FIP Recommendations Series Reports

FIP/1/1
First edition June 1975

GUIDES TO GOOD PRACTICE

FIP/CEB Recommendations for the design of reinforced and prestressed concrete structural members for fire resistance

Fédération Internationale de la Précontrainte

Prepared in association with CEB

15.336

First edition

ISBN 0 7210 1014 8

Published by the Fédération Internationale de la Précontrainte
Wexham Springs, Slough SL3 6PL

Designed and printed by the Cement and Concrete Association
Wexham Springs, Slough SL3 6PL

Price £3.00

FIP/CEB RECOMMENDATIONS FOR THE DESIGN OF REINFORCED AND PRESTRESSED CONCRETE STRUCTURAL MEMBERS FOR FIRE RESISTANCE

FOREWORD

The first draft recommendations for the design both of reinforced concrete and prestressed concrete structural members in regard to fire resistance were presented for discussion at the Sixth FIP Congress held in Prague in 1970 at an open meeting of the FIP Commission on Fire Resistance under the Chairmanship of Professor K. Kordina. These have been subsequently discussed and elaborated at meetings of the Commission in Paris, Brunswick and London and a final draft was agreed at the Seventh FIP Congress held in New York in 1974 for the publication to include both normal dense and lightweight concrete. The inclusion of reinforced concrete has been at the special request of CEB who had expressed a wish for detailed recommendations to be available for inclusion in their next revision of the CEB/FIP International Recommendations for the design of Concrete Structures.

The recommendations give detailed advice to the practising engineer on how to design structural elements to withstand the standard fire loads for stated periods which may be prescribed by building authorities on a national scale. The values given are safe values based on the results of research and testing on individual elements in a standard furnace. Analytical methods of assessment of fire resistance are being developed which take into account the interaction of structural members and these may well lead to further economy. Further investigations of the effects of continuity and end-restraint by the Commission may enable these recommendations to be revised in the future.

CONTENTS

INTRODUCTION

In the design of most modern buildings it is necessary to give consideration to fire resistance and to comply with the requirements of local building authorities. This is especially so in the design of modern structures which frequently provide finely proportioned, slender and highly stressed members.

Regulations defining the degree of fire resistance required in structures exist in most countries and apply to all materials of construction. The present recommendations for reinforced and prestressed concrete for both dense and lightweight construction do not restrict their use but synthesize the results of international research co-operation into the behaviour of reinforced and prestressed concrete members in fire, and present principles for the design to meet prescribed fire resistance ratings.

The recommendations provide design aids in the form of tables for one-way and two-way spanning slabs, for simply supported and continuous beams, for tensile members and for columns and walls. For their use by the designer extensive knowledge of the behaviour of concrete and steel at high temperatures and of the processes of heating and heat transfer is not required.

The tabulated values are safe values which can be applied generally and correspond to the existing state of knowledge. As further information becomes available it may be possible to issue revised recommendations. In specific cases, the results of fire tests on similar constructions may be accepted in place of the tables.

NOTATION

A_s Cross-sectional area of tensile reinforcement, wire or tendon.

a Axis distance, the distance between the exposed surface of the member and the axis of the tensile reinforcement, wire or tendon.

a_m Average axis distance $= \frac{\Sigma A_s a}{\Sigma A_s}$

a_{st} Side axis distance for single layer of tension steel.

b Width of member.

b_{min} Minimum value of b assigned to the required fire rating.

b_w Width of web of beam.

c Concrete surface cover to the steel.

c_{st} Side concrete cover to the tension steel.

f_{cd} Design compressive strength of concrete.

f_{cu} Cube crushing strength of concrete.

h Height of wall.

h_s Thickness of slab.

l Span of beam or slab.

l_x, l_y Spans of two-way slab.

T_{crit} Critical temperature.

t Thickness of wall.

τ_d Design shear stress of concrete.

R1 GENERAL - FACTORS AFFECTING FIRE RESISTANCE

The fire resistance periods for which the structural elements are to be designed should be in accordance with the fire resistance ratings applicable to the locality in which the building is to be constructed.

Structural elements gradually lose their load-carrying capacity and rigidity when subjected to fire. The fire resistance of structural members is assumed to have reached its limit when either:

(1) the characteristic imposed load can no longer be supported; or

(2) the member ceases to prevent the passage of flame and combustion gases; or

(3) excessive heat transfer to the side unexposed to the fire occurs.

Criteria (2) and (3) apply only to walls and floors which perform a separating function.

The fire resistance period is defined as the time (in minutes) required for one of the above failure criteria to be reached in a standard fire test. Fire resistance ratings in this report for specified periods in minutes are expressed as F 30, F 60, F 90, F 120, F 180 and F 240.

The principal structural parameters which affect the behaviour of members in a fire are:

(1) type of structure and level of loading

(2) type of concrete and aggregates

(3) type of reinforcement and quality of steel

(4) shape and dimensions of the member

(5) concrete cover and other protection of the reinforcement.

Values for the parameters (4) and (5) are given in the tables. They depend essentially upon factors (1), (2) and (3) which are discussed in the following sections.

R1.1 <u>Type of structure</u>

The results of fire tests which form the basis for these recommendations have usually been carried out on simply-supported members. Tests on continuous constructions have shown that the fire resistance of structural members is considerably improved where there is a suitable arrangement of upper reinforcement in the negative moment region. End restraint provided by adjoining members also increases fire resistance.

Good detailing to ensure bond and anchorage of steel is important in all cases of stress transfer but has increased significance in relation to fire resistance. In the case of all reinforced and prestressed concrete members, except solid slabs, the transfer of stress from steel to concrete must be ensured by the provision of suitable reinforcement in the form of stirrups.

R1.2 Type of concrete and aggregates

Values of cover and minimum dimensions are given in the Tables for both dense aggregate concrete and lightweight aggregate concrete. Lightweight aggregate concrete has a lower thermal diffusivity (20% less with density $\leq 1.2\ t/m^3$ reducing to 10% less when density $\leq 1.85\ t/m^3$) than dense aggregate concrete. However limestone or dolomite aggregate concrete has a diffusivity 5 to 10% less than that of other dense aggregate concrete, because of the endothermic reaction which occurs when calcium carbonate decomposes at high temperatures. Fire resistance design data for limestone aggregate concrete will therefore be intermediate between that given in the Tables for dense and lightweight concrete respectively. However, when dimensions are reduced, consideration should be given to the possibility of explosive spalling (See R1.5.3).

R1.3 Type and quality of reinforcement or prestressing steel

All steels lose strength when heated. The rate of decrease of strength is more rapid with work-hardened high-yield reinforcement and prestressing steel than with mild steel.

For rational design for fire resistance, it is important to know the critical temperature (T_{crit}) for the type of steel to be used in the structure. The critical temperature is that temperature at which the yield stress of the steel is reduced to the actual stress in the steel in the structural element. In the high temperatures reached in actual fires, the difference between the yield strength and the ultimate tensile strength is small and therefore the yield strength may be equated to the reduced tensile strength when considering fire resistance.

Figures 1a and 1b show the decrease in strength in typical reinforcement and prestressing steel. Values given refer to steel temperatures within the structure. In Figure 1a the yield strength at 20°C has been chosen as the reference, since under service load the safety factor in relation to the yield point is critical for reinforcement.

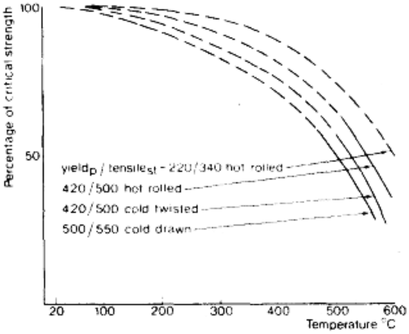

Figure 1a: Decrease of critical strength of reinforcing steels caused by heating.

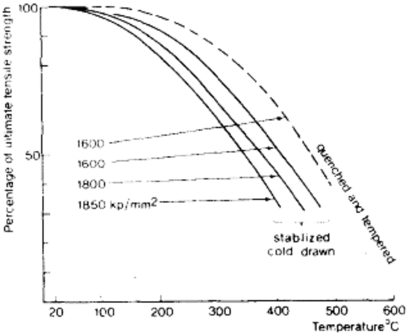

Figure 1b: Decrease of tensile strength of prestressing steels caused by heating.

Note: The above curves show safe values. Specific test results may replace these values when available.

Figure 1b, however, relates to the ultimate tensile strength of the steel at 20°C, since the permissible stress under service load with prestressing steel is, in general, related to the ultimate tensile strength.

In Figure 1a the first number on the curve refers to the yield stress of the reinforcement at 20°C in N/mm^2, the second number is the ultimate tensile strength at that temperature. In Figure 1b the number on the curve refers to the ultimate tensile strength of the prestressing steel at 20°C in N/mm^2.

R1.4 Size and shape of structural members

The rate of temperature increase in a concrete section during fire depends on the ratio of the fire exposed surface area to the area of the cross-section. It follows, therefore, that massive structural members are more resistant to fire attack.

R1.5 Concrete cover and other protection to steel

R1.5.1 Concrete cover. During a fire, the concrete cover protects the steel against excessive temperature rise and so prevents the critical steel temperature from being reached before the required fire resistance period is attained.

The concrete surface cover c to the main steel should contain supplementary protective reinforcement when $c > 40$ mm for dense aggregate concrete. This value can be increased to 60 mm for lightweight aggregate concrete and for some dense aggregate concretes which are shown to be less susceptible to spalling.

This supplementary steel may, for example, be of welded wire fabric with the wire diameter ≥ 2.5 mm and a mesh size 50 x 50 x 150 x 150 mm. The cover to this protective steel should be about 25 mm. Shear reinforcement, where provided, may also be considered as protective reinforcement.

R1.5.2 Additional protective cover. In special cases where the concrete cover to the steel for other purposes is less than that required for fire resistance purposes, the additional protection may be provided by applied coatings. In no case however should the concrete cover be less than that required for F 30 rating.

Examples of applied protection are:

Lime-cement plaster	15 mm equivalent to 10 mm concrete
Gypsum plaster	10 mm equivalent to 10 mm concrete
Vermiculite plaster or Sprayed mineral fibre	5 mm equivalent to 10 mm concrete

Adequate bond between concrete and the protective layer must be provided. In some cases, it may be necessary to use supplementary reinforcement of wire mesh or expanded metal.

R1.5.3 Spalling. Loss of concrete cover by spalling of concrete, especially explosive spalling in the region of the tensile steel, endangers the carrying capacity, because of the increased rate of heat transfer to the steel. Spalling of concrete in the web of beams increases the risk of shear failure. Spalling in the compression zone can cause a compression failure.

The risk of explosive spalling, which can occur within the first 25 minutes of a fire attack is diminished by reducing the moisture content of the concrete, by avoiding too small a size and rapid changes in shape and by limiting the compressive stress. Within the limits of present knowledge, a moisture content of less than 5% by volume of the concrete (2 to 3% by weight of normal dense concrete) has been found to inhibit explosive spalling.

Experience in the field of explosive spalling varies in different countries. Local knowledge of materials which are prone to explosive spalling should always be taken into account.

Non-explosive spalling may occur after heating for 60 minutes or more. Its effects can be minimized by the provision of supplementary reinforcement in the concrete cover (see R1.5.1).

R2 DESIGN RECOMMENDATIONS FOR INDIVIDUAL STRUCTURAL MEMBERS

R2.1 General

The minimum design recommendations in the following Tables refer only to fire resistance. Other requirements concerning thickness of cover and section sizes (e.g. for durability) must also be complied with.

In all structural members the minimum concrete surface cover to the outermost steel shall be at least 10 mm. Some values of a, the axis distance of the steel used in the Tables are therefore of a theoretical interest only. The axis distance a is the minimum distance between the exposed surface of the member and the axis of the tensile steel, wire or tendon (see Figure 2).

For practical design purposes it may be convenient to use the corresponding Tables in the Appendix which give direct values of the surface cover c of the steel as compared with those for the axis distance a.

To avoid excessive reduction in concrete cover to reinforcement when large diameter bars and/or cables are used and to facilitate the specification for construction of different elements the minimum cover c to the surface of the steel is limited by some countries to not less than a-5 mm.

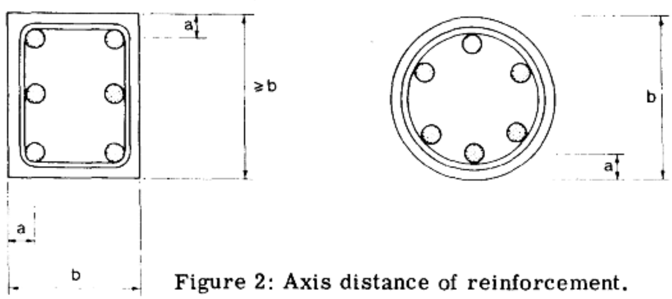

Figure 2: Axis distance of reinforcement.

The values given in the Tables apply to normal concrete with a moisture content of approximately 2 to 3% by weight of concrete and made with siliceous aggregates. If carbonaceous aggregates are used the minimum dimension either of the cross-section or the minimum value of the axis distance may be reduced by between 5 and 10%. With lightweight concrete the reduction may be 20% with a density of 1.2 t/m^3, but 10% when the density is 1.85 t/m^3, with linear interpolation for intermediate values (see also R1.2). Generally in walls and columns the reduction is only recommended with respect to the minimum dimension.

In all cases the minimum requirements in the Tables for F 30 must be observed.

The Tables have been prepared on the assumption that the critical temperature of the steel (T_{crit}) is 500°C, this being the temperature of the steel at which collapse of a simply supported and unrestrained member becomes imminent when subjected to the Standard fire test, when supporting its characteristic load.

If the critical temperature of steel in a member varies from the assumed 500°C (see Figure 1) the axis distance a should be adjusted to suit the actual critical temperature of the steel. The correction to be made should be an adjustment of 5 mm in the value of a for each 50°C change in the value of T_{crit}.

In addition for values of T_{crit} below 400°C the minimum width of the member b_{min} should be increased by 0.8 (400 - T_{crit}) mm.

R2.2 Reinforced concrete columns

The values in Table 1 apply to reinforced columns of both dense gravel concrete and lightweight concrete. They include recommendations for columns exposed to fire on all sides, and for columns built into fire resistant walls to their full height and so exposed to fire on one side only. The dimension b in Table 1 for columns exposed to fire on one side only apply to columns which lie flush with the wall or to those parts of protruding columns which are embedded in the wall and which carry load, provided that any opening in the wall is not nearer to the column considered than the minimum dimension b.

Columns dimensioned according to Table 1 and Figure 2 may be loaded eccentrically. Reinforcement should not exceed 4% of the cross-section of the concrete except at splices which should be arranged in the vicinity of column footings and supports.

TABLE 1
Columns (Reinforced)

Design details			Minimum dimensions in mm for fire resistance periods					
Type of concrete	Fire exposure	Dimensions	F30	F60	F90	F120	F180	F240
Dense aggregate concrete	All sides	b	150	200	240	300	400	450
		a	10	25	35	40	40	40
	One side only	b	100	120	140	160	200	240
		a	10	25	35	40	40	40
Lightweight concrete *	All sides	b	150	160	190	240	320	360
		a	10	25	35	40	40	40
	One side only	b	100	100	115	130	160	190
		a	10	25	35	40	40	40

*Valid for lightweight concrete with a density of about 1.2 t/m^3. For higher densities (which in all probability will be required in practice) reductions should be made according to clause R1.2.

R2.3 Walls

R2.3.1 Non load-bearing walls (partitions). Values for the minimum thickness t of partition walls are given in Table 2. These values ensure that the temperature rise on the side not exposed to the fire will not exceed 140°C during a standard fire test. In determining the actual thickness of the concrete allowance should be made for any additional protective cover or plaster provided in accordance with the conversion details given in R1.5.2.

R2.3.2 Load-bearing solid walls. The values in Table 3 apply to reinforced concrete load-bearing walls. They apply also to eccentrically loaded walls provided the resultant force remains within the middle-third of the cross-section. The ratio of height of wall-to-wall thickness h/t must not exceed 20.

The fire resistance of ribbed wall slabs shall be based on the average thickness including the concrete in the ribs provided that the ribs are securely tied to the slab by reinforcement or stirrups and the minimum dimensions of the ribs and the protection to the reinforcement in the ribs complies with the requirements for beams in Tables 5 and 6. The minimum dimensions in Table 2 will be required for the actual slab thickness to provide a satisfactory rate of heat transfer (see R1).

R2.4 Tensile members

The values in Table 4 apply to reinforced and prestressed concrete tensile members, such as tensile members in trusses or ties in arches. The total cross-sectional area of the member must be at least $2\,b^2_{min}$ where b_{min} is the appropriate dimension for b given in Table 4.

TABLE 2
Non load-bearing partition walls (reinforced or unreinforced).

	Minimum wall thickness (t) in mm for fire resistance periods					
Type of concrete	F30	F60	F90	F120	F180	F240
Dense aggregate concrete	60	80	100	120	150	175
Lightweight concrete *	60	65	80	100	120	140

*Note: Valid for lightweight concrete with density of about 1.2 t/m³.

TABLE 3
Load-bearing reinforced concrete walls.

Design details		Minimum dimensions in mm for fire resistance periods					
Type of concrete	Dimensions (mm)	F30	F60	F90	F120	F180	F240
Dense aggregate concrete	Wall thickness t	100	120	140	160	200	240
	Axis distance a	10	15	20	30	30	30
Lightweight concrete *	Wall thickness t	100	100	115	130	160	190
	Axis distance a	10	15	20	30	30	30

*Valid for lightweight concrete with a density of about 1.2 t/m³. For higher densities (which in all probability will be required in practice) reductions should be made according to clause R1.2.

R2.5 Simply supported beams

The values in Tables 5 and 6 apply to reinforced and prestressed concrete statically determinate (simply-supported and unrestrained) beams. For continuous and rigidly fixed beams, the values may be reduced in accordance with R2.6.

For beams with sloping sides, the width b should be measured at the centroid of the tensile steel.

Holes in the webs of beams may be neglected when considering fire resistance provided that the remaining cross-sectional area of the member in the tensile zone is not less than $2\,b^2_{min}$, where b_{min} is the minimum value assigned to the required fire resistance rating in Tables 5 and 6.

To prevent spalling of concrete in the webs of beams, the distance between the stirrup and the surface should not exceed $0.2\,b_w$ where b_w is the width of the web.

When the reinforcement or prestressing steel is arranged in several layers, an average axis distance a_m may be determined from the total cross-sectional area of all the steel (A_{s1}, A_{s2}, ... A_{sn}) and the corresponding minimum values of axis distance (a_1, a_2, ... a_n) measured either from the bottom or side of the member as follows:

$$a_m = \frac{A_{s1}\,a_1 + A_{s2}\,a_2 \cdots\cdots A_{sn}\,a_n}{A_{s1} + A_{s2} \cdots\cdots A_{sn}} = \frac{\Sigma A_s a}{\Sigma A_s}$$

(see Figure 3).

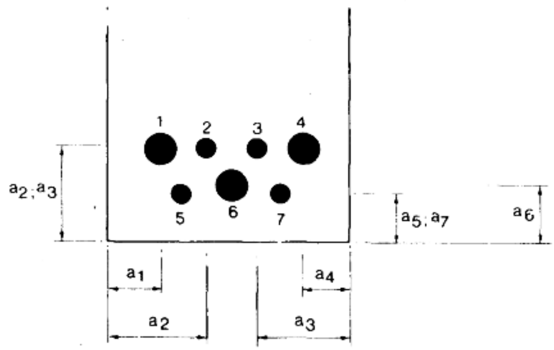

Figure 3: Average axis distance (see R2.5)

The minimum cover for any bar must not be less than that required for F 30 in Table 5 nor less than half the average axis distance a_m.

When the reinforcement or prestressing steel is arranged in a single layer, the side cover a_{st} must be at least equal to the value in Tables 5 and 6.

When the compressive zone or the pre-compressed tensile zone of a beam is exposed to fire, the concrete compressive stress under service load should not exceed 10% of the crushing strength of the concrete f_{cu} when the width of the beam is 80 mm increasing progressively to 30% for beam widths of 150 mm. For fire resistance periods of 2 hours or more simply supported I-beams, spaced at more than 1200 mm centres, shall have end blocks to enable them to act as tied trusses under ultimate load conditions.

TABLE 4
Reinforced and prestressed concrete tensile members.

Design details		Minimum dimensions in mm for fire resistance periods					
Type of concrete	Dimensions (mm)	F30	F60	F90	F120	F180	F240
Dense aggregate concrete	Minimum dimension of cross-section b	80	120	150	200	240	280
	Axis distance a	25	40	55	65	80	90
Lightweight concrete * A	Minimum dimension of cross-section b	80	120	150	200	240	280
	Axis distance a	20	35	45	55	65	70
Lightweight concrete * B	Minimum dimension of cross-section b	80	100	120	160	190	225
	Axis distance a	20	40	55	65	80	90

*Note: For lightweight concrete with a density of about 1.2 t/m^3 the requirements may be reduced to either of the values given in A or B. For higher densities (which in all probability will be required in practice) reductions should be made according to clause R1.2.

TABLE 5
Reinforced and prestressed concrete beams: dense aggregate concrete.

Fire resistance	Dense aggregate concrete					
	Beam width (b) in mm and corresponding minimum axis distance (a) in mm.					Minimum web thickness (mm)
F 30	b	80	120	160	200	80
	a	25	15	10	10	
F 60	b	120	160	200	300	100
	a	40	35	30	25	
F 90	b	150	200	280	400	100
	a	55	45	40	35	
F 120	b	200	240	300	500	120
	a	65	55	50	45	
F 180	b	240	300	400	600	140
	a	80	70	65	60	
F 240	b	280	350	500	700	160
	a	90	80	75	70	
		a_{st} = a + 10 mm			a_{st} = a	

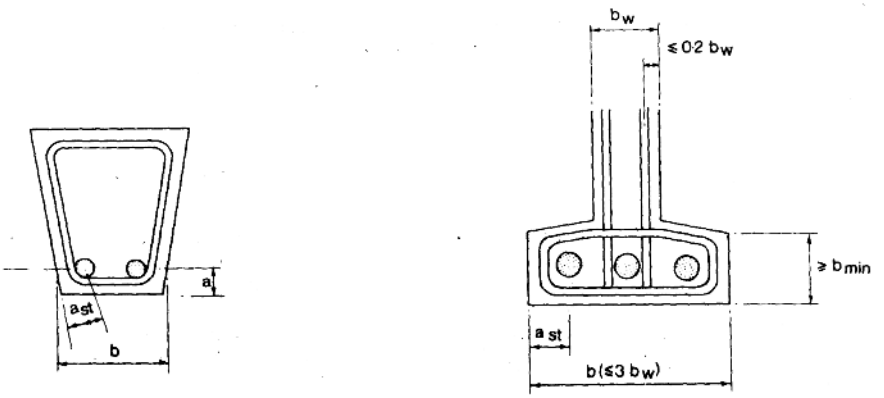

Figure 4: Beam reinforcement.

For beams of I-section where the web thickness b_w is less than b/2, (see Figure 4) shear reinforcement must be provided in the web. The area of steel provided must be at least 0.15% of the plan area of the web. Where the ratio of b/b_w is greater than 1.4 the axis distance or the average concrete cover to the reinforcement or prestressing steel respectively should be increased to $a.\,0.85\sqrt{b/b_w}$. When b/b_w exceeds 3, Tables 5 and 6 no longer apply and the member should be considered as a tensile member, (see R2.4).

In beams with high shear stresses where the shear forces are taken only by stirrups, arranged in the outer area of the cross-section, the axis distance a in Tables 5 and 6 shall be in relation to the stirrup in those regions where the design value of shear stress $\tau_d \geq 0.1\, f_{cd}$ where f_{cd} is the design compressive strength of the concrete.

TABLE 6
Reinforced and prestressed concrete beams: lightweight aggregate concrete.

Fire resistance	Lightweight aggregate concrete*: Beam width (b) in mm and corresponding minimum axis distance (a) in mm					Lightweight aggregate concrete*: Minimum web thickness (mm)
F 30	b	80	120	160	200	80
	a	20	15	10	10	
F 60	b	100	160	200	300	80
	a	40	30	25	20	
F 90	b	120	200	280	400	80
	a	55	40	35	30	
F 120	b	160	240	300	500	100
	a	65	50	40	35	
F 180	b	190	300	400	600	115
	a	80	65	55	50	
F 240	b	225	350	500	700	130
	a	90	75	65	55	
		$a_{st} = a + 10$ mm			$a_{st} = a$	

*Note: For lightweight concrete with a density of about 1.2 t/m^3 the requirements may be reduced to the values given in the able. For higher densities (which in all probability will be required in practice) reductions should be made according to clause R1.2.

R2.6 Continuous beams

Axial restraint due to thermal expansion in continuous systems causes an increase in the ultimate moment capacity at the supports and at the midspan. This redistribution of internal forces results in improved fire resistance.

The favourable influence of continuity may be taken into consideration when the arrangement of the upper (negative) reinforcement complies with the following:

(1) At least 20% of the negative reinforcement required at the supports is continued throughout the spans.

(2) The full negative reinforcement shall be continued to a distance of 0.4 l on both sides of the penultimate supports and then progressively terminated.

(3) The full negative reinforcement at the other intermediate supports shall be continued into the span for at least 0.15 l and then progressively terminated.

When the above conditions are met, the fire resistance rating in Tables 5 and 6 may be increased considerably. The increase shall be based on test results or on satisfactory analysis. Where no better values are available the ratings, as a guide, may be increased by 30 minutes for beams having a width b of less than 180 mm and by 60 minutes for beams with b equal or greater than 200 mm.

Flexural members which are restrained against deformation by their position in the building may be considered as continuous systems.