Base Isolation and Post-Tensioning

A perfect combination for long spans and vibration control

BY LUIS M. BOZZO

This article describes the use of base isolation and post-tensioning in the structural design of the new Sant Pau Hospital in Barcelona, Spain. The original Sant Pau Hospital is a historical sanitarium dating back to the 19th century (Fig. 1). The old buildings constitute an Art Nouveau architectural jewel and have recently been designated a World Heritage Site by UNESCO. The old hospital, however, isn't able to accommodate modern medical equipment. In addition, the layout of the many small buildings that comprise the hospital requires inconvenient patient transfers between services.

Adjacent to the old hospital, the institution owned sufficient property for a new facility. They commissioned a design competition, and selected a design that minimized patient displacements by optimizing the space.

As shown in Fig. 2, the new hospital comprises five radially-arrayed wings. The main wing is the longest, largest wing and houses primarily surgical rooms, ambulatory services, and obstetric services. The remaining four ancillary wings house offices and patient rooms. This plan optimized the footprint and reduced the distance required for patient movement. The largest wing is itself made up of five blocks, separated by construction joints spaced at about 50 m.

Unfortunately, the design also located surgical rooms as much as three floors underground, with the exterior walls only 2 m away from existing metro (subway) lines. The metro runs parallel to the longest side of the wing, about 5 m underground. Further, the design called for 12.5 x 7 m bays and limited the

Conversions

1 m = 1000 mm = 39.4 in.

1 kN = 2.248 kips

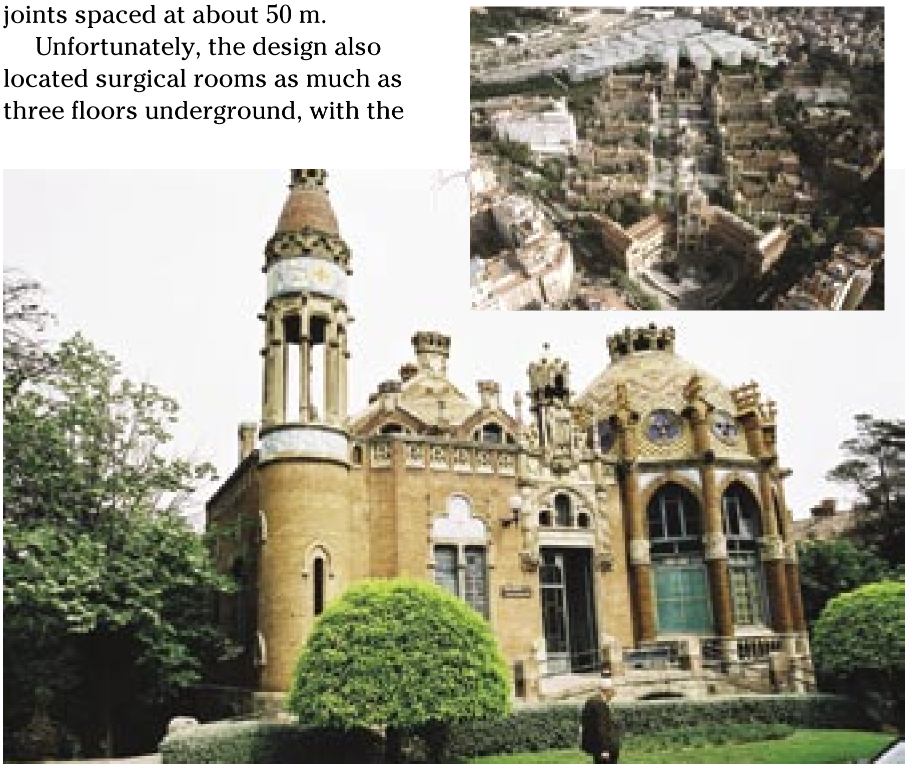

Fig. 1: One of the many Art Nouveau-style buildings comprising the Sant Pau Hospital (inset: overall view of the existing hospital with a superimposed rendering of the new construction). *Insert photo courtesy of the website, www.santpau.es*

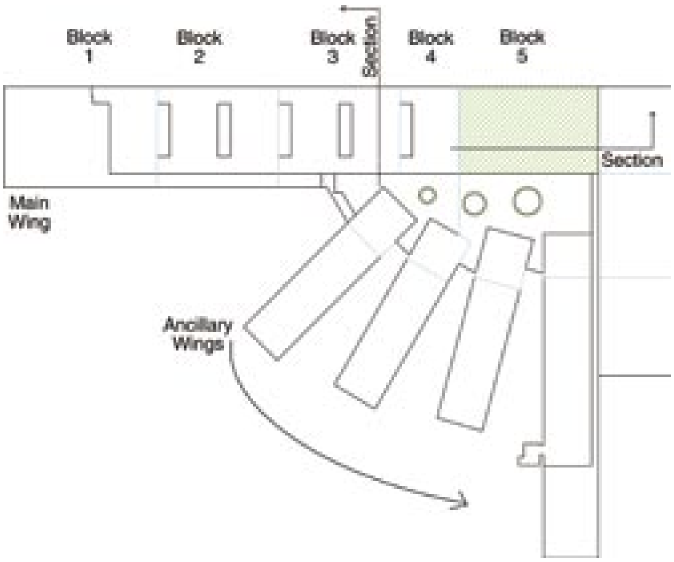

Fig. 2: Overall plan of the hospital (Block 5 hatched)

maximum floor thickness to 500 mm. The challenge for the structural engineer was to provide an economical, quiet, and stable system.

For the optimum solution, post-tensioned floors were combined with base isolation. Not only does post-tensioning allow large spans, it can significantly reduce the self-weight of a structure, thereby minimizing the costs of the isolation systems themselves.

BASE ISOLATION

In the past 20 years, base isolation and energy dissipators have become relatively popular techniques for protecting buildings against earthquakes. Base isolation significantly reduces the fundamental frequency of the building to a value that is much lower than the frequencies of the ground motion. Various friction or neoprene-based systems have been proposed and used.[1]

Although these systems are effective in reducing the effects of horizontal vibrations such as earthquakes, they typically are not effective in reducing the effects of vertical vibrations. Because it was known that metro operations could cause horizontal as well as vertical motions, special systems were investigated.

CONCEPTUAL DESIGN

Options considered for the isolation systems included global building isolation, individual room isolation, and isolation of the metro lines. The latter two options were both relatively expensive. Furthermore, isolation of the existing metro lines would have required an extended construction schedule, as work could be done only between certain hours of the night. Thus, a global isolation system was selected.

For global building isolation, both neoprene and spring-type systems were considered. The combination of large

Fig. 3: Spring isolation units for the Sant Pau Hospital

open bays and a total building height of up to eight stories resulted in large column loads at the foundation level. For example, even after using a 50% live load reduction to account for the low probability of simultaneous full live load at every floor, the average column service load was still 4900 kN. These large column loads would have made it necessary to either use specially designed neoprene isolation units or up to 20 standard neoprene units per column. Both options were cost prohibitive.

A spring system[2] was therefore selected, as it was capable of carrying the maximum loads using only four isolation units per column. Further, the spring system design incorporated metal tension rods that allowed the springs to be precompressed up to the column service loads. This feature helped to avoid vertical movement of the column bases as the column loads increased during construction. Although differential column settlements due to live load variations could not be avoided, only ±10 mm differentials were anticipated.

Vibrations induced by the metro trains were measured at the surface, before excavation of the three-story basement. Measurements indicated about a 10 Hz frequency in both the vertical and horizontal directions. Using a safety factor of 2, the design vertical isolation frequency was selected as 5 Hz. This factor of safety was selected to account for future changes in metro lines or frequency changes that could result from excavation of the building. Figure 3 shows the isolation units selected for this project.

Another aspect considered during conceptual design was the possibility that stray currents induced by the metro could potentially pass through the steel spring elements to the hospital and cause problems with medical equipment. To prevent this, the spring connections within the isolators were supplied with neoprene pads for electrical isolation.

Finally, inspection and future replacement of isolation units were important considerations. Replacement may be needed for a number of reasons, including fatigue, fire damage, and unexpected environmental conditions. The spring isolation system provided dual benefits—a reduced number of isolation units and simplified removal/replacement through the use of its prestressing feature.

BUILDING DESCRIPTION AND ANALYSIS RESULTS

The main wing of the building increases from three stories at Block 1 (at the end of the wing) to eight stories at Block 5. Figure 4(a) shows a typical transverse section through Block 3, where the isolation units are located directly on top of the foundation caps. Figure 4(b) shows a longitudinal section through Block 5, where the isolation units are located on top of the first-story columns. This configuration was used in most of the blocks to reduce the isolated weight and to provide for better accessibility for inspection. In both conditions, a flexible joint was also provided around the whole building to avoid infiltration of vibrations.

The floor structure is a simple one-way system. Post-tensioned frames support semi-precast, prestressed 7-m-long slabs. The depth of the one-way slab system is 200 mm (130 mm overlay + 70 mm precast slabs), and the total depth for the main post-tensioned beams is 500 mm. The beam width is 1500 mm, which allows the tendons to pass beside the column reinforcement, thus simplifying the construction process.

The floor load is transferred from the semi-precast slabs to the beams and to the isolation connection to the foundation. Two tendons with ten 15.24 mm strands prestressed up to 1900 kN each were used per beam. The post-tensioning layout (Fig. 5) is similar to the bending moment diagram: it is linear at the cantilevers and parabolic at the two 12.5 m main spans. Figure 6 shows a typical arrangement of the post-tensioning anchorages and the isolation connection.

Figure 7 shows a partial view of the upper part of Block 1 of the finished structure and features a 7 m cantilever with a 500 mm total depth. As can be seen at the end of the cantilever, three longitudinal post-tensioned beams were created (in addition to the typical transverse beams shown in Fig. 4(a) and Fig. 5). The cantilever was shown to significantly reduce unbalanced forces on the interior side of the columns. Because isolator connections are not capable of transmitting traction forces, various live load patterns were considered to ensure acceptable reactions at the column bases.

Throughout the building, it was necessary to use the following analysis process:

1. Assume an articulated pinned-fixed base, analyze the whole building, and estimate reactions;
2. Select the spring connections (select the smallest quantity of units for the column reaction);

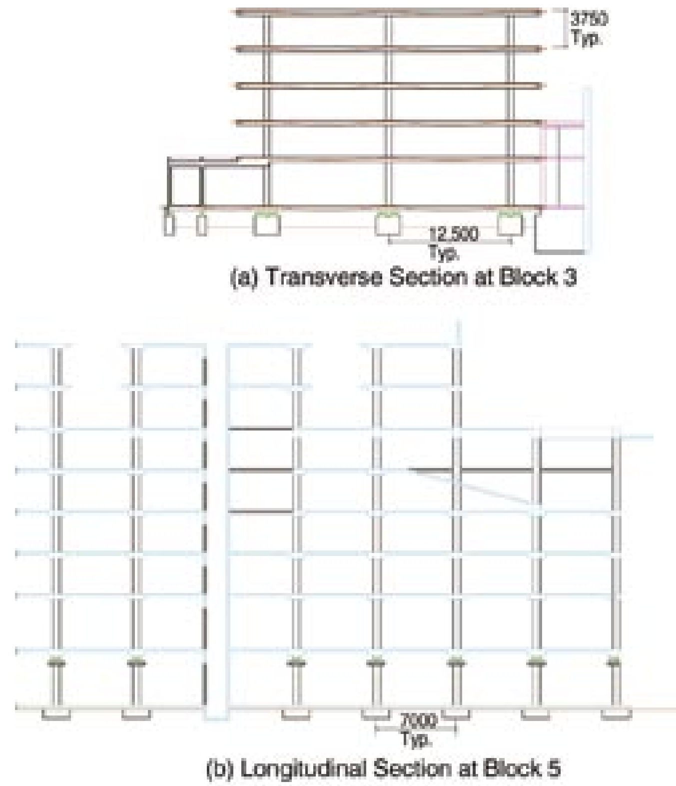

Fig. 4: Typical sections for: (a) Block 3; and (b) Block 5 (dimensions in mm)

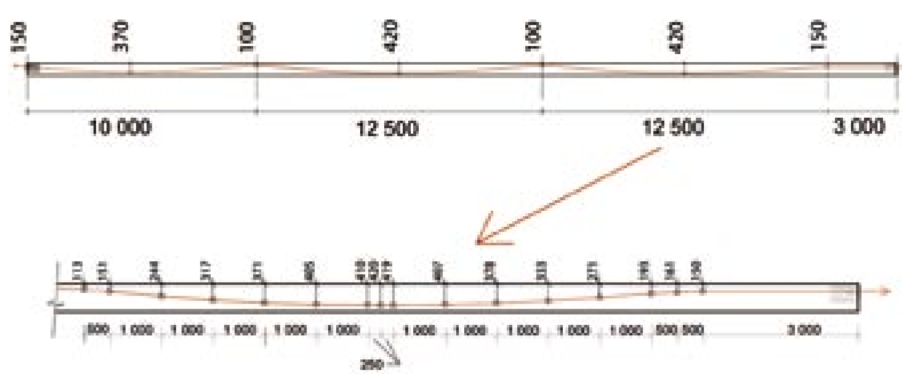

Fig. 5: Typical post-tensioning tendon layout following bending moment diagram (dimensions in mm)

Fig. 6: Base isolation unit and post-tensioning anchorages

Fig. 7: Partial view of the finished structure showing a long cantilever roof at Block 1

3. Analyze the building using the vertical and horizontal spring stiffness values, and calculate the revised reactions; and
4. Iterate until satisfactory convergence is obtained.

After three or four iterations, this process provided satisfactory reactions and connection units. The magnitude of the vertical reactions is very important because it affects the performance of the isolation. Underestimating the reactions may result in exceeding the capacity of the springs. In such a case, the spirals can be in contact, and the isolators will not filter the vibrations. Overestimating the reactions affects the isolator frequency and may also cause the isolators to work improperly (although some safety margin is provided by the use of a 5 Hz design frequency and having an anticipated excitation frequency starting at 10 Hz).

Ideally, at the end of the construction process, the initial prestress in the isolation units should be counteracted by the actual load. A significant error in determining the prestress force given at fabrication (corresponding to the service load) can be easily detected and corrected if necessary.

TABLE 1: PERCENTAGE OF REDUCTION IN LIVE LOAD

Number of floors				
2	3	4	5	≥6
10%	20%	30%	40%	50%

As previously noted, the full-service live load is usually not present at the same time. Consequently, live load reduction according to the number of stories was used to ensure proper performance of the isolation system. Table 1 shows the live load reduction used for the building.

Wind and earthquake loads are relatively small for this building and for Barcelona in general. Dynamic modal analyses indicated that horizontal vibration modes were not significantly affected by changes from a pinned to a fixed base model. Consequently, these loads did not significantly affect the design of the building.

Measurements verify that our design solution was very successful. Compared to a conventional building with a fixed base, the isolation system provides a 90% reduction in vibration motions resulting from metro operations. The hospital is now in operation and Barcelona can depend on an efficient medical facility equipped with modern medical and construction technology.

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