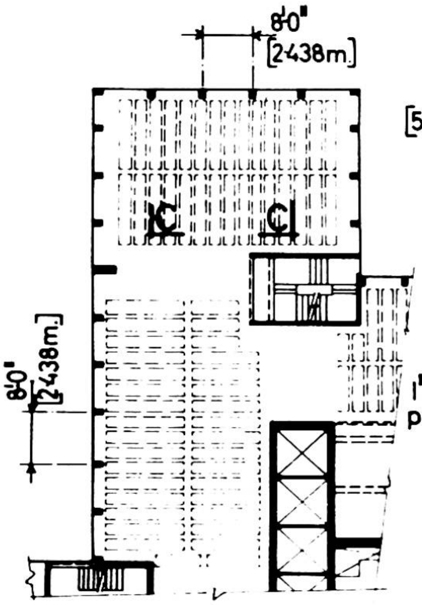
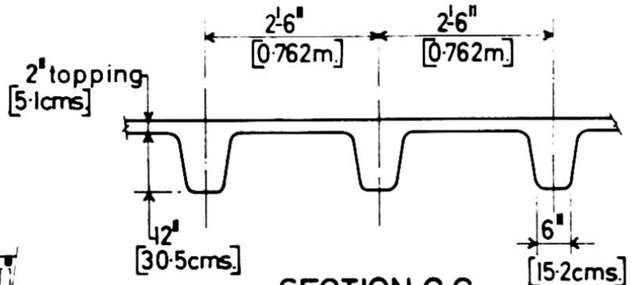


Fig.5. ALTERNATIVE FLOOR LAYOUT.



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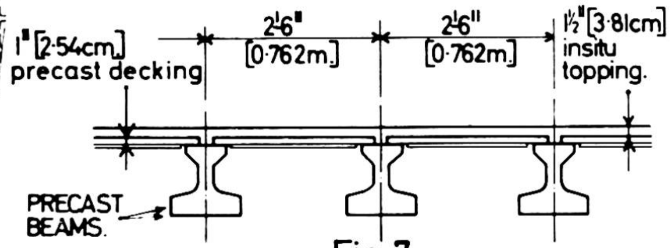

Fig.7.

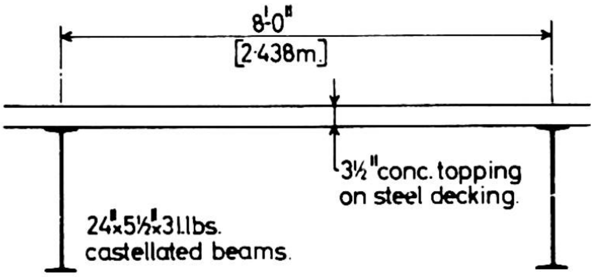

Fig.6.

Table 2 - Comparisons of alternative floor construction for Euston Centre

Case No.	Layout Fig.No.	Section Fig.No.	Ribbed Areas Wt. lbs/sq.ft.	Weight lbs/sq.ft.	% Weight	% Cost
1.	1	B - B	52	92	100	100
2.	1	-	38	64	70	107
3.	5	C - C	65	87	95	107
4.	5	C - C	48	64	69	108
5.	5	7	56	82	89	123
6.	5	6	-	42	46	125 *

* Excluding fire protection.

building thus fulfilling three functions i.e. vertical support, lateral support and service enclosures. The columns or hangers support vertical loads only, so that they may be designed to a minimum cross section and occupy as little floor area as possible.

The 35 storey Euston Tower, which is approximately 428 ft. high illustrates the principle of central core design with the external edges of the building supported on high strength (6,500 lbs/sq.in.) concrete columns. The core area and structure is limited so that 85% of the overall building area is usable.

Alternative floor constructions considered are shown on Figures 4,5,6 & 7 and Table 2.

Case 1 was in fact used and constructed using plywood formers and table forms. It provided a reasonably light structure with a minimum of reinforcement (8.5 lbs per sq.ft. including walls and columns) and a strong insitu structure to distribute lateral loads. The floor depth for the main floor areas was only 10 inches.

Case 6 using steel decking and beams was the lightest form of construction but was unacceptable due to the depth of floor construction and high cost.

Cases 2 & 4 using lightweight concrete were attractive but produced shear problems and required greater floor thickness than Case 1.

Case 3. The inclusion of structural mullions would have entailed large transfer girders at second floor level, which would have been expensive and were undesirable architecturally.

Case 5 using composite construction was more expensive than insitu construction with an increased floor thickness. Also it did not provide as rigid a structure as insitu construction and would have required a transfer girder at second floor level.

Suspended Structures

In this type of design the edges of the floors are supported by steel hangers, which are connected to cantilever trusses at the top of the building. These cantilever trusses are supported by a large central core. This arrangement produces the minimum area of external columns and provides additional dead load in the core to prevent tensile stresses being developed due to wind or lateral loading. The advantages of the method are that the contractor has the plant rooms available at an early stage in the contract, the floor space is uninterrupted by columns and there is a clear space at ground floor level which may be used for storage and access. It also allows a flexible ground floor layout. Due to the method of erecting the building from the top downwards, it is usual to build the structural floor of steel deck and castellated or lattice beams to avoid the need for formwork. Floor depths are greater than flat slab construction and building costs are usually slightly higher than an equivalent simple structure with columns.

Two examples of this form of construction are the Commercial Union Building and 20-23 Fenchurch Street, London. The difficulties of brittle fracture of the high strength steel trusses found in the latter seem to have been overcome in the P. & O. Building by using smaller made-up sections, which can be normalised instead of heavy welded Universal columns.

c. Central Core + Frame Action for Buildings over 400 ft. It is not normally economic to take all the lateral forces on the core as a vertical cantilever over 400 ft. tall, unless the core is very large; even if this is done, some account must be taken of secondary stresses induced in the remainder of the structure by consideration of the deflection of the structure. One variation is to allow the floor and columns to act integrally with the core to increase its stiffness. This solution is only practicable if the arrangement of the structural framing allows the stresses to be absorbed economically and is generally used in steel framed buildings. An alternative for reinforced concrete flat slab framed buildings is to provide trusses or beams at roof level to which the external columns are connected as shown in Figs. 2 & 3. This allows transfer of some of the tensile stresses which would otherwise develop in the core, to the external columns and therefore utilises more fully the total depth of the building. One example is Moorfields, London, 444 ft. total height and 36 storeys high, where the overall size of the floors were 66 ft. 9 in. x 202 ft. 9 in. and the core width only 21 ft.[4]

d. Hull Core Structures, where the external frame forms a hollow space tube and acts in conjunction with a central core.

No buildings, to our knowledge, have been erected in the U.K. which fall into this category, but several have been constructed in the U.S.A. One example is the World Trade Centre, New York, which is 1,350 ft. high. The principle is to use the external cladding not only to carry vertical loads but also to resist horizontal loads as a perforated box. It has the advantage that the internal floors can be constructed to give uninterrupted spans.

The external hull can be constructed in a variety of forms, either as a series of close centre mullions connected by beams at floor levels to form a series of inter-connected, very stiff portal frames, or, as a diagonal open lattice frame. The latter is particularly economical structurally since the forces within the cladding are mostly axial and result in high efficiency.

If the external cladding is constructed in steel as part of the curtain walling, it will be light in weight. If the floors are also constructed in steel joists and deck the resulting structure will be light in weight and capable of spanning 40 ft. clear without much difficulty.

This type of construction is particularly suitable in the United States where large floor areas are required and building heights are much greater than those permitted by the Planning Authorities in the U.K.

A variation on the hull core structure for buildings up to 400 ft. high is to omit the central core and use only the external wall frame to resist wind forces. The advantage is that flat slabs may be used within the building without the encumbrance of internal concrete walls, which would slow up progress of construction on site. e.g. The 42 storey DeWitt Apartments.[5].

DESIGN OF COMPONENTS

a. Floors

The two most favoured forms of floor construction are ribbed slabs, either precast or in situ, constructed as part of a floor of uniform thickness or a steel deck floor with concrete topping supported on steel joists. The former is most used in the U.K. as it is more economical for spans up to 30 ft. Generally storey heights are approximately 10 ft. 6 in. as against 12 ft. for steel deck and beam construction. In a 35 storey block another five floors can be built within the same building envelope using a ribbed slab instead of a steel deck and beam floor.

The relative costs of the two forms of construction vary according to the country in which they are built, since the ratio of labour and material costs vary considerably. The cost per sq.ft. of floor area of the steel in a steel framed structure as built in the U.S.A. or Canada would vary from 30/- to 50/- based on U.K. costs. Cost per sq. ft. of equivalent concrete building would be 20/- to 35/-.

A ribbed floor in normal gravel aggregate concrete 10 ins. thick weighs approximately 50 lbs/sq.ft. whereas a steel deck with concrete topping weighs only 35 lbs/sq.ft. If lightweight concrete were used in a ribbed floor the weights would be almost identical. The average weight of a floor incorporating ribs is much higher than might be expected because heavier solid strips have to be provided at the edges to support the ends of ribs and transfer loads back to the columns. It would seem unlikely that the dead weight of floor construction could ever be reduced much below 40 lbs/sq.ft. since a minimum thickness of floor would be required to provide mass to damp vibration and prevent undue sound transmission through the floors.

For long spans, prestressed concrete double T beams or I beams used at 2 ft. 6 in. to 3 ft. centres with precast planks provide a rapid method of erection. So far, the use of precast elements in tall buildings has not proved as successful in speeding up erection times as could be hoped. This is largely due to the labour required in propping, making and pouring insitu portions between precast elements and making joints, and also because the core areas often determine the speed of erection. As floors act as horizontal diaphragms to transfer lateral loads back to the core, it is essential that they have rigidity and any precast scheme must be carefully detailed to provide this. Shear heads should be avoided by the use of shear reinforcement either in the form of channels, collars or flat plates providing mechanical support, or diagonally inclined "snake" reinforcement in rings round columns.

b. Columns

To avoid the introduction of heavy beams or strips spanning between columns at the edges of the building, load bearing mullions at close centres may be used which do not project as far into the building as columns at greater centres and therefore do not break up the building area.

In order to reduce floor spans, columns may be inset a small distance to enable vertical service ducts to pass between column and cladding as shown in the Euston Centre. In this case the columns are designed in high strength concrete but even so are comparatively large in the lower storeys. At least one building (Drapers Gardens, London) has been constructed with solid steel columns (billets) to achieve the lightest weight and smallest amount of floor space occupied by columns. However, the increase in cost due to the billets is considerable and these should be carefully balanced against the increase in income due to the difference in lettable areas between concrete and steel columns.

c. Vertical Service Cores

These should be simplified as much as possible to enable them to be formed by slip-form or rapidly demountable large formwork panels; complicated core sections will slow down progress in the building as a whole. Small internal variations are most economically built in blockwork. The upper parts of the service core can be cast in lightweight concrete and in the lower parts the use of high strength concrete is essential to limit the wall thicknesses. Fire escape staircase enclosures can also contribute to the lateral strength of the building provided that this can be transmitted to the foundations. Unfortunately architectural requirements often prevent their being taken down to ground floor level.

d. Cladding

The lightest form of cladding is glass curtain walling amounting to within 3% - 4% of the total dead weight. The back-up wall to the curtain walling should be constructed in a lightweight, fire resistant material or wood-wool, rather than concrete or brickwork which has a greater density. Curtain walling has a further advantage in that it occupies a minimum thickness of wall, increasing the amount of floor area available for letting. This assumes that the exterior face of the building is fixed by the building line.

FACTORS AGGRAVATED BY LIGHTWEIGHT CONSTRUCTION

a. Thermal Movement

There is a faster build up of heat in exposed lightweight materials on the external face of the building which produces differential movement between the core and external columns. This can be overcome by making special provision in the structure to allow movement to take place, possibly by pin joints in the upper floors, or by inserting trusses to redistribute stresses between external columns. Internal partitions must be designed to allow a certain amount of distortion to take place in the frame. One method of minimising differential movement is to provide insulation to the external faces of columns to prevent such a rapid build-up. Careful detailing is required for glazing which fits between structural members of this type.

Thermal movement within the floor structure is usually easily accommodated and in fact, the use of lightweight concrete does help to reduce this.

If columns are set on the periphery they will be fully or partially exposed and therefore subject to temperature movement, which is considerable in buildings over 400 ft. high. The columns on one face of the building will expand or contract at a much greater rate than its core or columns on the other face. This will tend to crack the partition walls and possibly the structure, if excessive. Measurements taken on tall buildings give a differential movement of between .34 in. - 1.12 in. on structures varying between 200 ft. and 450 ft.; the amount of movement varying according to the height of the building and degree of exposure of the columns. The greater the degree of exposure, the greater the differential. Some cracking where the partitions join the external columns has been noted on existing buildings, although no structural damage has been recorded, probably because the ratio of depth:span did not exceed L/200. The reasonable limit for temperature movement seems to be approximately $\frac{3}{4}$ in. up or down from the horizontal position, assuming a clear floor span of 35 ft.[5]

b. Shrinkage

Lightweight aggregate concrete has a higher shrinkage rate than conventional gravel aggregate concrete and therefore adequate tensile reinforcement must always be included to control cracking.

c. Deflection

Generally lightweight concrete structures give rise to greater deflections than conventional structures due to their lower modulus of elasticity. There has been considerable research into the properties of lightweight concrete. This suggests that initial fears that the span:depth ratio would have to be adjusted to allow for the lower modulus are unfounded, provided that the stress in the reinforcement is not increased above 27,000 lbs/sq.in. The reduction of dead weight on the structure may give rise to tensile forces within the core and unacceptable horizontal deflections. In most practicable types of structure the height:width ratio is sufficient to avoid these difficulties. Reduction in weight also serves to decrease the damping effect of the building in its response to gusting of wind, although generally the likelihood of dangerous oscillations is improbable for conventional buildings up to 600 ft. unless very slender and with $ND<25$.(Where N is the natural frequency and D a typical cross section dimension.)

d. Sound Insulation

Lightweight structures and partitions allow greater sound transmission, which although acceptable in offices, would not be so in apartments. For this reason apartments are often constructed with solid plate floors to avoid too high a noise level. In offices, false ceilings help to reduce the level of airborne sound and the insertion of glass quilt under floors will reduce the transmission of structure-borne sound. In the case of plant rooms an acceptable solution seems to be to provide a thick concrete raft which rests on a layer of insulation material which will not transmit most of the troublesome frequencies of vibration from the plant above. If further insulation is required, wood-wool slabs may be suspended from the ceiling underneath.

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SUMMARY

The paper considers various designs suitable for lightweight superstructure, typical weights of differing construction and factors affecting the design of structural components.

RÉSUMÉ

Ce document envisage différentes conceptions convenant à des super-structures extrèmement légères, les poids types de constructions différentes et les facteurs affectant le dessin des componants structurels.

ZUSAMMENFASSUNG

Das Referat befaßt sich mit verschiedenen Entwurfen, die für leichte Aufbauten geeignet sind, sowie mit charakteristischen Gewichten verschiedener Konstruktionen und Faktoren, die den Entwurf von Bauteilen beeinflussen.