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Outstanding Composite Structures for Buildings

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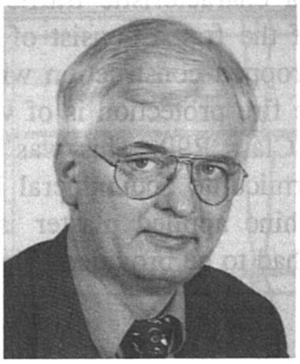

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Summary

The paper gives an overview of the development of composite structures for buildings in Germany in recent years. The background and advantage of partially concrete encased columns and girders is demonstrated with three buildings for the car industry, an office building and the extension of the airport in Hannover. Furthermore two impressive high rise buildings in Düsseldorf and Frankfurt will be presented.

1 Introduction

Comparing the development of composite structures for buildings in Europe it is obvious that in contrast with neighbouring countries, in Germany the technology with partially concrete encased members has been favoured over the last twenty years. The paper will show the advantages of this technology for some typical examples of outstanding composite structures for industrial and office buildings.

2 Buildings for the Car Industry

2.1 General

Industrial buildings for the car industry require a high flexibility because the technical equipment must be converted frequently during the design life. The Figures 1 to 3 show three typical buildings for the car industry built between 1982 and 1992. These buildings demonstrate the development of composite structures from the conventional type to the modern technology of concrete encased beams and columns with significant advantages, regarding fire resistance as well as durability and last but not least economic benefit.

2.2 Paint Unit of Opel in Rüsselsheim

In 1981 the Opel corp. erected a new paint unit in Rüsselsheim, shown in Figure 1 /1/. The building measures 405 x 80 metres and has three stories with a total height of 31.5 metres. Additionally a penthouse with dimensions of 340 x 20 metres with a height of 7 m is located between gridlines D and E. In the transverse direction the structure consists of sway frames with rigid connections at the top of each storey level on gridline C and with all the other connections nominally pinned. In the longitudinal direction the structure is stabilised by vertical bracings. For the composite slabs with a depth of 200 mm Holorib sheeting is used. The slabs with a span of 3.33 metres are supported by composite beams. Both slabs and composite beams had to be designed for a characteristic traffic load of 12,5 kN/m^2. The composite girders and the steel columns of the frame consist of welded sections The span length of the composite slabs required a propped construction with scaffolding truss girders according to Fig. 1. For a painting unit the fire protection is of vital importance. The whole structure is protected for a fire resistance Class R90. This was achieved by fire resistance boards and machine applied plaster on vermiculite and mineral basis. For the fastening of installations and suspended loads the machine applied plaster is especially unfavourabely. Therefore additional suspended steel beams had to be provided (Fig. 1).

2.3 Body Unit of Porsche in Stuttgart

Only 4 years later the new body unit of Porsche was built in Stuttgart (Fig. 2). The design philosophy had completely changed. In the meantime a code for composite columns had been published in Germany and intensive research work on fire resistance of partially concrete encased beams had been carried out. The building with three stories and an additional penthouse measures 125.5 x 65 m. The structure is stabilised in the transverse direction by concrete gable walls and in the longitudinal direction by truss bracings. Main and secondary beams are continuous and concrete partially encased sections are used; the columns are nominally pinned at both ends and fully encased composite sections are now used. The building has an extremely high degree of installation, requiring a lot of web openings in the main girders with a span of 20 metres. The highly stressed main girders have flanges and webs with a wide variation of plate thickness (Fig. 4). In comparison to the Opel paint unit the spacing of the secondary beams is reduced to 2.5 m to avoid propped construction for the composite slabs with a depth of 240 mm. The structural fire design was based on a model where the effect of temperature on material characteristics is taken into account by reducing the material properties and the dimensions of the cross sections. For the required fire resistance Class R90, additional reinforcement was necessary in the concrete encasement of the main and secondary beams. This reinforcement was not taken into account for normal temperature design.

2.4 Paint Unit of Opel in Eisenach

In 1992 the new Opel paint unit in Eisenach was one of the first major investments in the new states of reunified Germany (Fig. 3). The building is one of the most modern of this type in Europe and sets new milestones for the car industry /3/. The structure with measurements of 240 x 56 metres and up to 30 m high consists of two main production levels and an additional technical penthouse. The experiences with the body unit in Stuttgart showed that systems with nominally pinned columns lead to disadvantages during erection, because an enormous number of temporary bracings is necessary. Therefore a structural system with sway composite frames in the transverse direction and truss bracings in the longitudinal direction was chosen in Eisenach.

In order to minimise the time of construction and welding on site, the detailing of the connection is very important. Figure 3 shows the main frame joint used on gridlines B and C and the support of the main girders at the corner columns on gridlines A and D.

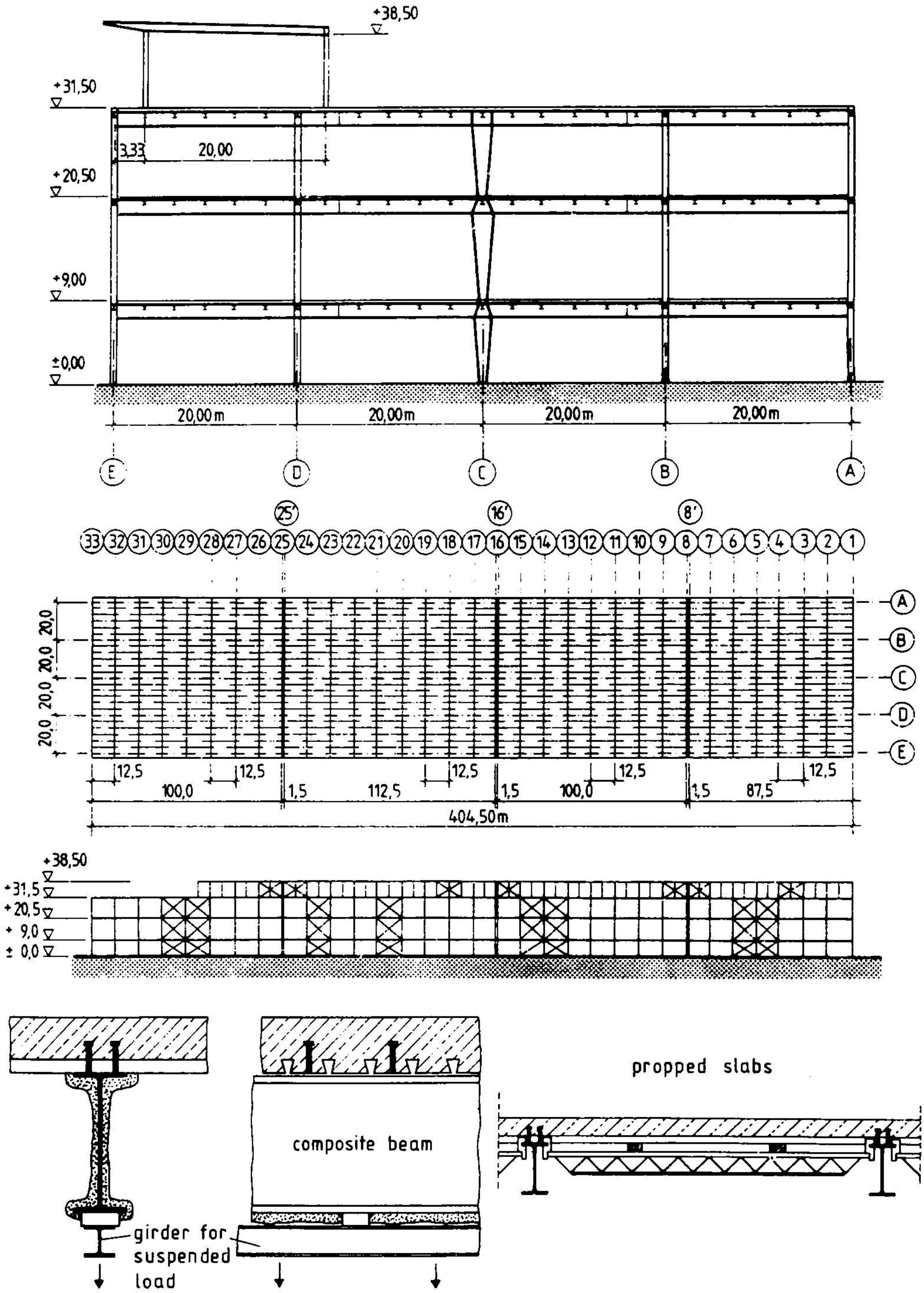


Fig. 1 Paint unit of Opel in Rüsselsheim (1981)

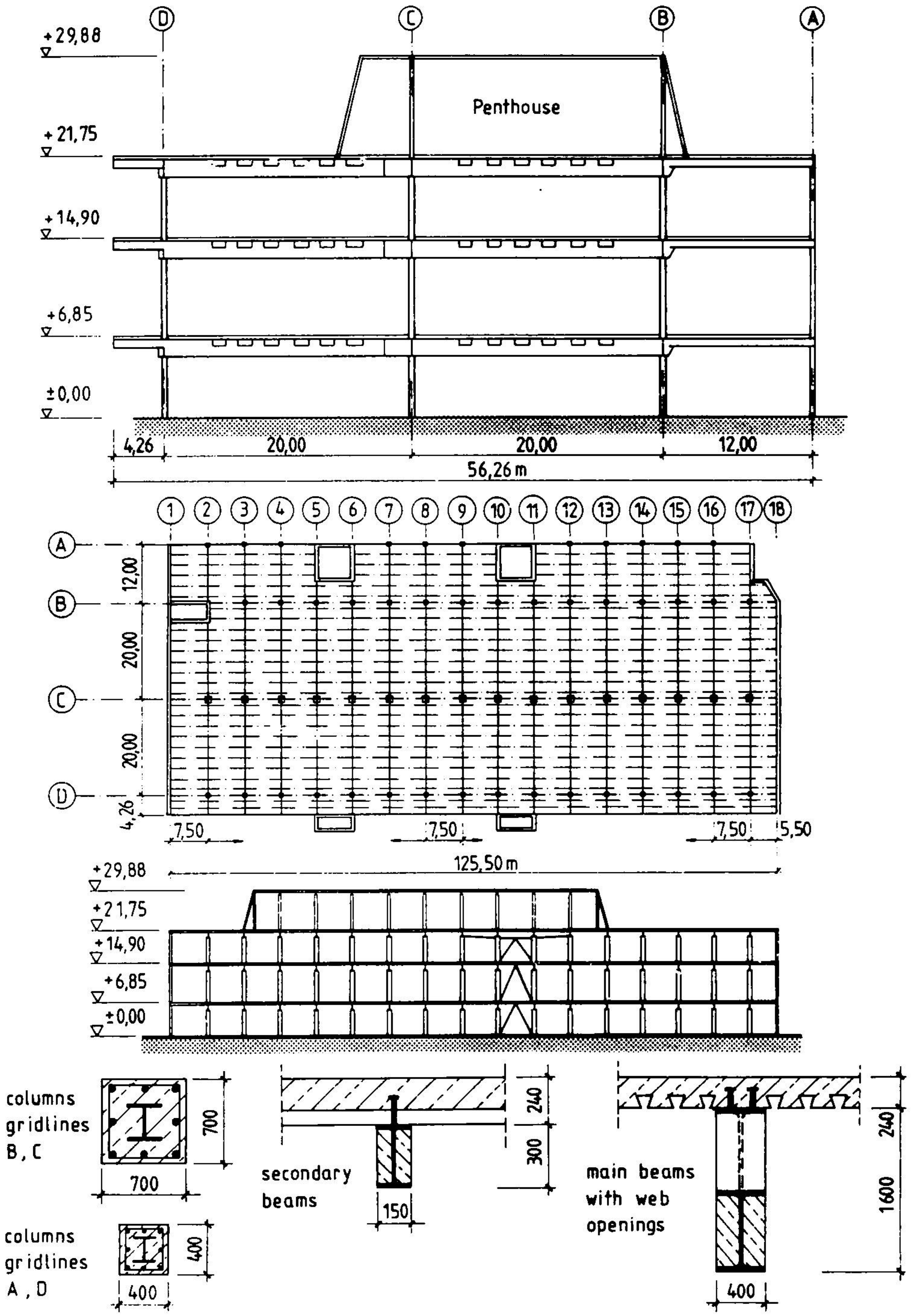


Fig. 2 Body unit of Porsche in Stuttgart (1985)

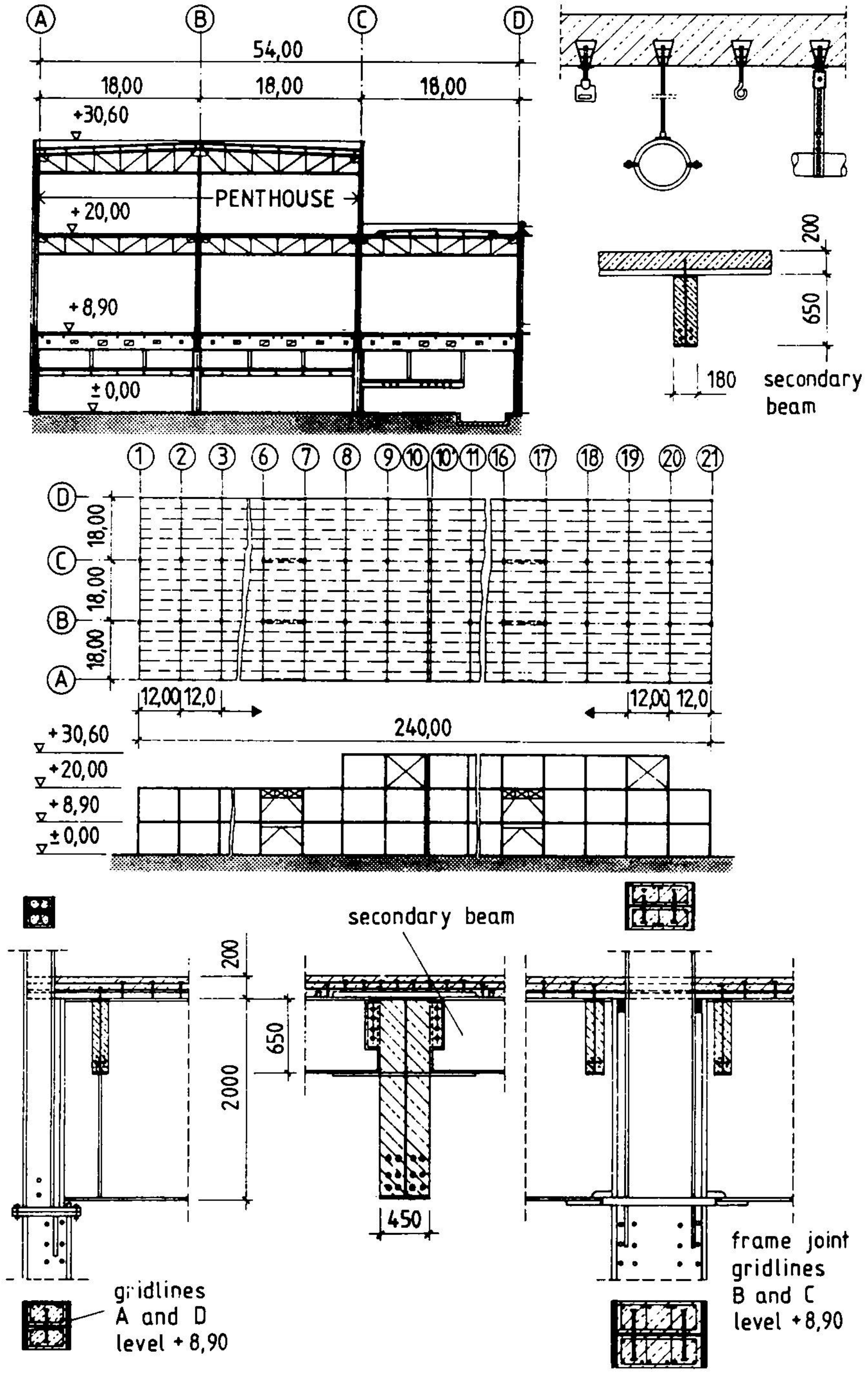


Fig. 3 Paint unit of Opel in Eisenach (1992)

The depth of the columns changes at each storey level, and the supporting reactions of the main girders are introduced into the columns by end plates. The bending moments are transferred into the columns by reinforcement and contact plates at the top flange and by contact in combination with welded plates at the bottom flange. In comparison with the paint unit in Rüsselsheim, the composite columns had the advantage of increasing the horizontal stiffness of the frame significantly. To avoid the high costs for the formwork of completely concrete encased sections, partially encased sections are used for the columns. Additionally this has the advantage that new installations can be fixed at the free steel flanges without difficulties. In Germany it was the first time that a mixed system with composite columns, composite girders and steel trusses was designed as a composite sway frame. The design of this type of framing is not covered by Eurocode 4 and the national German codes. In a first trial calculation an elastic calculation was carried out with an effective cracked stiffness for the columns. The effect of cracking of concrete in the main girders was taken into account by reducing the stiffness at internal supports to the stiffness of the steel section consisting of structural steel and reinforcement. Effects of creep and shrinkage were taken into account by use of different modular ratios for permanent actions, shrinkage and hyperstatic effects developing in time. For the standard frames the second order effects lead to an increase of bending moments up to 25%, which is significantly lower than the second order effects of the steel frame of Opel Rüsselsheim. In a second step, a non-linear calculation was carried out for critical load arrangements, taking into account cracking of concrete and tension stiffening effects. These calculations have shown that the simplified method gives safe results.

Figure 4 shows the material distribution of the main girders of the body unit of Porsche and the paint unit of Opel. It is noticeable that the number of changes of cross-sections of the flanges and the web of the Opel beam is significantly reduced. As explained above, in the design of the girder of Porsche the concrete encasement and the reinforcement were taken into account only for fire resistance. For the Opel girder the concrete encasement and the reinforcement were used to improve the bending resistance for normal temperature design as well as fire design. For economical reasons, instead of altering the flanges of the structural steel section, additional reinforcement in the concrete encasement was provided. Table 1 gives a calculation example for a typical main girder with concrete encasement and additional reinforcement, and in comparison for a girder with conventional fire protection by encasement with fire resistance boards, based on average unit prices of the year 1996. The comparison demonstrates that the concrete encased beam is more economical and has the additional advantages described above and has as well a significantly higher flexural stiffness.

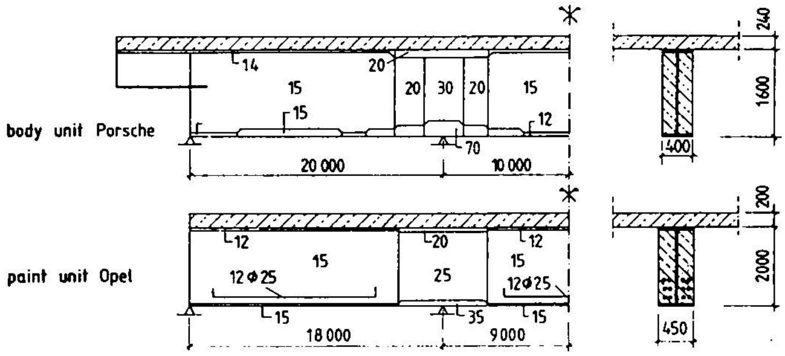
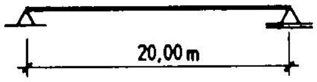
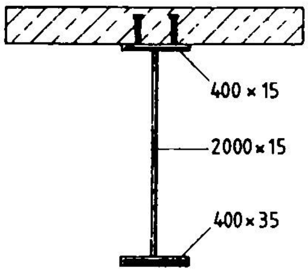
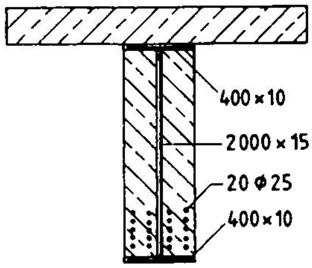


Fig. 4 Material distribution of the main girders of the body unit of Porsche and the paint unit of Opel in Rüsselsheim

Table 1 Comparison of costs for typical main girder

system	structural steel 7,85 tons		structural steel 6 tons	
				
	unit price in ECU	total costs ECU	unit price in ECU	total costs ECU
structural steel (wage costs)	500 ECU / ton	3925,0	460 ECU / ton	2760,0
structural steel (material)	500 ECU / ton	3925,0	500 ECU / ton	3000,0
headed studs (top flange)	2,5 ECU/stud	750,0	2,5 ECU/stud	750,0
erection costs/ton structural steel	200 ECU/ton	1570,0	300 ECU/ton	1800,0
fire resistance boards (88m²)	50 ECU/m²	4400,0	-	-
concrete encasement (15,25m³)	-		250 ECU/m³	3800,0
studs concrete encasement	-		2,2 ECU/stud	660,0
reinforcement concrete encasement 1,4 to.	-		700 ECU/ton	980,0
total costs for the beam	**14570.0 ECU**		**13750.0 ECU**	

In contrast to the body unit of Porsche the span of the composite slabs is increased to 3,0 metres for the Opel paint unit. Propping of the sheeting is normally necessary for a slab with Holorib sheeting and a thickness of 200 mm. The slabs were poured in two layers, in order to avoid the high costs of propping in industrial buildings with a height between floors of more than 10 m. The thickness of the first layer resulted from the bending resistance of sheeting acting as formwork without props. After hardening of the first layer the composite slab was capable to resist the remaining concrete for the required slab thickness of 200 mm. To achieve a sufficient longitudinal shear resistance between the two concrete layers, additional shear reinforcement had to be provided.

3 Office, Production and Storage Building of Siemens in Berlin

Figure 5 shows a multi-storey building for Siemens in Berlin, erected in 1993 /3/, /4/. Maximum flexibility was required by the client with regard to the usability of different parts as office, production and storage areas. The building rises five stories on an area of 81 x 81 meters with a column grid of 14.8 x 10.8 m. The slabs with a span of 3.6 m and a depth of 20 cm are composite with Holorib steel sheeting. All beams with a depth between 450 mm and 900 mm are continuous with concrete encasement and additional reinforcement taken into account in the design at normal temperature and for fire resistance. Slabs and beams had to be designed for traffic loads up to 30 kN/m^2. In the areas with a height between floors of 11.5 m the concrete was poured in two layers to avoid propping of the sheets. In all other areas propped construction was preferred for the sheeting. The columns are partially concrete encased I-sections and concrete filled tubes. In the centre of the building, a big composite grillage with an integrated composite ring beam is located for a domelight. The building of Siemens is an good example how the architectural requirements showing the steel members can be combined with high fire resistance and high load bearing capacity of the structure.

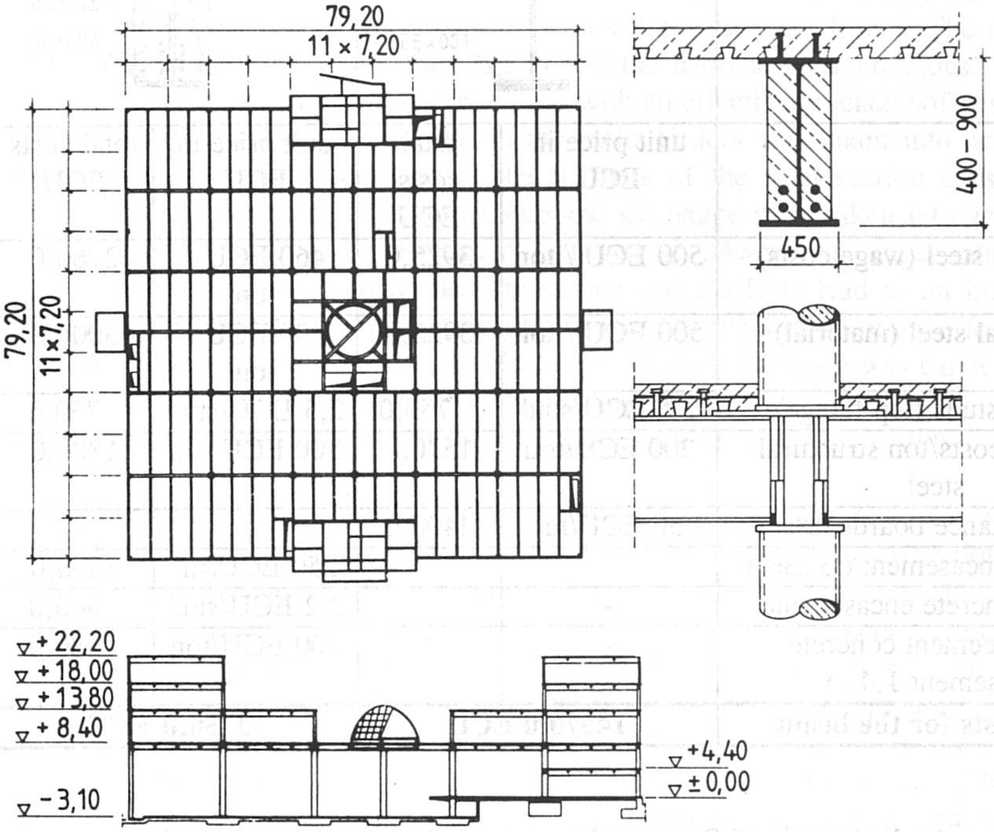


Fig. 5 Cross section and plan of Siemens in Berlin

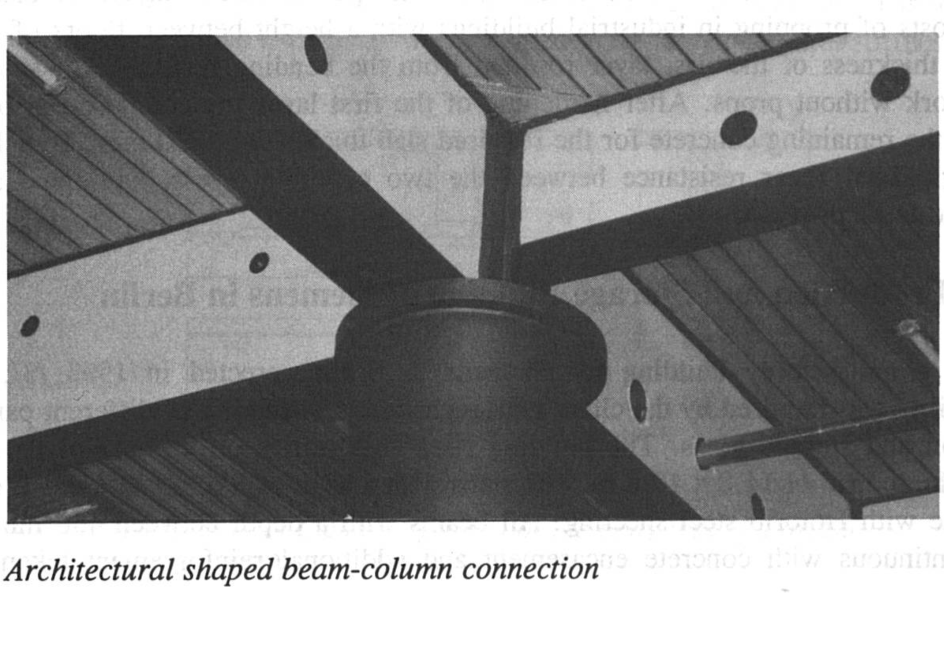


Fig. 6 Architectural shaped beam-column connection

4 Extension of the Airport in Hannover

Figure 7 shows the extension of the airport in Hannover under construction in 1997. The two storey building has a triangular plan with a side length of approximately 144 m. It is stabilised for horizontal action by concrete cores. Most columns are concrete filled steel tubes. The beams are concrete encased welded I-sections with an extremely high ratio of reinforcement. Between the flanges, up to 20 bars with a diameter of 28 mm are provided. As explained above, this type of beam is economical because the unit prices for reinforcement are significantly lower than those for structural steel and because the bending resistance at normal temperatures and not the fire resistance governs the design. For this special type of composite beam, tests were carried out to ensure that the total reinforcement of the concrete encasement can be taken into account for the plastic bending resistance, where there is only 50% of full shear connection. Furthermore the crack formation, the crack width and the deformation behaviour of the beams were checked because of the special public interest in the building. The test results have shown, that for beams predominately loaded by point loads the design rules in Eurocode 4 regarding the minimum degree of shear connection are very conservative. In addition to the main reinforcement of 28 mm bars, small-diameter bars near the surface had to be provided, to ensure a sufficient distribution of cracks in the concrete encasement in order to develop the full plastic bending resistance and to avoid early failure of the main reinforcement at single big cracks.

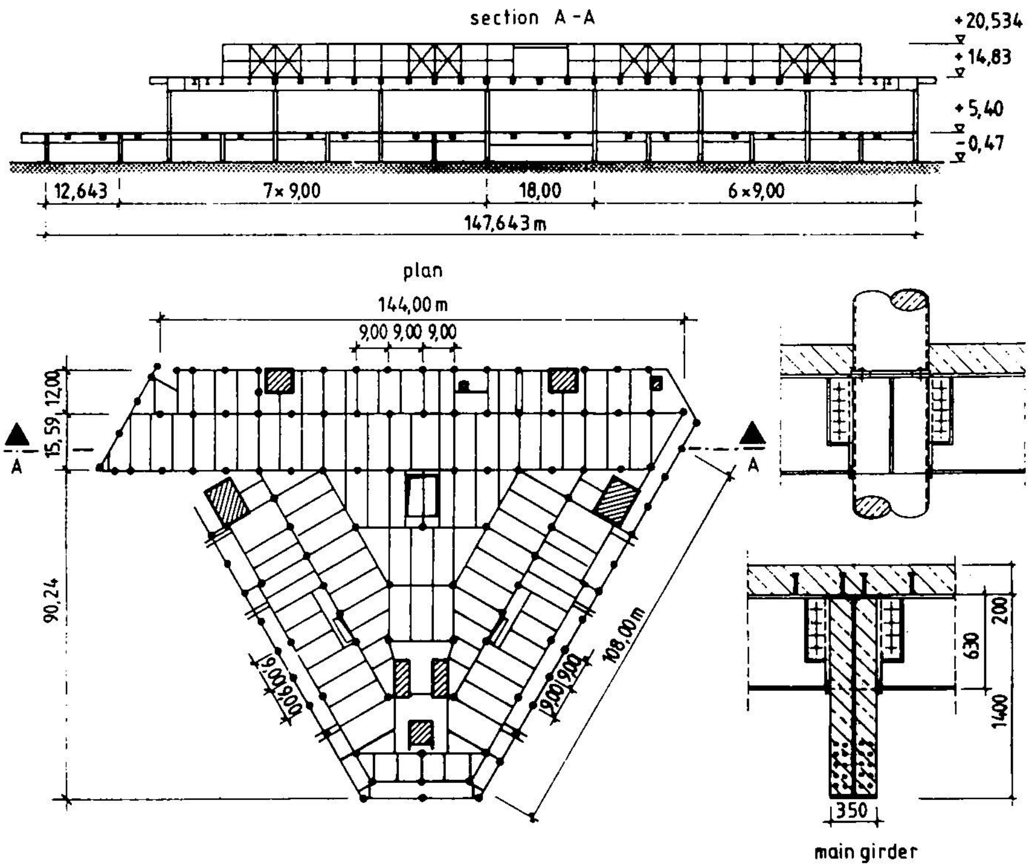


Fig. 7 Plan of the extension of the airport of Hannover

5 High-rise Buildings

5.1 General

In 1997 two very interesting building projects will be finished in Düsseldorf and Frankfurt. The Stadttor (Towngate) in Düsseldorf /5/ and the Commerzbank tower in Frankfurt /6/. Both high rise buildings use a large variety of different composite members with sophisticated load-bearing structures.

5.2 The Towngate Düsseldorf

The building with a rhomboid plan consists of two 16 storey office towers connected by horizontal truss members extending through the three top floors (Fig. 8). The horizontal stability is realised by small concrete cores and mainly by three portal frames consisting of composite truss-columns and the horizontal truss members. The three portal truss-frames form a z-shaped system in the plan. The trusses are made by concrete filled steel tubes where the horizontal and diagonal members above the fourth floor are without concrete. Composite slabs in combination with concrete encased composite main beams and secondary composite beams without concrete encasement are used for the vertical loads. With regard to the required fire resistance Class R90 cementious coatings or fire resistance boards are employed for the secondary beams. The fire resistance of the columns is ensured by concrete and additional reinforcement without any further protection of the steel tubes.

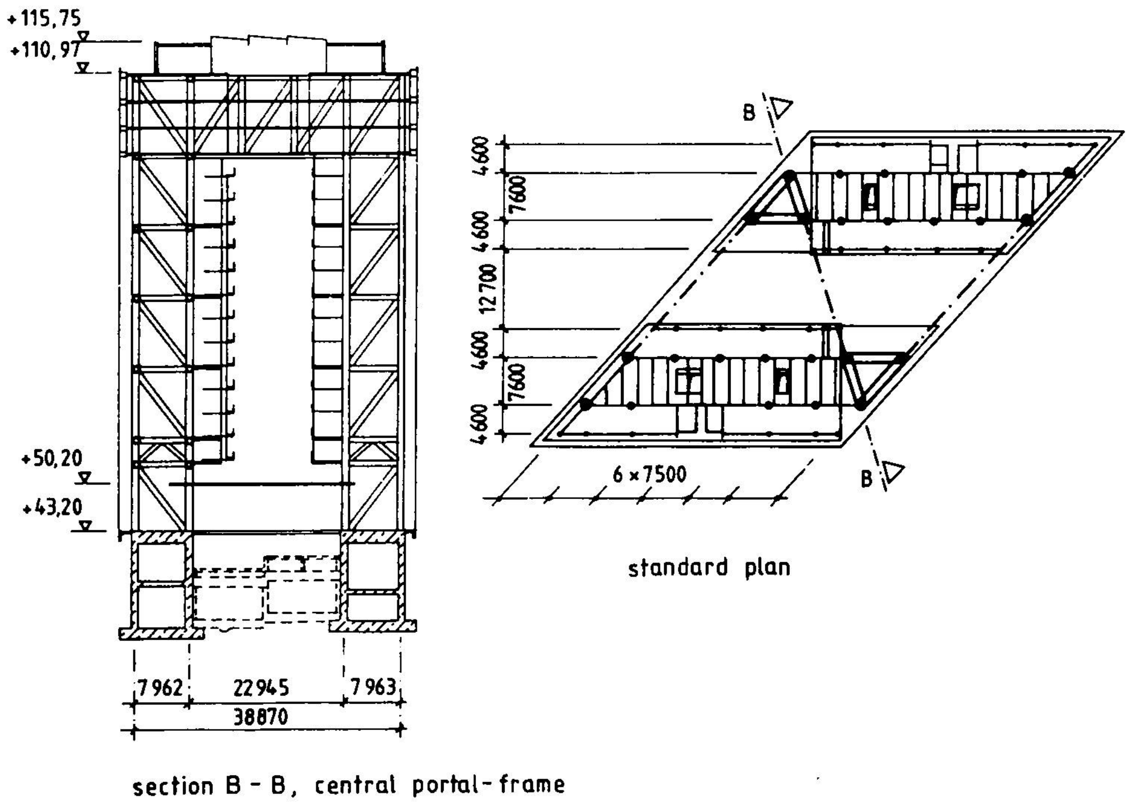


Fig. 8 Plan and section of the Towngate Düsseldorf

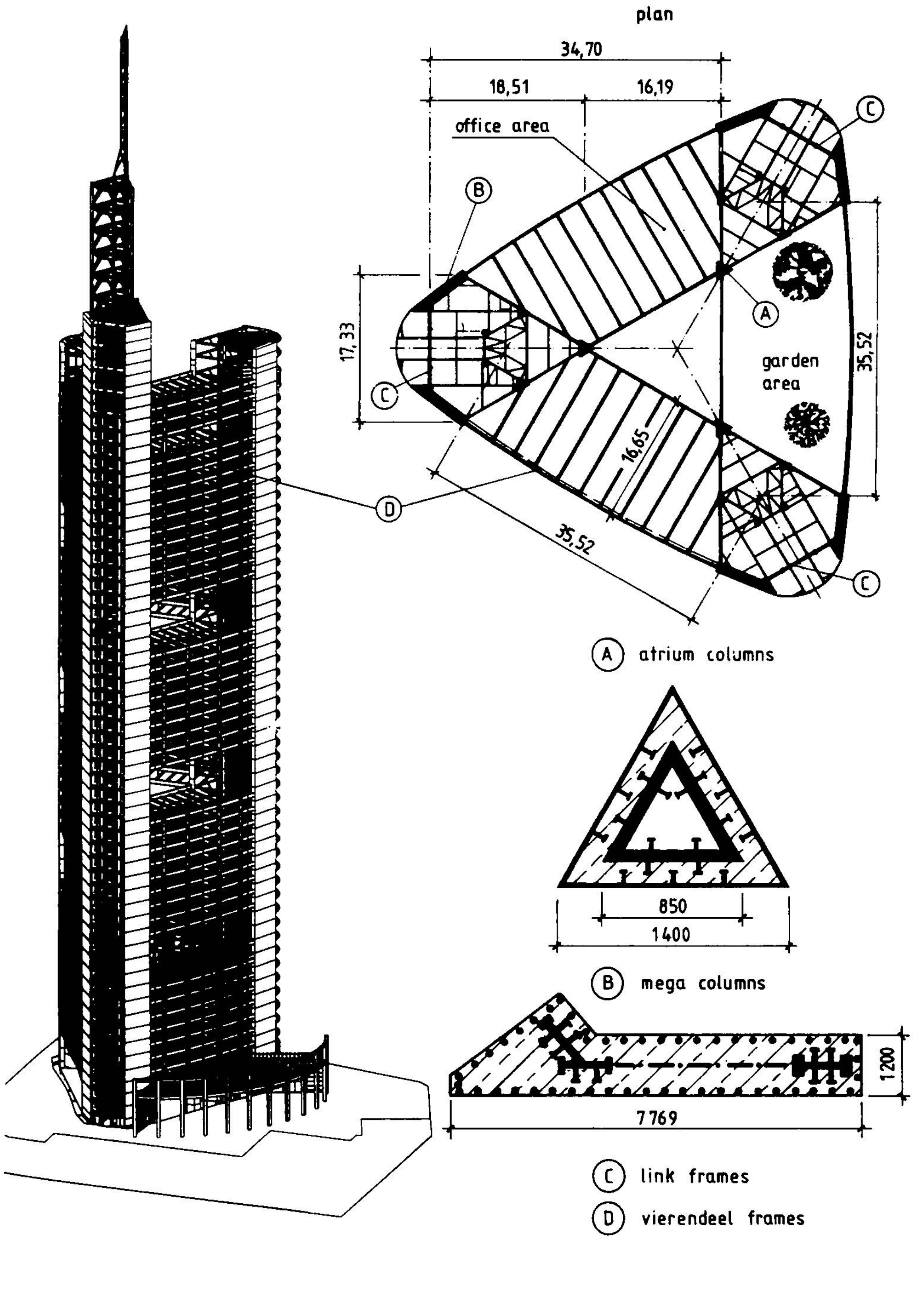


Fig. 9 Commerzbank Headquarters Frankfurt/Main

5.3 Commerzbank Headquarters in Frankfurt /Main

The new building of the Commerzbank is the most interesting project in Germany at the present time. With a overall height of 298.74 m, including antenna, 63 floors and an effective area of 52700 m^2, the building will give room for 2400 employees of the Commerzbank. The plan of the building has the shape of an equilateral triangle with rounded corners and slightly curved sides with length of approximately 60 m (see Fig. 9). Three cores at the corners, ending at different heights, contain stair cases, elevators, adjoining corridors and the installation for the building. The cores are connected by office areas where the standard floors consist of two office areas. The third side is kept free over 4 storeys and contains a garden area. This standard floor plan is turned by 120 degree every four storeys. For the horizontal loads, a three dimensional structure (consisting of the mega-columns connected by link frames, the vierendeel frames located in the facade, and the composite slab floors) forms a tube, which is fixed in the foundation. All other columns inside the cores and the atrium columns are nominally pinned at both ends and do not contribute to the horizontal stability of the building. The composite floors consist of Super-Holorib sheeting in combination with light weight concrete with a density class of 20. In the office area composite beams with welded sections and large web openings span between the atrium beams to the outside vierendeel steel frames. Within the cores mixed systems with steel and composite beams are used. The required fire resistance Class R120 for the beams was achieved by fire resistance boards. The atrium columns are designed as composite columns with an inner and outer equilateral-triangle steel section with steel grades S460 and S355. Composite action is achieved by headed stud shear connectors. Because this type of section is not covered by Eurocode 4, an elasto-plastic design had to be carried out. The design for fire resistance is based on a reduced effective section with decreased material properties. The mega columns in the edges of the plan consist of fully concrete encased steel trusses forming a composite column together with concrete and additional reinforcement. All other columns are designed as steel members.

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