

Strengthening Category

Structural Reinforcement of Jaime Roldós Aguilera Bus Terminal

Guayaquil, Ecuador

Submitted by BASF Construction Chemicals



Fig. 1: Overall view of bus terminal

The construction of the Jaime Roldós Aguilera Bus Terminal project in Guayaquil, Ecuador, started in October 1980 and was completed in May 1984 (Fig. 1).

In April 1987, pieces of concrete fell from the elevated roadway second-level slabs. For almost 16 years, there has been a controversy about the causes of this problem, with the most accepted reason pinpointing potential flaws in the structural design, construction mistakes, and material deficiencies of the precast sections of the slab.

The overall analysis of the structure, however, revealed a lack of lateral stiffness of the building in the longitudinal direction, as well as a lack of strength of the slabs in the two stories of the bus lanes. This caused vibration in the bus lanes, leading to the progressive deterioration resulting in the falling concrete.

Evaluation of the Structural Vulnerability

First, an evaluation of the damage present in the building was undertaken, putting emphasis on the

location and size of the structural members, and on nonstructural issues such as cracks. The investigation evaluated the spalling of the concrete, deflections and deformations of main structural elements, corrosion on reinforcing bars, humidity stains, and cracked masonry. All reported damage was classified in a damage matrix.

A structural laboratory carried out a series of nondestructive tests to assess the strength of the concrete, the depth of the carbonation front within the concrete, and the periods of vibration of the structure. From these tests, the following conclusions were made:

- The concrete strength was variable depending on the elements tested, which indicated poor quality control during construction as shown below:

Concrete from columns	3500 psi (23.9 MPa)
Concrete from beams	2700 psi (18.2 MPa)
Concrete from slabs	4000 psi (27.2 MPa)
- The depth of carbonation of the structural elements was acceptable for the concrete strengths found, which indicated there was no apparent risk of massive corrosion of the reinforcing steel. There

were localized conditions of corrosion due to other factors, however, but these did not represent any danger to the structure if proper care and maintenance was undertaken.

Determination of Dynamic Properties of the Structure

Two kinds of tests were carried out to determine the main period of vibration of the structure: an ambient vibration test and a forced vibration test. These results were used to calibrate the mathematical model of the structure using the SAP2000 structural analysis program.

Ambient Vibration Test

The ambient vibration test was performed using a seismograph, and the recorded signals were analyzed using the Fast Fourier Transform and Power Spectrum analysis functions. This procedure obtained the predominant frequencies of the signal and therefore the inverse of the frequency—the natural period of vibration of the structure in the vertical and two horizontal directions could be determined. The period of vibration of the soil was obtained using the Nakamura procedure.

Forced Vibration Test

The forced vibration test obtained the real periods and modes of vibration of the structure, which were used to calibrate the mathematical model of the structure. It consisted of applying a harmonic sinusoidal vibration force to the structure with variable frequency through a dynamic exciter located on top of the structure. The structure was then subjected to this sinusoidal force with a known magnitude and frequency, and the acceleration of various points of the structure recorded with accelerometers fixed to the slab. Later, the signals were processed and the results were obtained.

Structural Analysis

The building is formed by 15 different independent blocks, separated by 2 in. (50 mm) wide seismic joints. The 15 blocks have an overall dimension of 656 ft long x 305 ft wide (200 x 100 m).

The 15 blocks were modeled using the SAP2000 computer analysis program, using links to join the individual structures to form only a single building. This was attained by the addition of reinforced concrete walls located on each end of the building to compensate for the lack of stiffness in the longitudinal direction.

The loads considered for analysis corresponded to those of vertical loads (dead + live + bus and truck) and lateral loads. (Elastic acceleration spectrum [Fig. 2] for the city of Guayaquil was developed with a reduction factor of 4.5 employed).

Results of the Analysis

The analysis of the existing structural elements showed excessive flexibility of the different individual

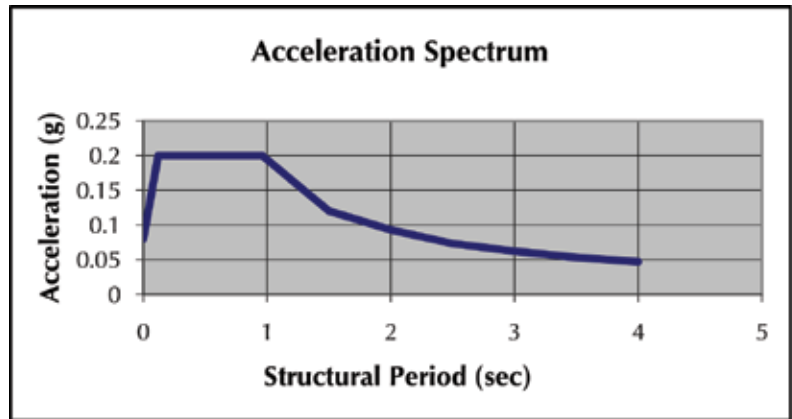


Fig. 2: Elastic acceleration spectrum with $R = 4.5$



Fig. 3: Diagonal cracking on the columns

blocks in the longitudinal direction because there were no beams in this direction. The only contribution of the stiffness was provided by the joists of the slab. Consequently, there was no frame action in this direction; as a result, columns displayed diagonal cracking (Fig. 3). In the transverse direction, there were frames made of columns and beams.

The theoretical periods of vibration were calibrated with the results of the ambient and forced vibration tests, which determined the real periods of vibration of the structure. Once the model was calibrated, a series of options were implemented to increase the lateral stiffness of the structure. First, all 15 blocks were joined together by means of rigid links. Concrete walls were added on each end of the building in the longitudinal direction together with the creation of new beams in this direction as well. The new periods of vibration obtained with this model were considered compatible with this type of structure.

Project Details

- The existing building had a notable lack of stiffness in the longitudinal direction due to the fact that

there were no beams in this direction to connect the frames. In the case of a severe earthquake, significant damage to the structural elements would be expected.



Fig. 4: Filling the gaps with a special high-strength, low-shrinkage rheoplastic repair mortar



Fig. 5: Carbon-fiber bands were used to wrap adjacent columns and to ensure that the 15 blocks behaved like one unit



Fig. 6: Wrapping of the overhead ramp support beams

- The new joint block details give a structural response that limits the lateral displacement of each individual block and allows the structure to have much more rigidity (stiffness) in the longitudinal direction.
- This retrofit procedure was obtained by cleaning the existing joints and then filling the gaps with a special high-strength, low-shrinkage rheoplastic repair mortar (Fig. 4). Using state-of-the-art technology, carbon-fiber bands were used to wrap adjacent columns and to ensure that the 15 blocks behaved like one unit. This provided significant confinement to the columns adjacent at the joints, which provided an increased ductility in the seismic behavior of the structure (Fig. 5).
- The implementation of new structural reinforced concrete walls on each end of the building considerably reduces the period of vibration of the structure, making it considerably stiffer. This is achieved with the construction of new concrete beams in the longitudinal direction, which adds stiffness and allows the shear transfer of the concrete walls when subjected to seismic forces.
- Carbon-fiber bands were also used as reinforcement to increase strength (in flexure and in shear) to some existing beams that were subjected to additional vertical loads due to the new architectural requirements of the project. Figure 6 shows the wrapping of the overhead ramp support beams. The damaged beams and columns were repaired with a structural grade rheoplastic high-bond-strength repair mortar capable of developing a rapid modulus of elasticity.
- The slabs were increased in thickness to add stiffness and strength to reduce the local vibration of the slabs on the lanes where buses and trucks circulate. An additional 4 in. (100 mm) of high-strength concrete was added to the slabs using shear connectors to ensure a proper connection to the existing slab.

Jaime Roldós Aquilera Bus Terminal

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