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Structural innovation at the Millennium Tower, Vienna

Figure 1: The completed Millennium Tower.

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The 202m-high Millennium Tower to the north of Vienna is the highest building in Austria (Figure 1). With new techniques helping to speed construction, the tower is an example of mixed building technology, combining steel/concrete composite frames with a concrete core. Special attention was paid to the moment connections between the slim floors and column tubes, resulting in reduced construction time and thin slabs. The moment-resisting joints were considered in the design at ultimate and serviceability limit states.

In 1996, the Vienna municipal council agreed to the Millennium City project, containing 37,000m^2 of residential blocks, a 25,000m^2 commercial area and a 38,000m^2 office tower. This 'city within a city' was planned by the architectural team Peichl-Podrecca-Weber of Vienna, and construction started in 1997 on a ground area of 15,500m^2. The total capital expenditure is around €145m (£87m).

The first part of the project involves the creation of four basements with a parking area for 1500 cars. The tower foundation plate is positioned on 151 bored piles with a length of 25m. The tower itself is the second section, with 50 upper floors and a 30m antenna. The third section contains two shopping and six residential floors. It has been constructed simultaneously with the tower.

Millennium Tower

Work started on the tower in May 1998 with the rate of construction being two-and-a-half to three floors a week. The shell was completed in January 1999 after only eight months (Figure 2). The 1080m^2 tower plan consists of two overlapping circles for offices and a concrete core containing lifts and stairways (Figure 3). The core was built using conventional technology to transfer vertical forces and horizontal seismic and wind forces. The tower circles were formed by concentric composite frames, designed for vertical forces. This

Figure 2: Completing the concrete shell.

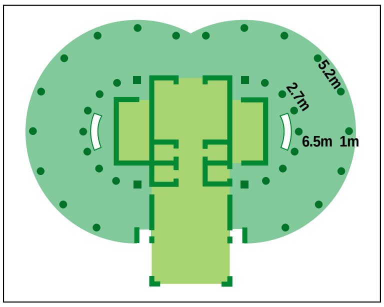

Figure 3: The tower plan consists of two overlapping circles and a concrete core.

combination of concrete and composite building technologies has resulted in a mixed building.

The design and timescale necessitated extremely rapid construction, regardless of the weather. Slabs were very thin, reducing dead load and facade costs. A flat ceiling was selected for ease of installation, with slender columns. The eventual solution included several innovations: composite slim floor beams fully integrated into the thin slabs; moment-resisting joints enabling a frame action between the beams and columns; and a new type of shot-fired shear connector within the composite columns. The cost of the tower shell was €12.5m (£7.5m), which contained 1,500 tonnes of constructional steel, 2,500 tonnes of reinforcement steel and 15,000m³ of concrete.

Composite frames

The vertical forces in the two overlapping tower circles are carried by concentric rings of 20 outer and 18 inner columns 6.5m apart. The outer column and joint, slim floor beam, inner joint and column form a frame system that considerably reduces sagging moments, deflections and slab vibrations. The ability of the frame to transfer horizontal forces to the concrete core has not been taken into account. The large number of similar joints justified detailed planning to optimise erection time and cost savings derived from moment connection.

Floor beams

The composite slim floor beams are welded T-shaped steel sections with a concrete slab containing minimum bottom reinforcement (Figure 4). There is a considerable amount of reinforcement in the hogging region within the effective width. Shear connection is provided by headed studs. The non-linear characterisation of the sagging cross-section takes into account the partial shear connection and the hogging cross-section includes the effect of tension stiffening. The design was undertaken using software based on Eurocode 4: *Design of composite steel and concrete structures* (ENV-1994)[1].

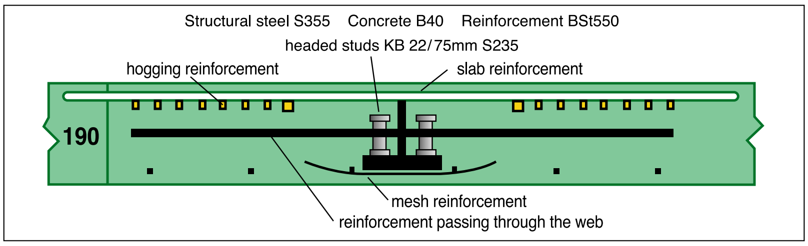

Figure 4: Floor beam cross-section.

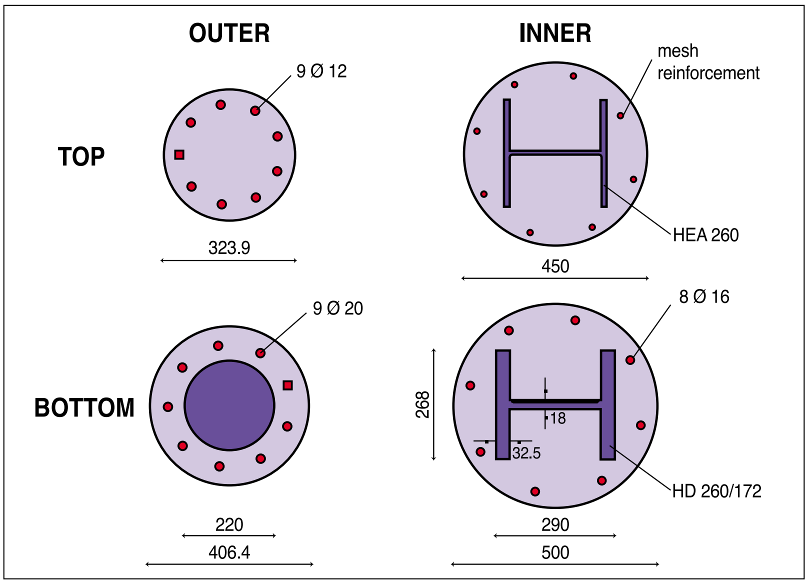

Figure 5: Column cross-sections.

Columns

The demand for slender columns led to the use of composite sections with steel tubes and steel cores, both of S355 steel (Figure 5). Tube diameter, core size and concrete grade were adjusted to the actual stresses at each storey. Outer column diameter varied from 324 to 406mm. Self-compacting concrete of grades B40 to B60 was used to fill the remaining space between tube and core. To reduce the problem of differential creep and shrinkage between the composite columns and concrete core resulting from differing steel/concrete ratios, the inner columns closer to the concrete core were concrete-encased rolled I-sections with a higher proportion of concrete. Diameters range from 450 to 500mm.

Normal stresses in the columns are determined by plastic redistribution. Except for the top columns, the normal force is dominant in comparison with the bending moments resulting from the frame action due to the moment-resisting joints. Design calculations under normal conditions and in fire (R90) were based on Eurocode 4.

The vertical support forces of the beams are transferred to the column steel tube via a welded bracket (under normal conditions) and a fin-plate (in case of fire). Some of these concentrated forces are transferred to the concrete within the tube and then to the steel core (Figure 6). Shot-fired nails and bolts were used instead of conventional welded studs to increase installation speed[2,3].

Moment-resisting joints

The use of composite slim floor beams supported on composite columns simultaneously solved two problems associated with conventional concrete joints: punching and low moment resistance combined with possible brittle failure due to the limited load capacity of concrete in local compression. At joints between an

Figure 6: A composite column in position.

Figure 7: Additional U-bars were used on the lower five floors.

external column and outer slim floor, the compressive force is transferred from the beam flange via shims onto a bracket welded to the column tube. From there, it spreads vertically and horizontally into the hollow steel section, the concrete within the tube and the steel core. The tensile force goes through the beam's shear connection into the hogging reinforcement. A 20mm-diameter U-bar encircles the column in direct contact, while a pre-welded saddle determines the precise location of this bar and the lever arm of the joint. The remaining restraint reinforcement (seven 12mm bars each side of the column) extends into the cantilevered part of the slab. Together with the transverse reinforcement and concrete struts, a truss is built to carry the tension force into the column via bearing pressure. For such slim floor joints with a small lever arm, careful construction is crucial, as a small deviation would result in loss of stiffness and moment resistance.

The combination of U-bar and reinforcement truss can be used only on cantilevered slabs. On the lower five floors, the facade was immediately behind the column. An alternative to the regular joint had to be developed, with additional U-bars, resulting in a slab outstand of only 60mm (Figure 7). An additional top saddle was provided to avoid splitting due to the arrangement of three U-bars. By optimising reinforcement layout, the stiffness and resistance of these joints are similar to the other configuration.

Concluding remarks

The Millennium Tower demonstrated that a simple support could be converted into a moment-resisting joint with considerable stiffness and resistance. Activating this frame action between beams and columns facilitates the adoption of very slim floors while maintaining ultimate and especially serviceability limit states. A full-scale joint test, in conjunction with site measurements, confirmed the calculated joint behaviour. Several innovative approaches to the project, such as the use of shot-fired nails and bolts as shear connectors within the hollow column sections speeded erection.

Author's acknowledgment

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The use of self-compacting concrete in the Millennium Tower

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The concrete decks of each storey on the Millennium Tower are supported by composite steel/concrete columns. These consist of an inner steel tube, 220mm in diameter, and a steel tube 450mm in diameter. There is some additional reinforcement, with bolts used to maintain the bond between the steel tube and concrete. The 100mm annular gap between the two tubes is filled with concrete, but it was impossible to use vibrating pokers in this situation. Instead, self-compacting concrete (SCC) was selected and research was undertaken by the Institute, which has been involved with the development of SCC since 1997.

Concrete strengths ranging from 40N/mm^2 for the top floors to 60N/mm^2 for the ground floors were required. The ready-mixed concrete supplied contained only about two-thirds of the total superplasticiser, the remainder being added on site, taking into account the workability on delivery. Concrete remained workable for two hours after delivery, although with warm weather or longer waiting periods, additional superplasticiser had to be added. Immediately before placing, a flow-table test was carried out to determine the amount of superplasticiser to be added.

The higher the spread on the flow table, the more difficult it is to dose the superplasticiser correctly, as small amounts are difficult to add to the concrete mix. There are two potential problems: overdosing (spread over 800mm) results in segregation or waiting up to an hour until the concrete is stiff enough. If the spread is insufficient (under 400mm), it may be impossible to obtain the required spread of 700–750mm, even with a large dose of plasticiser. The optimal range for the spread on the flow table was found to be 500–560mm.