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Slim Floor Construction: Why?

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Summary

Slim floor construction is being used increasingly in Europe. Several construction systems have been developed and their characteristics are described on behalf of some buildings which just have been completed.

1. Historical Background

The architects and owner wish for greater flexibility in multi-storey construction has led to more frequent use of slim floors. The main characteristic of this form of construction is a shallow floor in which beams and slab elements are integrated within the same depth.

In fact the principle of the slim floor exists at least since the middle of last century. In 1845 timber floors were replaced in Great Britain by stone arches comprising integrated iron beams. A typical development consisted in the so-called "Prussian Cap Floor", shown in figure 1.

By the end of the nineteenth century standard rolled sections were used as integrated within the concrete slabs. However as the span of the concrete was still quite small, the distance between the steel beams was also quite reduced.

New developments in steel and concrete construction have favoured a real "Renaissance" of slim floor construction since 1975. According to Dr. Lars Wallin of the Swedish Institute of Steel Construction [1], "One effective way to reduce the total floor construction height is to support the floor elements on the bottom flanges of the floor beams. For that purpose a low, welded floor beam with a wide bottom flange and a narrow top flange has been developed. The selected beam height should be approximately equal to or somewhat lower than the floor element thickness. Hence the floor construction height can be reduced quite substantially. This type of floor beam can also be used with composite action through welded studs and with continuity to further reduce the beam height."

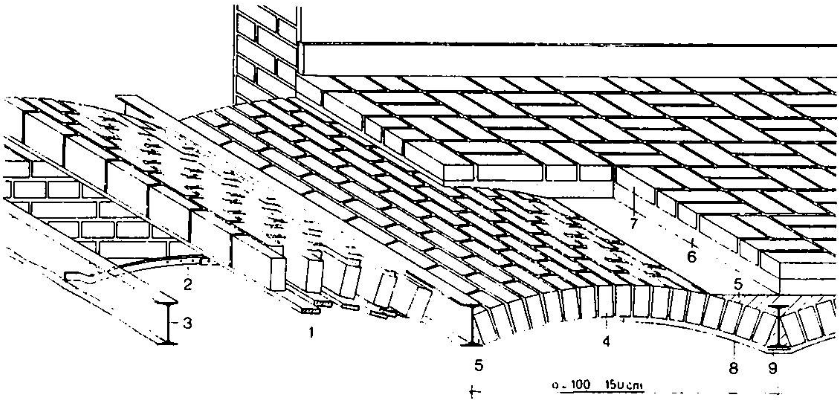


Fig. 1 Prussian cap floor

1 Shutter	*4 Wall bricks*	*7 Floor bricks*
2 Guide	*5 Concrete*	*8 Parget*
3 Floor beam	*6 Sand*	*9 Parget support*

Consequently a particular steel frame system characterized by slim floors and integrated fire resistance has become the dominant system for many buildings in Nordic Countries. Corresponding steel beams are shown in figure 2a, b and c. Slightly different integrated floor beams are now being used in Continental Europe and in Great Britain according to figures 2d and 2e, and to chapters 2.1 and 2.3 [2].

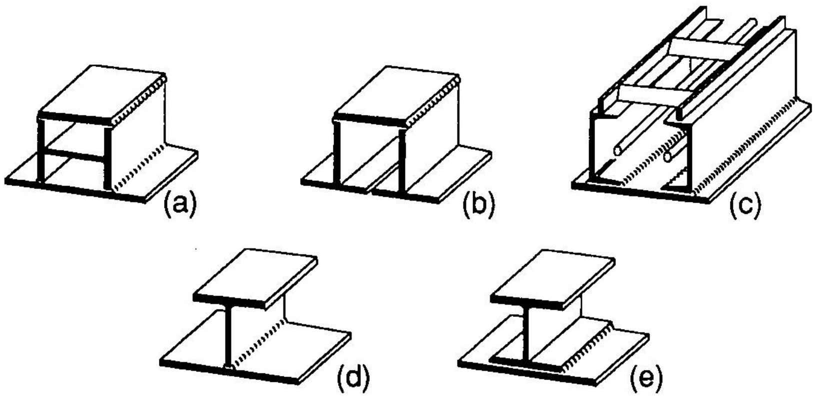


Fig. 2 Slim floor beams in the Nordic countries (a,b,c) and in Continental Europe and Great Britain i.e. IFB (d) and SFB (e).

2. Variety of Applied Systems

Various slim floor systems are presently available with different combinations of steel beams and concrete or composite slabs such as

- integrated floor beam IFB with hollow core prestressed units HCU,
- rolled profiles with in-situ normal weight concrete, the S+V system,
- slim floor beam SFB with deep decking and in-situ light weight 7concrete, the "Fast Track Slim floor",
- rolled profiles with deep decking and in-situ normal weight concrete, the so-called "Additional Slab".

2.1 IFB Slim Floor

The slim floor based on the integrated floor beam IFB was developed by PROFIL-ARBED [2,3,4,5] since 1991. It represents a part of a dry construction system based on steel columns, one directional steel beams and prestressed hollow core units (see figure 3).

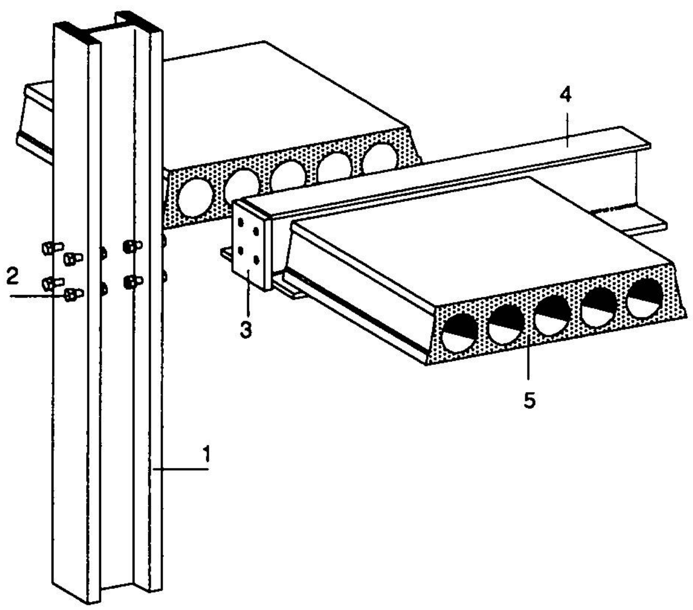


Fig. 3 Typical IFB slim floor system

1 Steel column
2 Bolts
3 End plate welded to beam
4. Steel beam IFB
5 Hollow core unit

The IFB concept is characterized by the following items described in figure 4:
- the steel beam is composed of a lower steel plate welded to the web of the half of a rolled section,
- various steel profiles and steel grades with a yield point of 235 up to 460 N/mm^2 are available,
- the integrated floor beam may be designed as simply supported or as a continuous beam,
- the void between hollow core units and the web of the steel profile is filled with in-situ concrete,
- it is strongly recommended to supply an in-situ topping with reinforced concrete in order to improve the transversal load distribution between hollow core elements. This structural topping is also increasing the shear resistance of hollow core units [6],
- a similar effect is produced by filling the cores at each end of the slab units,
- to ensure sufficient shear resistance to hollow core units during exposure to fire, it is recommended to provide complementary stirrups [7],
- complementary reinforcing bars, parallel to the steel beam, guarantee its ISO-fire resistance up to 120 minutes, whereas the lower steel flange may remain unprotected [8].

As a consequence the floor slab, supported on the bottom flange of the steel beam, presents from beneath a straight and clean ceiling surface.

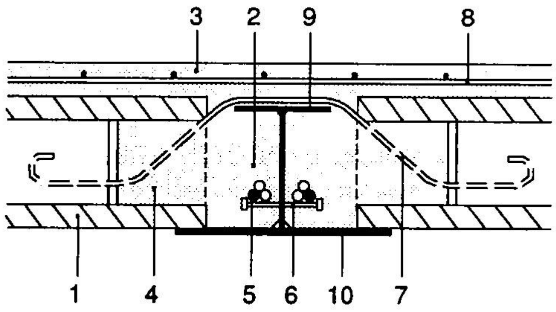


Fig. 4 IFB cross section

1 Prestressed hollow core unit
2-3 In-situ concrete
4 Core filling with concrete
5 Reinforcing bars
6 Welded studs
7 Stirrups
8 Slab reinforcement
9 Half of rolled profile
10 Welded bottom plate

2.2 S+V Slim Floor

This slim floor based on rolled profiles with various shapes was developed by STAHL & VERBUNDBAU GmbH [2]. It represents a part of a construction system based on steel or composite columns, steel beams and in-situ reinforced concrete slab (see figure 5).

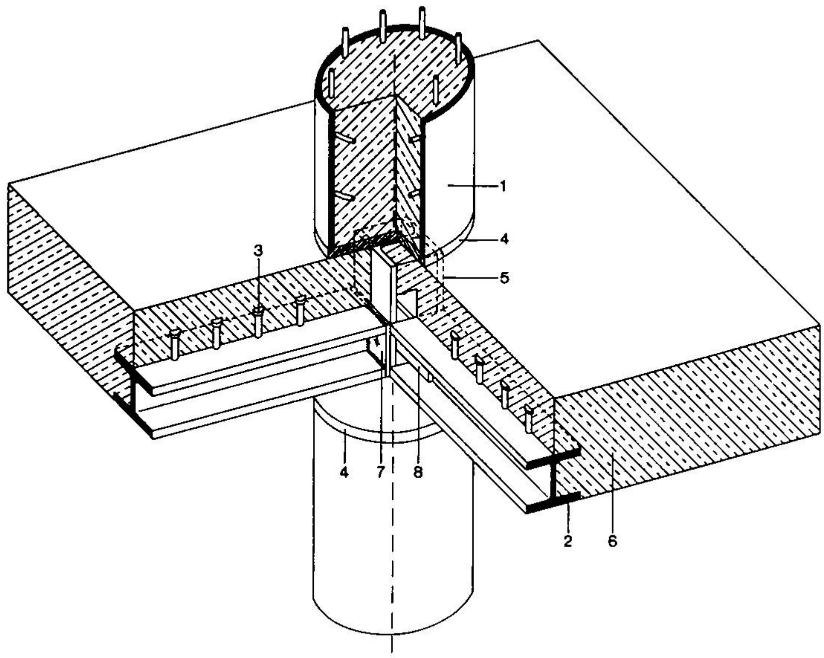


Fig. 5 Typical S+V floor system
1 Composite hollow section column
2 Slim floor steel beam
3 Shear studs
4 End plates of columns
5 Steel profile
6 In-situ reinforced concrete
7 End plate of beam
8 Shear flat for 2

The S+V concept is characterized by the following items described in figure 6:

- the steel beam is composed of rolled profiles or half sections with or without a steel plate welded to the free web end,
- various steel profiles and steel grades with a yield point of 235 up to 460 N/mm^2 are available,
- the steel beams may be designed as simply supported or as continuous beams,
- during in-situ concreting of the reinforced slabs, concrete may be supported either by a timber shutter, prefabricated filigree concrete decks or profiled steel sheets,
- the steel profile, encased in concrete with the exception of the lower steel flange, behaves as a composite cross-section, also thanks to the shear studs welded on the profile,
- this cross-section may be designed according to ENV1994-1-1 for normal temperature conditions [9] and following ENV1994-1-2 for fire exposure [8]; the lower steel flange may remain unprotected up to the ISO requirement of R120,
- this slim floor cast in-situ has an assured monolithic behaviour, useful in certain design situations when f.i. large openings have been foreseen in the floor or for special loadings due f.i. to earthquake shocks !

This slim floor, similarly as the previous one, presents from beneath a straight and clean ceiling surface.

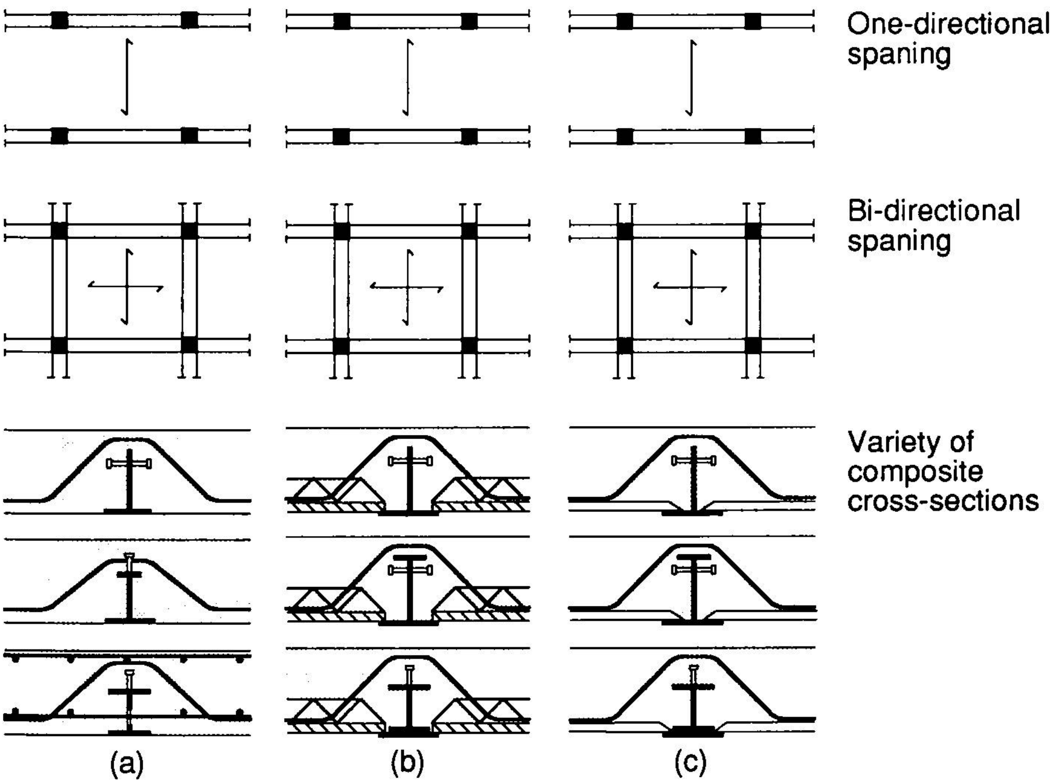


Fig. 6 S+V cross sections based either on a timber shutter (a), prefabricated filigree concrete decks (b) or profiled steel sheets (c)

2.3 Fast Track Slim Floor

This slim floor based on the SFB beam was developed by BRITISH STEEL [2,3,4]. The corresponding construction system is based on any steel or composite column type, steel beams with enlarged lower flange supporting the deep decking, and in-situ reinforced light weight concrete (see figure 7).

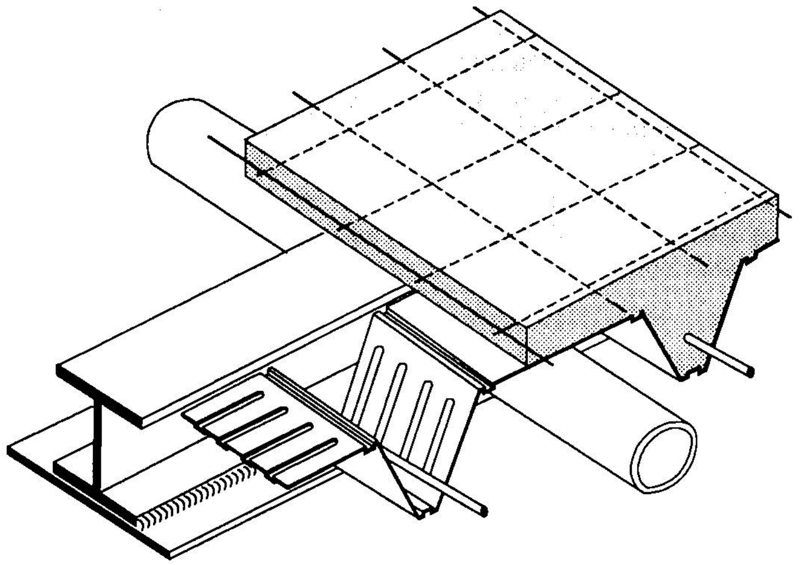


Fig. 7 Typical Fast Track Slim Floor

The Fast Track Slim Floor is characterized by the following aspects:

- the steel beam is composed of rolled profiles reinforced on the lower flange by an enlarged and welded steel plate,
- various steel sections and steel grades up to a yield point of 355 N/mm^2 are used,
- reinforcing bars are foreseen inside and on top of the deep decking,
- light weight concrete cast over the whole floor constitutes a concrete lattice in which the steel beam is fully integrated,
- composite actions is activated by welding shear studs on top of the steel beams and by the embossments of the deep decking,
- large openings may be realized through the webs of SFB beams, permitting to integrate all types of pipes beneath the deep decking but still localized within the height of the slim floor,
- this slim floor system may be designed according to ENV1994-1-1 and ENV1994-1-2 [9,8]; specific design rules have been confirmed by full scale testing in the Netherlands as well for normal temperature conditions as for fire exposure [10,11,12,13].

2.4 Additional Slab-Slim Floor

This slim floor based on rolled profiles of any shape was developed by HOESCH SIEGERLANDWERKE GmbH [2]. The corresponding construction system is based on any steel or composite column type, steel or composite beams fabricated out of rolled profiles with shear studs and bearing blocks welded on to the upper flanges which are supporting the deep decking, and in-situ reinforced normal weight concrete (see figure 8).

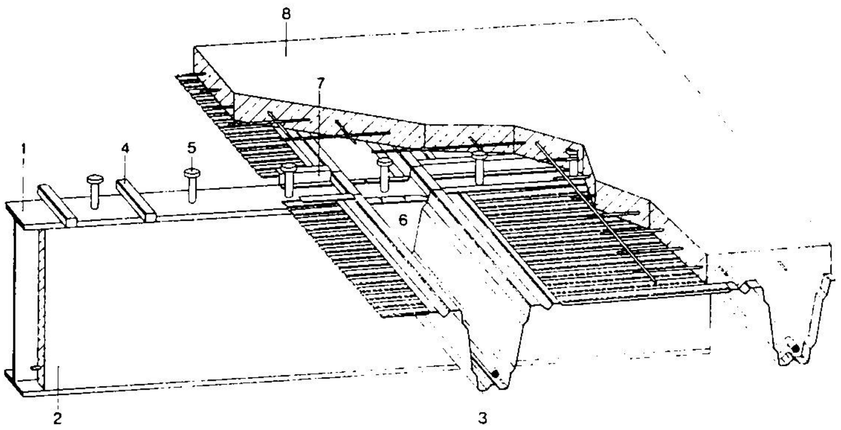


Fig. 8 Typical Additional Slab-Slim Floor
1 Composite beam *5 Shear stud*
2 Partially encased concrete *6 PVC end plate*
3 Deep decking steel sheet *7 Z shaped stanching profile*
4 Bearing block *8 Reinforced concrete lattice*

In fact this "Additional Slab" is not, generally spoken, a slim floor, as the steel beam may be higher than the deep decking. This floor system is characterized by the following aspects:

- the steel beam is composed of rolled profiles of any shape and height and any yield point up to 460 N/mm^2,
- reinforcing bars are foreseen inside and on top of the deep decking, supported by special bearing blocks welded on top of the steel beams,
- normal weight concrete cast over the whole floor constitutes a concrete lattice,
- composite action is guaranteed by welding shear studs on top of the steel beams and by the embossments of the steel decking,
- this floor system may be designed according to ENV 1994-1-1 and ENV 1994-1-2 [9,8]; the ISO-fire requirement R120 may be fulfilled.

3. General Design Recommendations

Design recommendations may be split in general and specific principles and rules, function of the various slim floor systems described in chapter 2, whereas general recommendations should be issued concerning global fire safety considerations.

3.1 General Design Principles

It is in the interest of construction in general and of steel construction in particular to conceive safe slim floors for normal temperature conditions and for the fire situation. Consequently it should be checked that design rules, both for bending resistance and shear resistance, have been calibrated on the basis of thorough calculations and realistic tests.

It may be assumed that these requirements are fulfilled for the bulk of slim floor systems given before and designed according to ENV 1994-1-1 and ENV 1994-1-2 [9,8].

3.2 Specific Design Rules for Slim Floors with HCU

The following special features shall be considered for normal temperature conditions and for the fire situation.

3.2.1 Normal temperature design

Shear resistance of hollow core units, HCU, should be established as a function of the flexibility of the corresponding supports. Investigations and research, undertaken in Nordic countries since 1990, clearly indicate that the shear resistance of HCU elements decreases when the flexibility of the supporting beams increases [14,15].

Furthermore it is considered that in-situ structural topping may contribute in a significant way to improve the shear resistance of hollow core units [4,6].

Finally it would be useful to study the "General Shear Design Method" established by COLLINS & MITCHELL [16]. This so-called unified method is presented for the shear design of both prestressed concrete members and nonprestressed concrete members. The method can treat members subjected to axial tension or axial compression and treats members with and without web reinforcement. In fact the normal cracked concrete contribution V^{c}_{Rd} is added to the reinforcement contribution V^{s}_{Rd} and to the effect of prestressing V^{p}_{Rd}, so that the shear resistance follows from:

$$V_{Rd} = V^{c}_{Rd} + V^{s}_{Rd} + V^{p}_{Rd} \quad (1)$$

3.2.2 Structural Fire Design

It appears that the structural fire design of the steel beams composing slim floors may be performed according to well established procedures [8]. However when analysing hollow core units, HCU's, for the fire situation, it becomes quite fastidious to get hold of a complete set of design rules including bending and shear resistance. Whereas DIN 4102, Teil 4, gives constructional requirements related to bending resistance [17], other regulation codes give some guidance only concerning the shear resistance.

In chapter 2.7.3.2 (ii) of the FIP RECOMMENDATIONS [7] it is written that *"The shear capacity of hollow core units during exposure to fire is affected by (a) the increase of the tensile stresses in the webs due to the temperature gradient etc."* and in chapter 4.5, Rule (4) of ENV 1992-1-2 [18] it is declared that *".... special consideration should be given when tensile stresses are caused by non-linear temperature distributions (e.g. voided slabs, thick beams, etc.). A reduction in shear strength should be taken equivalent to these tensile stresses".* Unfortunately no quantified design rule is given permitting to check the shear resistance in the fire situation, $V_{Rd,\theta}$, of hollow core units.

For that reason several slim floor fire tests were performed in France and in Switzerland [19,20], clearly testifying the beneficial effect when providing a structural topping and stirrups (see figure 4). Furthermore a first attempt was done to quantify, in connection to finite element calculations, the shear resistance of HCU's [21,22]. In that respect the procedure explained in [16] was adapted to the fire situation

$$V_{Rd,\theta} = V^{c}_{Rd,\theta} + V^{s}_{Rd,\theta} + V^{p}_{Rd,\theta} \quad (2)$$

Consequently it is recognized, that slim floors based on HCU's constitute a quite complex construction system with steel, concrete and prestressed components. This situation requires multi-disciplinary research based on a scientifically sound background and supported by a set of realistic fire tests.

3.3 Global Fire Safety Considerations

Developments under way since 1985 in the field of fire safety engineering permit nowadays to take advantage of the new structural fire design standards of CEN. Indeed global structural analysis may be performed on the entire structure, the combination rule for actions during fire shall be considered and the evolution of a natural fire may be assumed ! This realistic structural fire design may even be improved by considering the effect of active fire safety and fire fighting measures. Consequently this produces real safety for people, f.i. by adequate partitioning, by sufficient escape routes and proper smoke venting [23,24,25].

4. Specific Architectural Outcomes

Our intention is not to discuss principles of architecture, like those concerning the so-called architecture of freedom. But it is worthwhile to remember MIES VAN DER ROHE who said: *"A clear structure is the backbone in it all and makes the free plan possible".*

From that point of view slim floor construction is quite attractive as
- it allows an integrated layout for services and ventilation ducts (see 2.3 and 2.4)
- it permits in general a reduced floor to floor depth,
- it leads to a clear and straight ceiling surface so that to make the structure of the floor visible and so that a shifting of inner partition walls is always possible (see 2.1 and 2.2).

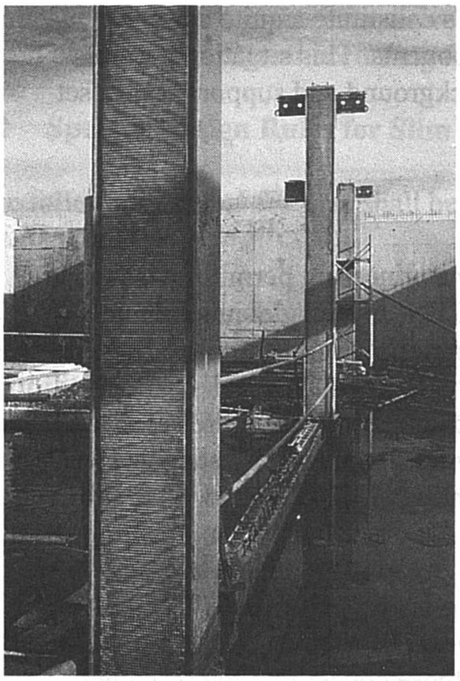
In order to illustrate architectural advantages of slim floors, the following buildings are shortly described hereafter.

4.1 Ecole Nationale des Ponts et Chaussées, Marne-la-Vallée, France, 1994-96

This ENPC high school building with a total clear surface of 31.200 m^2 has been erected in the "City Descartes" in the East of Paris. The bulk of floors is conceived as IFB slim floors [26].

The following special features may be underlined:

- composite columns with partially encased steel profiles (HE300AA), designed according to ENV 1994-1-2, were erected in elements covering two levels. The grooved concrete and the steel flanges are remaining visible (see figure 9),
- the integrated floor beams IFB are composed of the half of the rolled profile HP400 on top of which the steel plate 140x40 mm was welded. Furthermore shear studs were welded to this upper flange in order to create composite beams (see figure 10),
- a structural reinforced topping of 8 cm thickness was put on top of the hollow core units HCU, so that the total floor thickness is 25 cm.



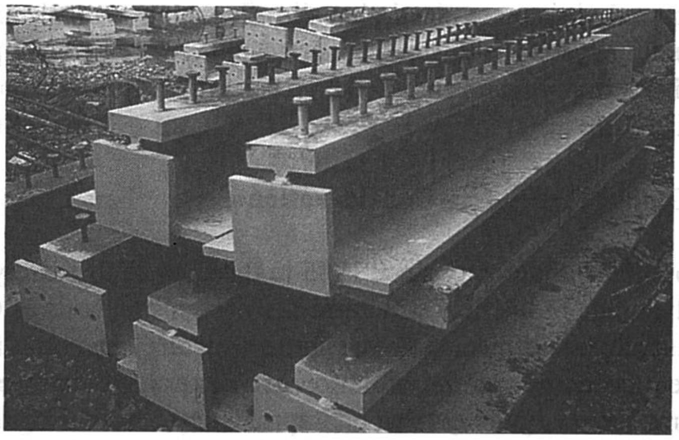


Fig. 10 ENPC, IFB beams with shear studs

Fig. 9 ENPC, Composite columns

4.2 PROFILARBED Office Building, Esch-sur-Alzette, Luxembourg, 1991-93

This AOB office building is composed of two wings with nine levels and a total volume of 61.000 m^3. The global fire safety has been designed according to 3.3, so that the steel structure remains visible in the entire building. Floors are conceived as IFB slim floors [23,24].

The following special aspects could be underlined:
- the integrated floor beams IFB are composed of the half of the rolled profile IPEA500 below which a steel plate 420x10 mm was welded,
- a structural reinforced topping of 10 cm thickness was cast on top of the hollow core units HCU, in order to guarantee sufficient ductility (see figure 11),
- this building shows in a striking way the lightness and beauty of a steel frame when a global fire safety concept is used together with slim floors (see figure 12).

Fig. 11 AOB, IFB slim floor based on hollow core units reinforced by stirrups at supports and by a structural topping

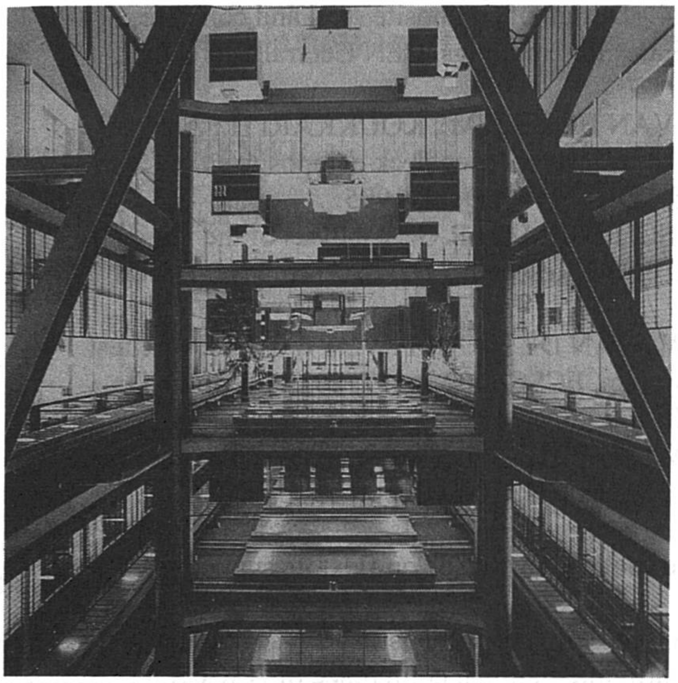


Fig. 12 AOB, View inside the building atrium on slim floors and visible steel structure

5. Conclusion

Multi-disciplinary and correctly guided research is needed to develop fully transparent design rules in relation to slim floors. In that case slim floors in general, and those based on hollow core prestressed units in particular, may be considered as the most promising construction models in the future.

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