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ST. RAFCA CATHEDRAL: CONCAVE BEAMS SPANNING 100 FT

BY CAROL HAYEK AND RICHARD MUZANAR

St. Rafca Cathedral, located in the mountains of Lebanon, was designed to blend seamlessly with its surroundings, appearing to form a continuation of the hillside. The Cathedral and its roof designs are inspired by the nearby St. Rafca's grave, with both incorporating the suggestion of a lamp and a ship. Concave beams are used to imitate the ship-like structure. With spans averaging 32 m (100 ft) and a concave shape with variable sectional geometry, it was this roof that presented a number of challenges to CCL design team.

PROJECT DESCRIPTION

Approximately 86 m long by 41 m wide (282 x 134 ft), the cathedral has a rectangular footprint and consists of three levels: a ground floor which includes a reception area, a conference hall, a library, and meeting rooms; a basilica floor level; and the roof level.

The exteriors of the walls slope inward as they rise to meet the concave roof. A set of steps on the outside of the building provides access to the roof, which is used for open-air services during the summer months.

The roof has the shape of inverted arches from below with cantilevers on all four sides and a central span.

STRUCTURAL CONCEPT

The roof is designed as a one-way slab resting on concave post-tensioned beams with a concrete strength f'_c of 45 MPa (6500 psi) and the following applied loads:

- Super-imposed dead load: 6.0 kN/m^2 (125 lb/ft^2); and
- Live load: 5.0 kN/m^2 (104 lb/ft^2).

The columns extend 14.3 m (47 ft) in height and are designed as reinforced concrete, (Fig. 1). The slab is composed of 11 continuous 7.5 m (25 ft) spans. The internal spans are reinforced concrete and post-tensioning is used in the outer bays. The post-tensioning consists of a bonded flat slab system using CCL XF30, which houses 5xT15 (15 mm [0.6 in.]) strands per tendon.

Fig. 1—One-way slab roof.

Fig. 2—Long span concave roof beams.

The concave post-tensioned beams have one central span between 29.5 and 33.7 m (97 and 110 ft) long and cantilevers on both sides (Fig. 2). Besides the concave shape, the beams' sectional geometry is non-conventional. The upper face has a mild slope, while the bottom face has an inverted curve shape. In addition to that, the beams have a variable section with plain sections at the ends and a voided box section in-span with variable depth between 1.5 and 3.65 m (5 and 12 ft). This can be seen in Fig. 3, 4, and 5 showing a two-dimensional elevation of the beam, a cross section, and a completed beam view, respectively.

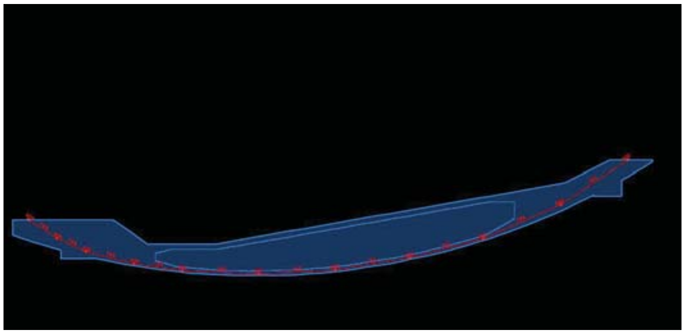

Fig. 3—Beam elevation with PT tendon in red.

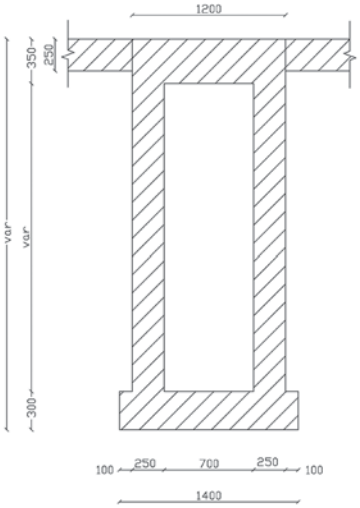

Fig. 4—Beam cross section.

Fig. 5—Beam geometry.

Fig. 6—CCL XM and XF multistrand PT systems.

DESIGN CHALLENGES

Sectional Geometry

Given the long spans and imposed geometrical shape, it became obvious that the weight of the beams would be problematic and would yield large flexural effects. To reduce the self-weight impact, a voided section became unavoidable; this reduced the self-weight by 26%, an equivalent of 350 kg/m^2 (70 lb/ft^2).

With the high prestressing forces reaching a maximum of 13,000 kN (2900 kip), multistrand bonded post-tensioning with round ducts was used consisting of CCL XM 40 and XM 60, which house 12T15 and 19T15 (15 mm [0.6 in.]) per duct, respectively (Fig 6). Thorough detailing was carried out to ensure proper placement between post-tensioning tendons and nonprestressed reinforcement, proper transition between plain and voided sections, as well as post-tensioning system spacing requirements and bursting steel placement.

Beam-Column Joint

The beam-column joint required special attention, because cast-in-place beams of lengths to the order of 32 m (100 ft) are uncommon in building structures. The concern was that the displacements from elastic shortening due to post-tensioning, concrete shrinkage and creep were large. In addition to the effect of shortening displacements, the concave shape of the beam yields inwards displacements under applied load. If restrained, lateral reactions, as represented in Fig. 7, will be induced at the joint similar but opposite to a dome effect.

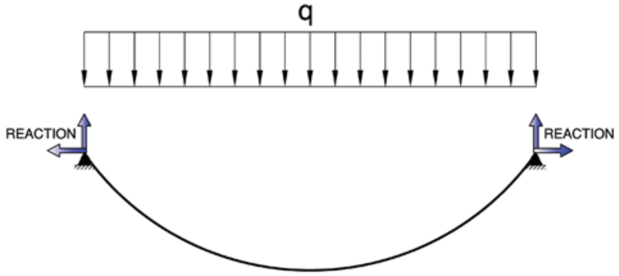

Fig. 7—Concavity effects under applied loads.

If the connection was monolithic, the structure would behave like a frame. A frame analysis calculation has shown high restraining lateral forces at the joint and reactions in the column which can potentially lead to undesireable cracking.

With an average precompression of 10 MPa (1.45 ksi), a restrained scenario would yield a displacement of 15 mm (5/8 in.) from elastic shortening alone. The elastic shortening shearing force can be calculated using equation below, where δ represents the displacement; E_c is the concrete modulus of elasticity at stressing; I is column inertia; and h_{col} is column height.

$$F = \frac{12\ \delta\ (E_c I)}{h_{col}^3} \qquad (1)$$

To alleviate the restraining effects, the joint was designed in a similar way to bridge construction. The beam-column joint includes a complete separation between the beam and the column. Mechanical pot bearings type CCL PG Guided Temporary Sliding (Fig. 8) are used on one end of the beam and CCL PF Fixed bearings on the other end. The PG sliding bearing provides unidirectional movement but is fixed in the transverse direction. This has allowed the beams to displace freely at stressing in the XX-plane (along the span) while ensuring stability in the other direction.

After stressing, the actual total displacement under elastic shortening, drying shrinkage, and beam displacement under its self-weight was measured and compared against calculated values. The agreement between measured and calculated displacement has confirmed the design philosophy; therefore, the long-term values used to calculate the fixity requirements for the bearings are valid. The PG bearings are then locked in place and fixed to ensure displacement fixity. This enables the joint to behave as a pinned connection which can transfer lateral loads for long-term displacement without transferring any flexural moments to the column.

Composite Beam Design

The construction sequence entails casting the beam separate from the slab. The slab has downward steps and is not leveled with the top of the beam at all sections. The slab is cast at a later stage and is designed to be fully monolithic with the beam by designing for horizontal shear at all slab-beam interfaces and adding the required reinforcement. Like all composite sections, the shoring and loading at each stage needed to be taken into account for stresses and deflection calculations. For this project, the shoring was removed after casting the beams, as noted in the construction sequence below.

Construction Sequence

1. Casting of beams
2. First stage stressing
3. Monitoring of beam displacement
4. Second stage stressing
5. Locking of pot bearings
6. Shoring removal
7. Casting of slab
8. Stressing of slab tendons

Fig. 8—CCL PG Guided Temporary Sliding Bearing.

To maximize the effect of post-tensioning in the beams, the stressing was completed before the slab was placed. This has helped reduce the diversion of precompression into the slab, and maintaining a higher precompression value in the beam section. The increased precompression leads to increased compression stresses at the bottom fiber, which gives the beam more capacity to resist the tensile stresses due to loads. The tensile/compression stresses at the top and bottom of the beam were verified under ACI 318-08: 18.4 and 18.3 so they do not exceed the allowable stresses at transfer and service limit states.

Due to the complex sectional geometry, the design was done using in-house tools in combination with finite element software and frame analysis. The design used variable sections and calculated the corresponding sectional parameters to determine load effects. Based on composite beam design, the stresses were added incrementally for the different load stages. In this case, for serviceability design, the post-tensioning, beam, and slab self-weight act on the beam section, and the super-imposed dead plus live load act on the T-section whenever the slab is leveled with the top of the beam. In the areas where the slab was beneath the top of the beam, the design was based on the beam section alone.

Stressing Sequence

The beams are at a height of 14.3 m (47 ft) from the ground with a height-to-depth ratio reaching 3.1, sitting solely on pot bearings at the ends. This created an additional challenge through the risk of beams flipping or overturning due to wind load or accidental loading during construction. Transverse beams had to be cast with the main beams to provide lateral resistance (Fig. 9). As a result, the stressing operation was sequenced to achieve a uniform and gradual displacement of the beams.

When concrete reached 30 MPa (4400 psi), stressing was initiated. The stressing was done in two stages. The first stage consisted of partially stressing all the beams sequentially. An initial set of tendons in each beam was stressed starting from the middle beam then moving outward to the adjacent beams one by one. Once all the beams were stressed, the stressing team moved back to the middle beam and performed another round of stressing in a similar manner until all the beams were partially stressed to the required force. The displacements were monitored and checked against calculated values. After the displacements were approved, the second stressing stage was carried out following the same sequence.

Fig. 9—Tranverse beams to provide lateral resistance

SUMMARY

The 32 m (100 ft) span concave and variable geometry roof was achieved through a series of design solutions:

- Voided sections: allowed the reduction of beam self-weight while providing an efficient inertia.
- Concave beams (inverted dome): lateral forces and displacements under applied load due to beam geometry were significant and needed to be considered.
- Beam-column joint with mechanical pot bearings: allowed the beam-column joint to act as a pinned connection without transferring any moment to the column.
- Temporary sliding bearings: allowed the beams to displace under post-tensioning, shrinkage, and self-weight deformation. The locking of the bearings for the final stage secured the beams laterally.
- Composite section: stressing the PT tendons prior to casting the slab maximized the precompression in the beam. Accurate calculation, depending on the loading stage and shoring status, was necessary for stresses and deflection assessment.
- Stressing sequence: the sequencing of the post-tensioning within the beam itself and with the other beams helped introduce the post-tensioning in a gradual manner.
- Displacement monitoring: allowed validation of design equations in the case of complex slab geometry.

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