Design/construction feature

Large precast prestressed Vierendeel trusses highlight multistory building

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A major feature of the new 28-story International Civil Aviation Organization headquarters building in Montreal, Canada, is the use of large architectural precast, segmental Vierendeel trusses which are post-tensioned together on site.

Precast prestressed segmental construction was used effectively to erect a major portion of the new 28-story International Civil Aviation Organization (ICAO) Tower in Montreal, Canada (see Fig. 1).

Prefabricated Vierendeel truss segments which were post-tensioned together on site, helped provide an efficient architectural and structural solution to a building that had to satisfy several design requirements. Economy was achieved because the precast prestressed trusses not only supported the floor loads but also gave the structure an attractive architectural finish.

The new world headquarters for the ICAO, which is located in Montreal between the existing Engineering Institute of Canada Building and the McGill University Campus, will form part of a major complex to be known as Aviation Square. An architect's model of the complex is shown in Fig. 2.

Aviation Square presently comprises the ICAO Tower, a plaza, and a connected low building housing the main assembly hall and various conference and meeting rooms. It will eventually include an adjacent linked building providing additional office space.

The ICAO Tower is 115 x 115 ft in plan with 27 stories plus a mechanical penthouse. The interior of the Tower is completely column free. The entire structure is supported by the service core and eight exterior columns which also contain mechanical shafts.

Between these columns (starting at the sixth floor) span one-story high precast prestressed Vierendeel trusses which support two floors each. A structural floor plan of the Tower shows (see Fig. 3) the location of the trusses.

A total of 44 Vierendeel trusses, each 75 ft 7 in. long by 16 ft 8 in. high, frame the building from the sixth floor up. An elevation and typical

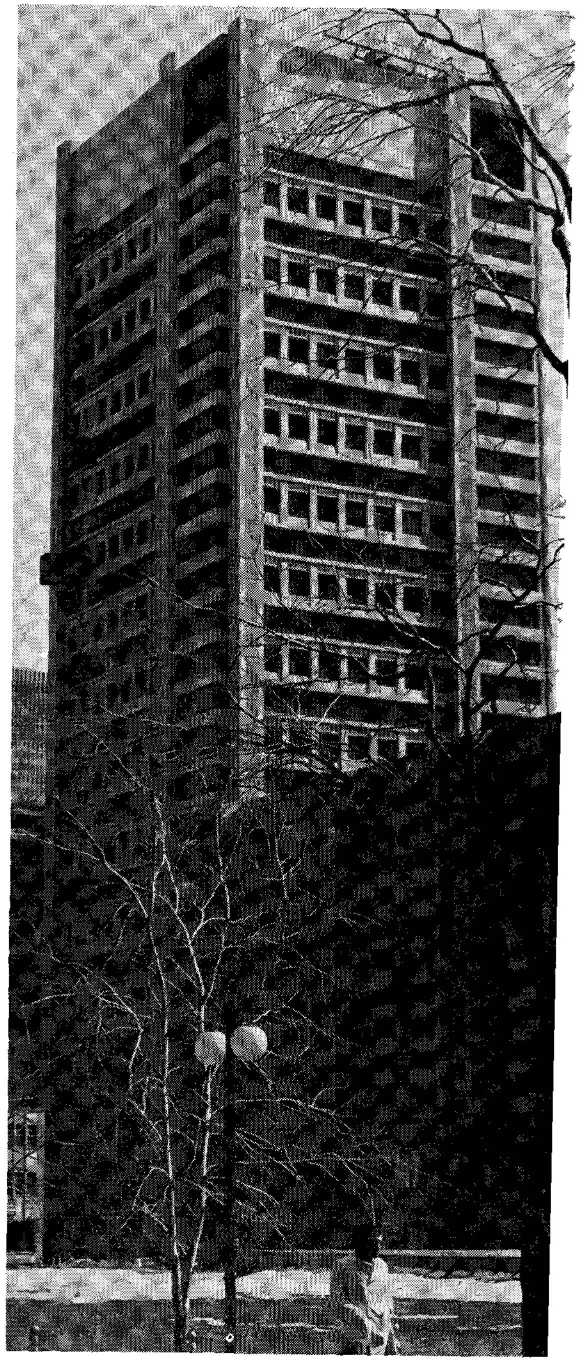


Fig. 1. New ICAO Headquarters building. North view looking from McGill University campus.

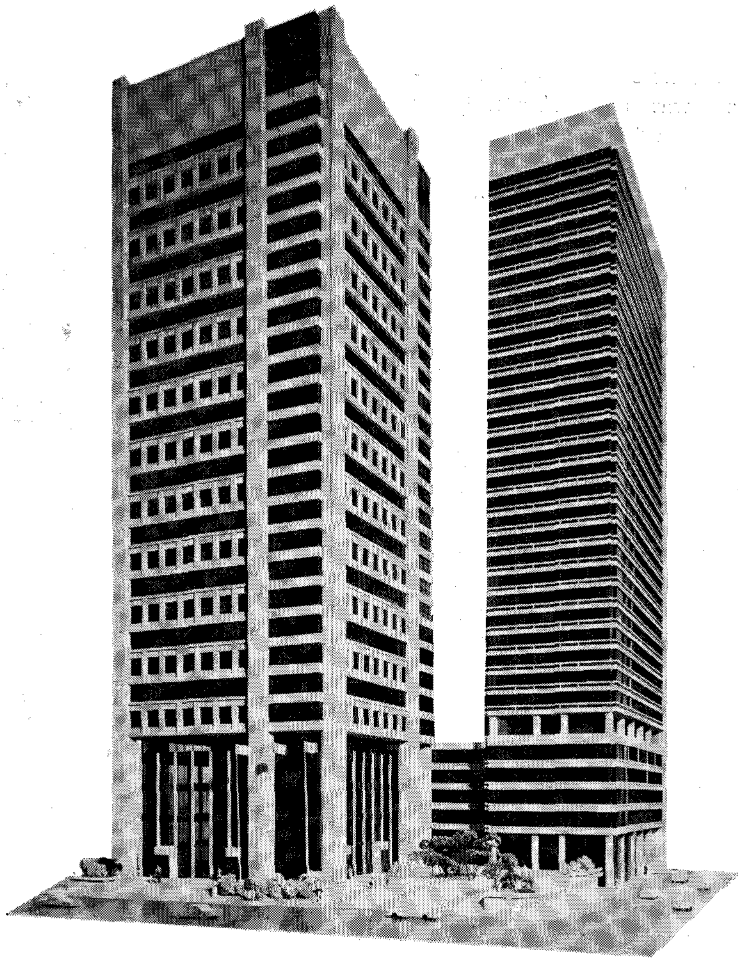


Fig. 2. Architect's model of Aviation Square, showing ICAO Tower, plaza, and second phase project.

structural details of the trusses are shown in Fig. 4.

Erection of the first truss started in September 1973 and the last one was finished 40 weeks later. Approximately one floor was erected every 12 days.

This article will discuss the reasons why a precast prestressed Vierendeel truss system was chosen and then will describe the structural design, prefabrication, erection, and post-tensioning of the truss segments.

Reasons for Using Vierendeel Trusses

There were several good reasons for deciding on the use of precast prestressed Vierendeel trusses. For example:

- The trusses reduced considerably the number of exterior columns. By using the chosen structural floor plan, all floor slabs span between the ex-

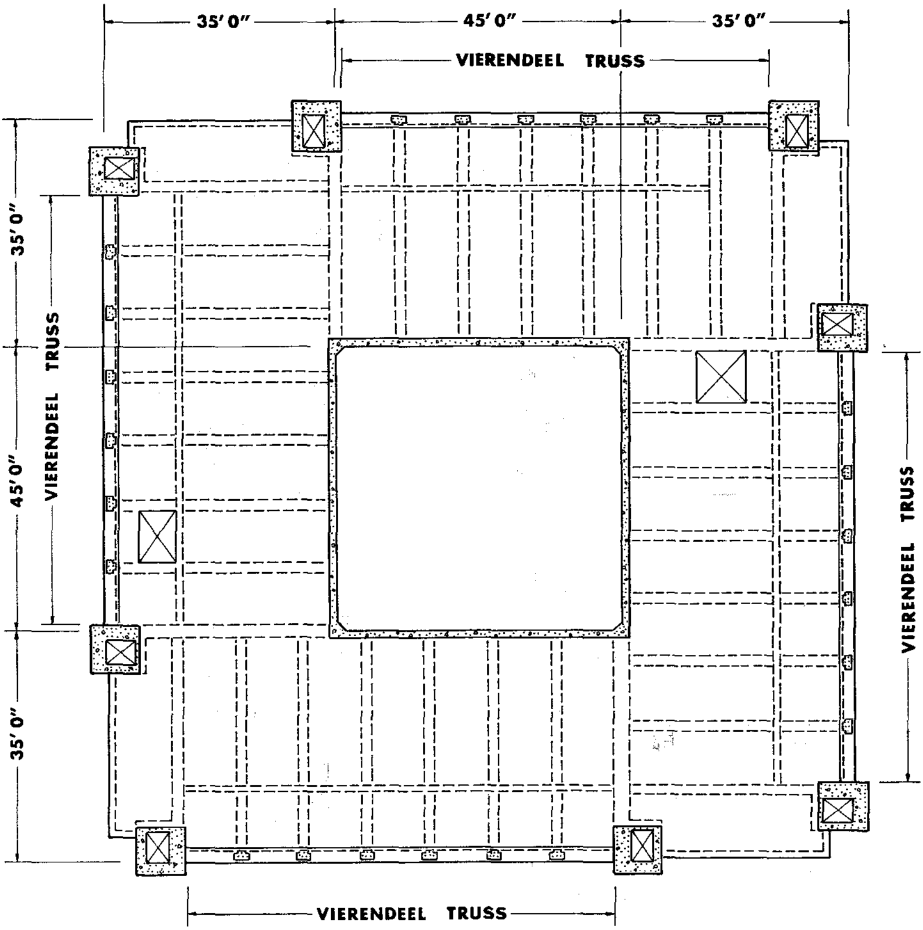


Fig. 3. Typical structural floor plan of ICAO Tower (starting at sixth floor) showing location of Vierendeel trusses.

terior trusses and the inner service core which is enclosed in a concrete box. There are no interior columns (see Fig. 3).

- An architectural appearance in harmony with the neighboring buildings on the McGill University Campus across the street was desired. All four sides of the tower are exposed and the pattern resulting from the design is pleasing and avoids the monotony which characterizes many of today's buildings.

- Economy was achieved because the precast concrete sections provide at the same time the exterior architectural finish and the supporting structure for the floors. The additional costs of making and handling separate cladding was avoided as well as the dead weight involved.

- The use of segments precast in the factory allowed excellent control of the shape and color of the finished member. It also made it possible to erect very

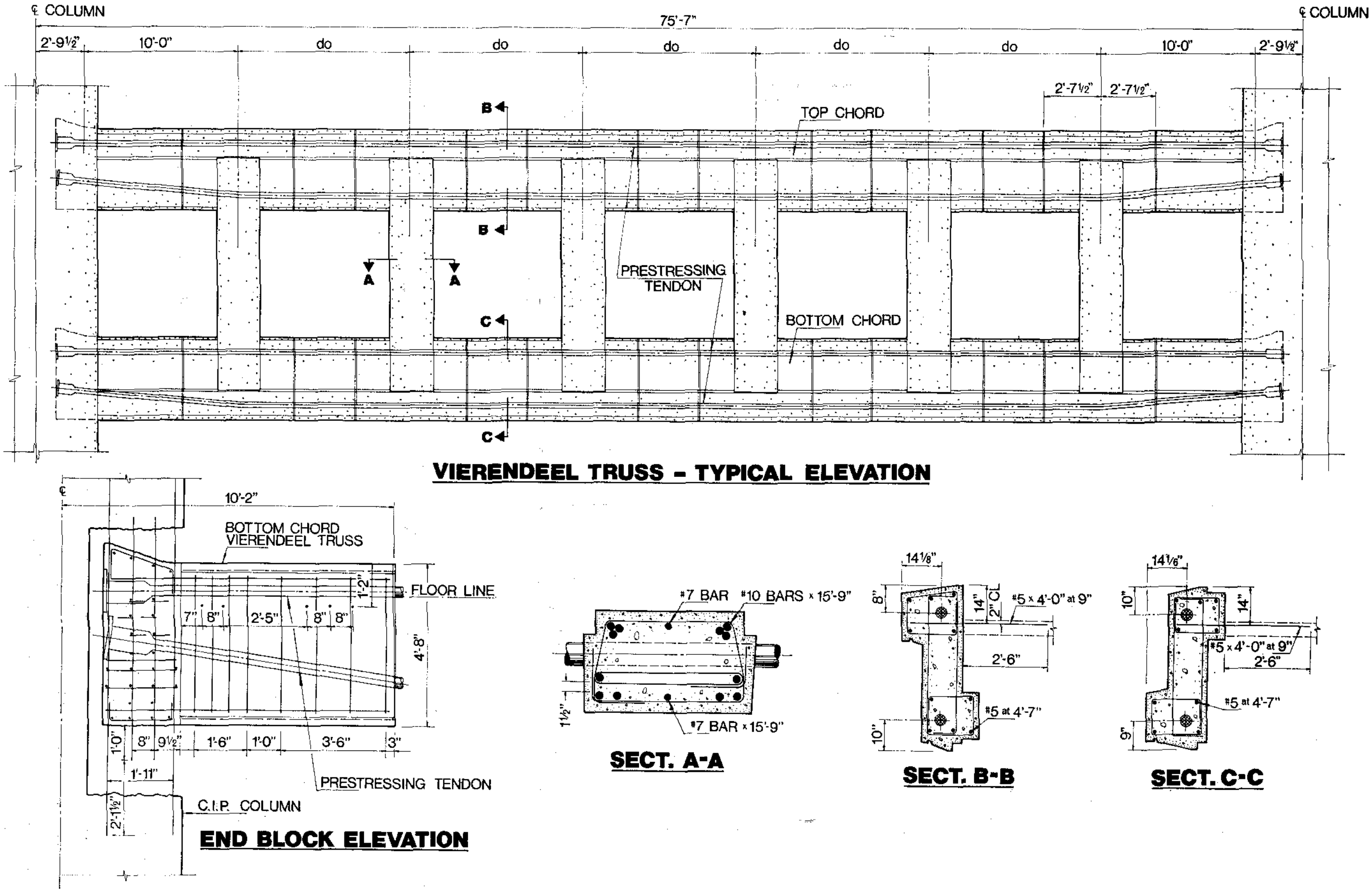


Fig. 4. Elevation and section details of Vierendeel truss. Note location of prestressing tendons and reinforcing steel details.

large heavy trusses using the normal field crane. The heaviest segment was limited to 9 tons.

- Control of the positioning of the reinforcing cages and the sheaths for the prestressing tendons was done easier in the plant than in the field.

- Lastly, it was a challenge to the design engineers, the architects, and the builders to come up with a structure which in many ways had not been tried before.

Structural Design

Our firm, in collaboration with the architects for Aviation Square, had designed an earlier project, namely, the Engineering Institute of Canada Building, using the same basic structural approach.

In this case, Vierendeel trusses were used on the front and back walls, each truss supporting two floors. The trusses were cast in place, which gave rise to problems of control both as regards appearance and structure.

In the case of the ICAO building, two designs were made; one cast in place and the other precast in segments.

At this stage there were still problems to be solved, but the precast solution was so much more attractive that it was decided to proceed with it.

With the earlier cast-in-place units there had been difficulty in obtaining uniformity in appearance as well as consistency in the formwork.

It was felt that appearance would dictate the use of separate precast cladding if a cast-in-place structure were used, and this would add to weight and cost.

These problems would be avoided by precasting and there would also be the saving in curing time required for on site work. The total weight of the truss dictated making it in segments.

It was therefore decided to use a Vierendeel truss design made up of 20 segments, six I segments for the verticals and ten short link segments plus four longer end pieces for the top and bottom chords (see **Fig. 4**).

The end pieces would be tied into the columns. All pieces would be cast in the shop with carefully controlled finishes on all exposed faces.

All segments would be assembled on shoring at the site and post-tensioned. The total weight of each truss was 86 tons and they are designed to carry an additional live and dead load of 180 tons.

There are two columns on each face of the building. The pairs of columns each support eleven trusses. The resulting frames are offset from the center line of the facades in such a way that a portion of cantilevered floor is left at every corner.

The columns are solid up to the level of the first truss and thereafter they become hollow boxes with one side open towards the inside of the building. The free space inside the columns increases as the columns go up so the structural working area is a minimum at the top where loads are the least.

The mechanical services are located at the top of the building and supply and exhaust ducts are fed down through the columns to serve each floor. The space requirements for ductwork decrease as they descend which suits the structural requirements.

Perhaps the two main design problems with the segmental truss were the interface between sections and the connections to the columns, as it was desired to have the whole act as a frame.

The first problem was solved by applying a coat of form oil to the previous segment and then casting the next segment against it. When erected, no adhesive was needed between segments. After stressing, when the tubes were pressure grouted, absolutely no leakage appeared between segments.

The tie in to the columns was achieved by placing the reinforcement in the end pieces extending vertically up and down into the columns as well as horizontal shear bars through the sides. This vertical reinforcing matched and lapped the vertical column reinforcing.

In addition, the surfaces of the end pieces to be encased in the column were made rough. Each end piece and the columns themselves at the junctions are heavily reinforced for shear. Fig. 4 shows the essential details of a typical truss and the tie to the columns.

The frames made up of the two vertical columns and the eleven trusses are designed to take 25 percent of the horizontal forces due to earthquake. The balance of the horizontal forces are taken by the walls of the center core.

In addition to the trusses, the columns are tied at the top by a crown wall which is 35 ft 3½ in. high and 10 in. thick. This wall is prestressed with three tendons. The wall carries the mechanical penthouse, a mezzanine and the roof.

Each truss is tensioned so that there will be no tensile stresses in the concrete under the total design load, including earthquake. The calculated deflection was 3⁄16 in.

At one stage, under construction loads which were calculated to be 30 percent over design load, the deflection was measured as ¼ in. The small deflection was foreseen in order to avoid any damage to the glass of the window inserts.

All columns were clad with precast facing to match the finish on the trusses. In order to avoid bending and displacement of the columns themselves due to temperature differences inside and outside the building, the columns are insulated outside the structure.

Air temperatures in Montreal range from −30 to +38 C (−20 to 100 F) while indoor temperatures vary from 21 to 25 C (68 to 75 F).

The trusses on the other hand are subject to exterior temperatures and allowance was made for the effect of changes in length on the column and truss stresses.

Prefabrication of Vierendeel Trusses

The casting of the segments was done in the plant of Prefac Concrete Co. Ltd. in Montreal approximately 9 miles from the site.

The complete form for one truss was made of plywood built so the truss lay on its side with the outer side down. This was to allow removal of the sections due to their shape. One form was used for all 44 trusses.

Dividers were placed in the forms between each segment. A stiff 2-in. layer of concrete made with white cement and pink granite aggregate was used to line the forms of the segments to be cast. The reinforcing cages were prepared and tied in the usual way and fixed in place. The tensioning sheaths were carefully placed and aligned in each segment.

Concrete, mixed in the plant, and having a design strength of 6000 psi, was used to complete the casting of each segment.

After a reasonable delay the dividers were removed and the exposed interfaces painted with form oil. The intermediate segments were then completed, using the same procedure already described.

Every truss segment was tied to the next by means of steel angle cleats at the top and bottom of each joint and bolted to the segments. The Vieren-

Fig. 5. Precast I segment being spliced to adjoining truss in precaster's yard.

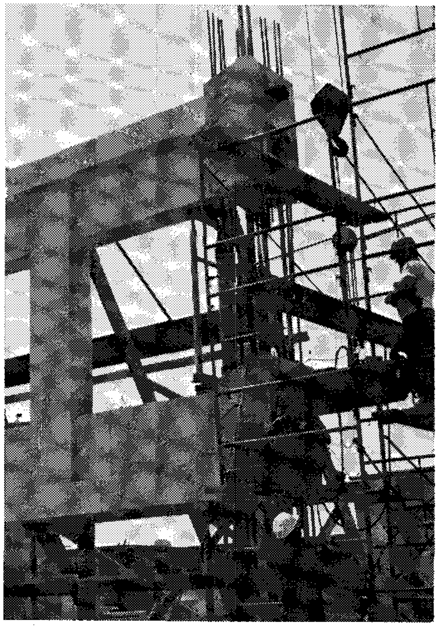


Fig. 6. End section of truss in precaster's yard showing anchorage ducts for post-tensioning.

Prior to construction, a full-scale mockup of the truss was made in the precaster's yard.

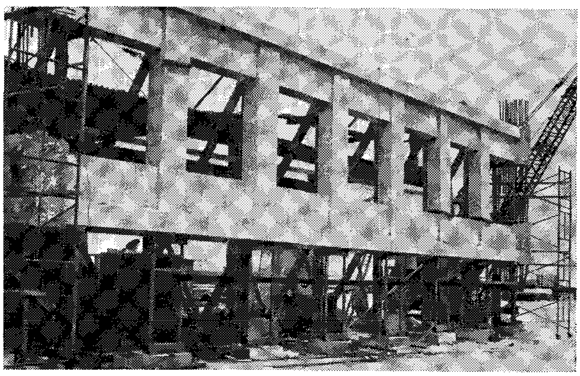


Fig. 7. Precast segments of truss fully assembled in precaster's yard prior to post-tensioning and testing.

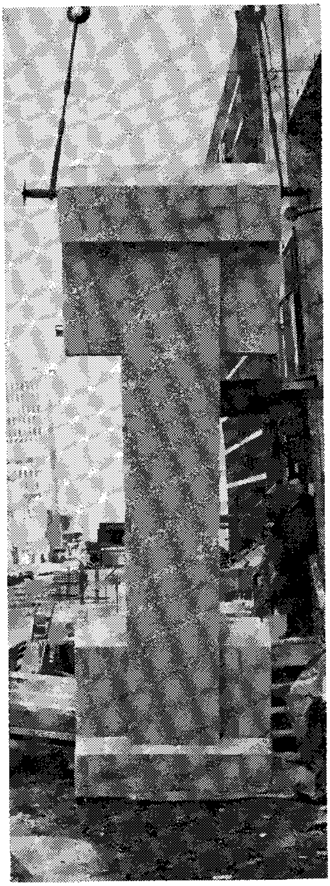
deels and their respective segments were numbered for identification.

Each truss was wet cured in the forms for 24 hours and then removed in segments to the yard for 2 or 3 days additional curing, depending on weather. The rate of production was two trusses per week.

Full-scale testing

Many job problems were solved by erecting a full-scale mockup of the truss in the precaster's yard. (Figs. 5-7).

This foresight provided the opportunity to evaluate field procedures in advance of construction, and allowed the development of the most economi-



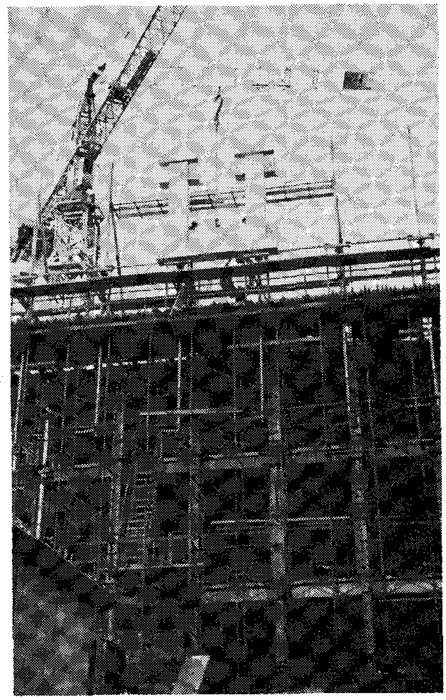


Fig. 9. Precast segments being lifted into position on sixth floor where they will comprise first truss.

Fig. 8 (left). Precast I segment ready for lifting at building site.

cal erection methods for placing, tensioning, and grouting of the trusses.

The first Vierendeel truss made was erected on supports in the yard and fully stressed to test the effectiveness of the joints.

There were the usual moments of uncertainty when it came time to remove the supports, but the truss proved sound and no faulting appeared. The truss was subsequently dismantled and reused on the job.

The Vierendeel trusses were shipped to the site in segments by truck as they became available. They were either hoisted directly into position or stored on the site.

It is quite clear that the work done in the plant was more reliable and less costly than could have been accomplished by casting the trusses on site.

Erection Procedure

The erection procedure required some detail planning although in principal it was quite straightforward and went without any serious hitch.

Fig. 8 shows a precast I segment ready for lifting at the building site. Fig. 9 is a shot of segments being lifted into position on the sixth floor

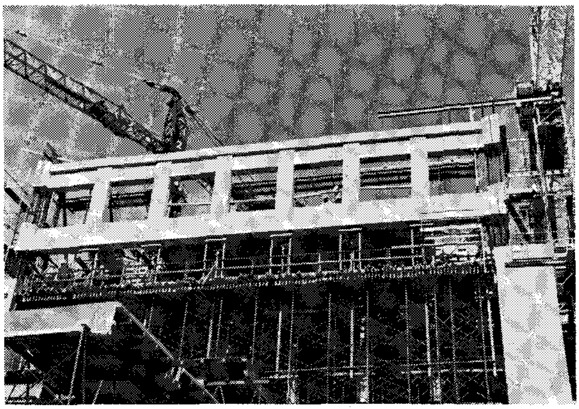


Fig. 10. First precast Vierendeel truss assembled. Note cast-in-place columns with dowels projecting, ready for subsequent casting.

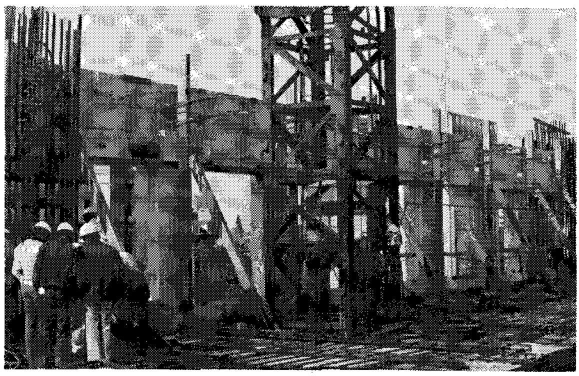


Fig. 11. Assembled Vierendeel truss showing diagonal bracing system prior to post-tensioning. Note projecting column dowels and reinforcement for cast-in-place construction.

where the post-tensioned structure starts.

Each assembled truss had to be aligned vertically and horizontally, at the same time keeping the matching segments in alignment with each other. Fig. 10 shows the first truss assembled.

To provide horizontal support, chairs with three or four jacks were provided, one support under each vertical segment and one each under the horizontal end segments.

Except for the first truss, the chairs rested on the top chord of the truss below. For the first trusses, a five-story scaffolding was required (see Figs. 9 and 10). For vertical stability and support, eight steel frames two stories high were erected, for each truss.

The diagonal brace for each vertical steel frame was bolted to a completed floor and then passed through the floor level at the bottom of the truss being erected to catch the vertical near the top. Fig. 11 shows an overall shot of the diagonal bracing system used.

By means of threaded connectors between the vertical frames and inserts in the segments, it was possible to control the verticality and alignment of each segment.

One of the central vertical I segments was first placed on its chair and fastened to the vertical brace. After

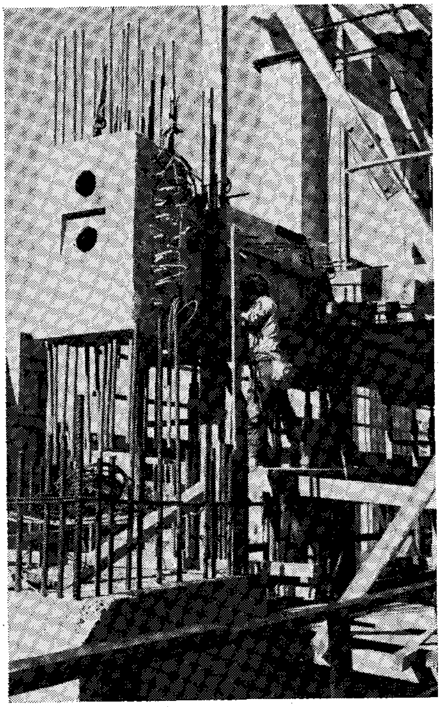


Fig. 12. End of Vierendeel truss showing ducts for post-tensioning tendons and column dowels.

Fig. 13. The BBR post-tensioning system was used to stress the precast truss segments together.

placing and attaching a second vertical I segment, the top and bottom chord link pieces could be supported between the verticals.

This was accomplished by means of the steel lugs which were bolted to adjacent segments when concreting and could now be used both for temporary support and to assure a perfect rematch of the segments. This procedure was continued working towards each end of the truss.

Fig. 11 shows a truss erected in place. The steel lugs between sections as well as the adjustable connections to the vertical braces may be seen. The reinforcing ties to the floor beams as well as the column connections are also visible.

Post-tensioning operation

The Vierendeel truss segments were stressed together using the BBR post-tensioning system.

The basic concept of the BBR system is the use of bundles of high strength, smooth, low friction, steel wires as tendons.

The wires were cut to a predetermined length and a button-head was cold-formed at one end to provide a permanent fastening to the anchorage. Each tendon was partially manufactured and assembled in the factory. These tendons were then coiled and shipped to the site.

At the job site, the wire bundles were uncoilded from its shipping reel at one end and pulled through the duct to the opposite end of the truss. Fig. 12 shows the ducts at the end of a typical truss. Also visible are the column dowels and the diagonal bracing.

In the stressing operation, the anchor head was grasped by a continuously threaded pull rod which extended through the center hole of a hydraulic jack. Stress is locked, by placing steel

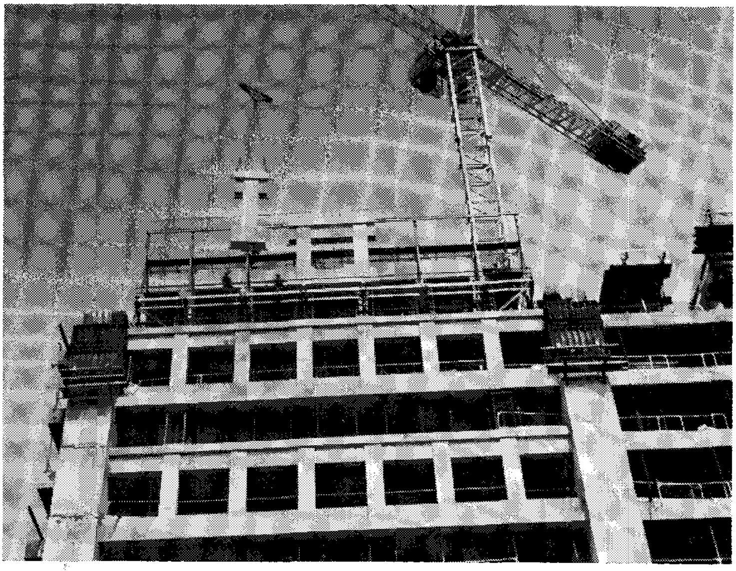


Fig. 14. Each succeeding Vierendeel truss was erected using the same erection procedure, i.e., by lifting the individual precast segments on to the proper floor position, and assembling and post-tensioning the truss elements.

shims between the anchor head and bearing plate in combinations to achieve the required total thickness. Fig. 13 is a closeup of the jacking operation.

When the final stressing was completed, a cement-water grout was injected under pressure into the tendon duct, thus creating a permanent bond between the tendon and the surrounding concrete.

Erection was usually done during the day and tendon threading and tensioning at night. Grouting was done some time later after the floors had been completed.

There were four sets of prestressing tendons, two in the upper chord and two in the lower chord. The tendons were tensioned progressively, the order and extent being important in order to avoid undesirable variations in pressure between the contact faces of the sections.

Approximately 6 days were required to erect and tension the four trusses which would eventually support two floors. A delay then ensued until the completion of the forming and concreting of these two floors.

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The supporting columns were cast in two lifts per floor, a high lift for the piece between chords then a shallow lift encompassing the floor and one chord of the truss.

With the casting of the upper floor of each truss, the truss was fully tied in. Thereafter the column was considered to be capable of carrying the truss when the test strength reached 3000 psi. Design strength was specified at 4000 psi.

At this stage, the chairs supporting the truss immediately below could be removed. Thus two trusses would im-

Fig. 15. Overall shot of construction operations from south side. The truss on the west wall is in place, diagonal bracing is prepared on the east wall, and the south wall truss is partially erected.

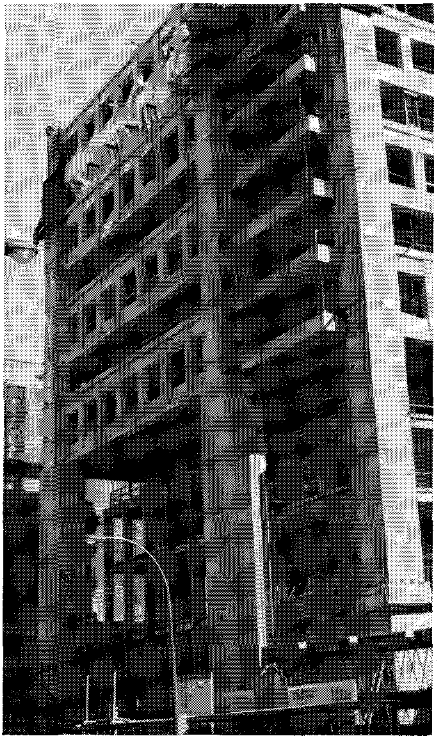

Fig. 16. Structure partially completed. Cast-in-place elements of upper floor are being cured.

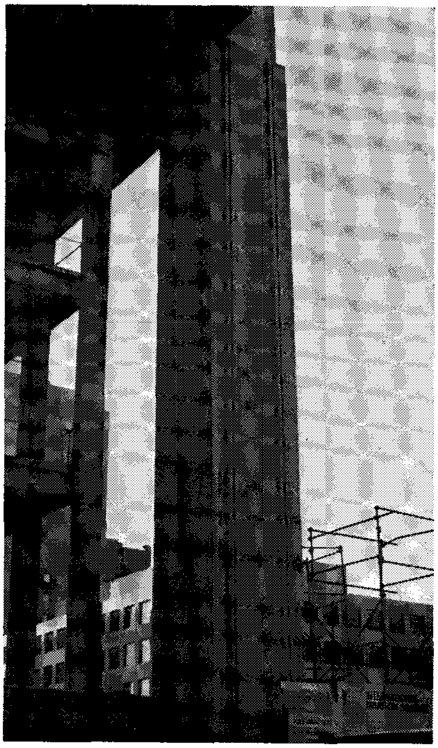

Fig. 17. Closeup of exterior column showing elegant form finish.

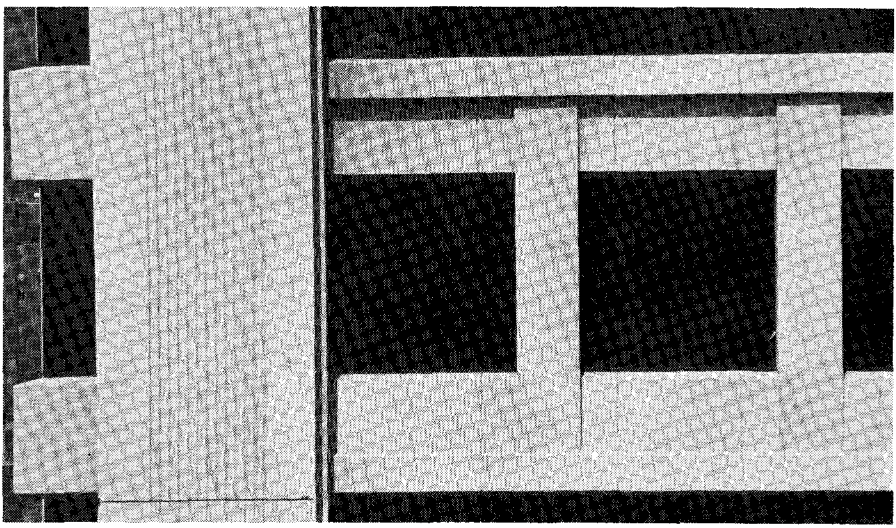

Fig. 18. Closeup of architectural precast concrete finish of Vierendeel truss. The surface was lightly sandblasted.

Fig. 19. ICAO Tower nearing completion (1974).

mediately support four floors plus the dead load of the next truss being erected and the formwork of the lower floor of this next truss.

At a certain stage, two trusses would be supporting their own full dead loads plus the dead load of the next truss above and its two floors and their formwork. This was calculated to be 30 percent higher than the eventual working load.

The same erection procedure was then repeated for succeeding sets of truss segments. Fig. 14 shows an I segment being lifted into place at an upper story level.

Fig. 15, which is taken from the south side, gives an excellent general view of the various construction phases. The truss on the west wall is in place, diagonal bracing is prepared on the east wall, and the south wall truss is partially erected. The column concreting is also visible.

Fig. 16 is a progress shot of the building erection. The trusses on the lower stories are at this stage fully integrated into the structure. A closeup of an exterior column is shown in Fig. 17.

Fig. 18 is a closeup of the architectural precast concrete finish of the Vierendeel truss.

The construction phase described above started on September 26, 1973, and was completed in 40 weeks with the casting of the 27th floor supported on the top of the eleventh group of trusses on July 5, 1974.

Approximately 2 weeks must be deducted for holidays and slowdowns, resulting in a net rate of 12 days per floor.

Fig. 19 is a shot of the Tower nearing completion and Fig. 20 is a view of the finished structure taken last summer (1975).

Closing Remarks

In conclusion, it may be stated that the use of segmentally precast prestressed Vierendeel trusses on this job achieved the objectives which were desired. The building has a striking architectural appearance with the structure clearly expressed.

In the case of the trusses, the structure is also an integral part of the architectural finish, with excellent uniformity and control. The interior areas are free of intermediate supports.

Finally, the contractor was able to reduce on-site concrete by about 3200 cu yds and to maintain a rate of one floor per 12 days.

Since completion a year and a half ago, the structure has performed very well. There has been no evidence of major cracking or other distress. The measured deflections have agreed closely with the design calculations.

Credits

Architect: Rosen, Caruso, Vecsei, Architects, Montreal, Quebec.

Structural Engineer: McMillan & Martynowicz, Consulting Engineers, Montreal, Quebec.

Architectural Precast Concrete Producer and Erector: Prefac Concrete Co. Ltd., Ville d'Anjou, Quebec.

Post-Tensioning: BBR Quebec Limitee, Division of Canadian BBR Limited, Agincourt, Ontario.

General Contractor: Louis Donolo, Inc., Montreal, Quebec.

Owner: Gamma Properties Limited.

Discussion of this paper is invited. Please forward your discussion to PCI Headquarters by April 1, 1976.

Fig. 20. Completed structure. Picture taken last summer (1975).