Structural Evaluation and Strengthening Strategy for a Reinforced Concrete Commercial/Residential Complex in Northern Beirut

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Abstract

Two decades of civil strife and regulatory vacuum have left a legacy of poorly designed and executed large reinforced concrete structures in the suburbs of Beirut. Two major dramatic collapses in buildings constructed in the last decade have occurred, with problems reported in a host of other buildings. A structural evaluation of a nine years old mixed use commercial / residential reinforced concrete building was carried out involving materials sampling and testing, structural modeling, and soil-structure interaction.

The structure was built on a high slope terrain, and consists of a total of thirteen slabs with up to six basements. The residential six story building is supported on a ground floor of "pilotis" or unbraced columns, to allow for covered street level parking. Small to medium cracks had been reported by occupants especially in the one way ribbed slabs of the lower underground floors. Emergency measures included temporary shoring and unloading some of the live loads in the structure with minimal disruption to residents lives.

Field investigations showed a large variability in concrete strength with unacceptable lows, and various reinforcement, foundations, and retaining walls problems.

Original designs and execution methods were investigated, and a realistic structural model was built to assess the current safety of the building. Two dimensional frame analysis as well as three dimensional modeling where carried out showing good agreement with observed conditions. Large oversights in the design, as well as unaccounted for soil-structure interactions called for strengthening measures. An optimal strengthening action plan was developed and proposed to the municipal authorities for immediate execution.

Keywords: Structural Evaluation, Structural Strengthening, Concrete Testing, Failure Analysis, Forensic Engineering

1-Background

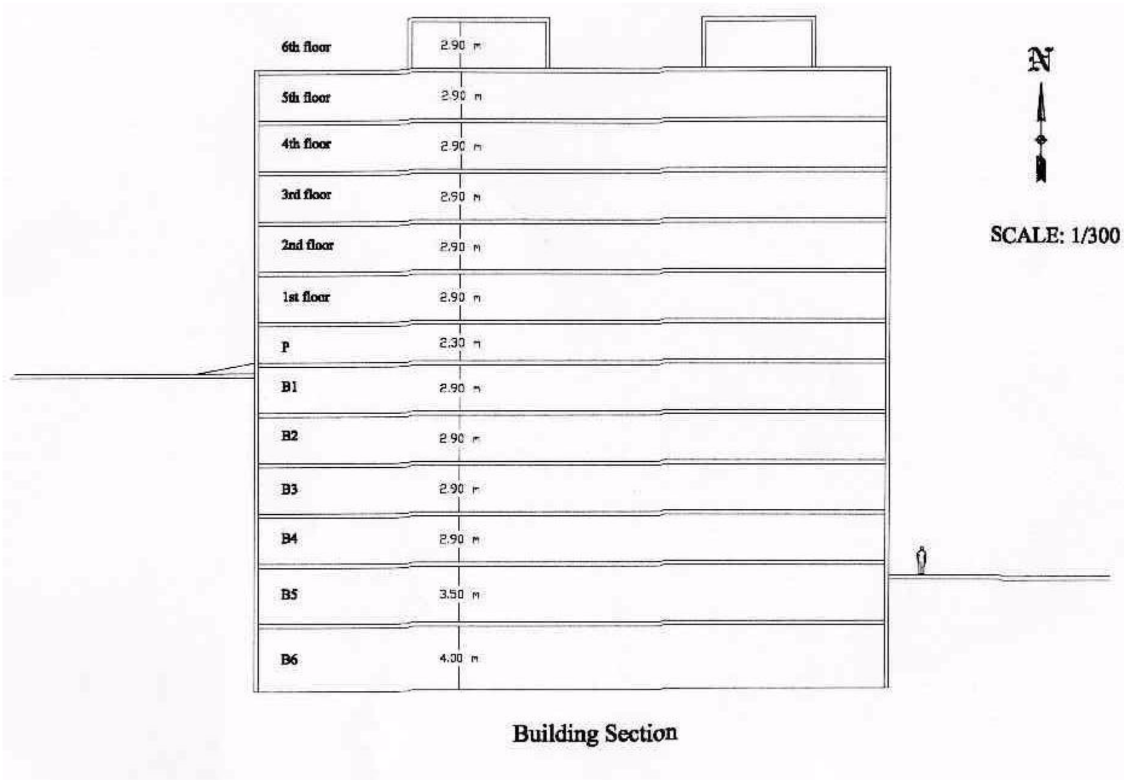
Two decades of civil strife and regulatory vacuum have left a legacy of poorly designed and executed large reinforced concrete structures in the suburbs of Beirut, Lebanon. Two major dramatic collapses in buildings constructed in the last decade have occurred, with problems reported in a host of other buildings.

In November 2000, the Institute for Geotechnics and Materials s.a.r.l. (IGM) was called in by the municipal authorities to investigate the structural condition of a nine years old mixed use commercial / residential reinforced concrete building in the northern suburbs of the capital Beirut. Residents had been complaining about multiple small to medium width cracking in the floors and columns, water seepage through cracks between floors, and occasional localised crushing and deterioration of concrete.

The structure was built on a lot between two parallel streets separated by about nine to ten meters in elevation. The original slope from the north-east to the south-west was graded, the structure constructed, and the sides backfilled to restore the streets back to the levels of the municipal urban plan (ref. to Figure 1). A total of thirteen slabs were built with six basements from the upper level street (two from the lower level street). The lower three basement floors were used industrially by a furniture factory, a sewing shop, and for paper and charcoal storage. The upper residential six story building is supported on a ground floor of “pilotis” or unbraced columns, to allow for covered street level parking. Small to medium cracks had been reported by occupants especially in the one way ribbed slabs of the lower underground floors.

Emergency measures were implemented and a full investigation carried out. The emergency measures consisted of :
a-reducing live loads by removing all cars parked on the pilotis level, reducing or emptying water reservoirs, and unloading as many of the storage space as possible in the commercial part of the building.
b-temporary shoring of the slabs showing cracking in the lower underground floors.
c-removal of some asymmetrically applied lateral loads by excavating an area of 5x18x6m on the upper northern side of the building, in order to reduce temporarily the lateral earth pressure on the structure.

Figure 1. East-West Building Section



2-Investigation and Testing Program

A full investigation program was carried out including visual inspection**,** assessment of verticality and building deformations, testing concrete strength, checking steel reinforcement, and investigating the foundations condition.

2.1Visual Inspection

The major results of the visual inspection are summarized in the following:
a-cracks less than 1mm wide were observed in the floors of the residential upper part of the structure, touching about 60% of the thirty or so apartments, with a higher concentration in the lower levels. 20% of repaired cracks had opened up again.
b-large longitudinal cracks were observed in the floors of the basements, parallel to the rib direction of the one-way ribbed slabs.
c-large cracks were observed in the partition walls of the third basement.
d-cracks and large deflections were observed in the perimeter northern and eastern retaining walls, on the side of the highest backfill.
e-localized crushing in a few columns due to poor quality yellowish sandy concrete pockets.
f-asymetric earth loading conditions on the structure with the northern and eastern sides backfilled to higher levels than facing sides.

Representative cracks were monitored for the duration of the investigation works (two months) showing no measurable displacements.

2.2 Verticality and Displacements

Plumb lines were installed to measure any vertical tilt in the structure, and a grid of points was surveyed with a total station on all four facades of the structure. The results, of the same order as the building geometric imperfections, did not show any consistent displacements.

2.3 Steel Reinforcement

The location and quantity of steel reinforcement was investigated using a magnetic rebar locator. The existing steel reinforcement was found to match that required in the design documents made available to IGM.

2.4 Concrete Coring and Non-Destructive Testing

Twenty 2 inch diameter cores were obtained from columns, and five 4 inch diameter cores were obtained from footings and retaining walls. These cores were tested according to ASTM C42 (ASTM, 1994).
Additionally five Schmidt Hammer rebound numbers were averaged at each of 120 locations, including those where cores were obtained. A calibration of the Schmidt Hammer results against the results of the cores was used to develop a general picture of the concrete strength distribution throughout the building. The relationship used to obtain the equivalent core concrete compressive strength f'c from the Schmidt Hammer was:

$$f'c = f'c_{(Schmidt)} \times 0.6 \qquad [1]$$

Figure 2 shows the density of cores vs compressive strength, and Figure 3 shows the Schmidt Hammer concrete strength versus core compressive strength with the site calibration factor of 0.6 being the slope of the line bisecting the fan shaped distribution of the results. The site calibration line leaves above it as many data points as it leaves below it.

Figure 2. Concrete density versus core compressive strength

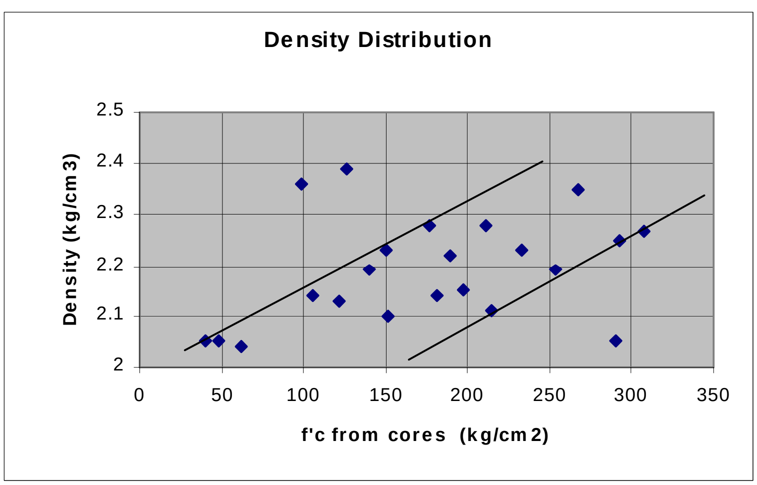
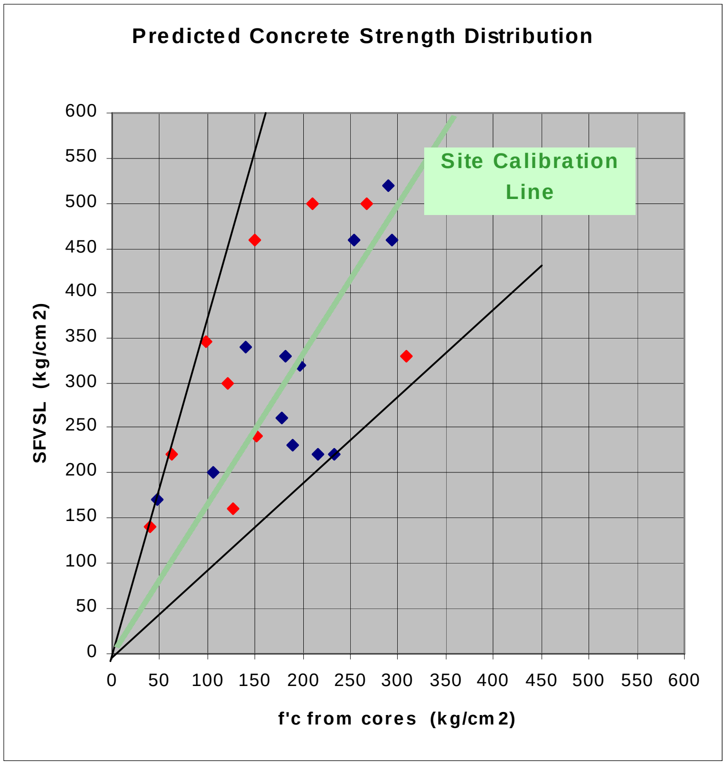


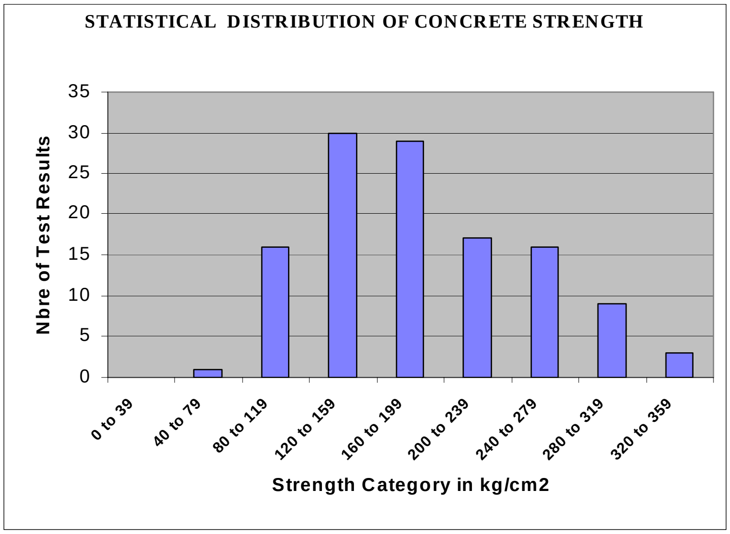
Figure 3. Schmidt Hammer vs core compressive strengths



The results showed poor concrete quality throughout with very large variation between different locations. A research of the general conditions during the construction of the building showed that no quality control was performed at the time, and that there were large variations between different concrete batches.

The distribution of the compressive strength results is presented in Figure 4. The average value was 227.55 kg/cm^2, the median was 180 kg/cm^2 , and the standard deviation was 63.26 kg/cm^2.

Figure 4. Distribution of concrete compressive strength.



2.5Foundations Investigation

Test pits were excavated at random footing locations and extended below the bottom foundation level. The foundation soils were exposed and found to be limestone bedrock with some sand content. Rock proofing by coring 1m below each footing tested was done. An unconfined compression test on a secured rock core gave a compressive strength equal to 330 kg/cm^2. A deep crack cavity 30 cm wide and filled with dense clayey sand was found under one footing which leads to the assumption that some footings may need strengthening pending a cavity search underneith.

3-Structural Modeling

The original structural design was reviewed based on the documents made available by the engineer and the owners of the building. A simple two dimensional frame analysis was used with a simply supported assumption for all beams. Lateral earth loads, and the addition of top floors were not included in the original design as well as some additions and structural modifications.

However in the construction of the building continuity and monolithic joining of beams and columns was effectively realized. A two dimensional analysis with reduced concrete strength was found to be too penalizing especially in that part of the underground building where unaccounted for lateral earth load were actually being resisted by the whole framed structure.

A conservative three dimensional frame model was created for the building and analyzed under all applicable dead and live loads using ROBOT 97 v.13.0 . This model allowed for a more realistic distribution of loads and hence an efficient assessment of the actual loading ratios of the beams and columns.

The concrete strength used in the structural modeling was obtained from the statistical data as f'c=150 kg/cm^2 at an 88% level of confidence, assuming a normal distribution of the results (ACI 214.3R-88, 1988).

Table 1 shows a typical comparison for the beams of the B4 level. The last column represents the ratio of the maximum moment from the analysis divided by actual moment capacity.

On average the beams are 17% overloaded which explains the cracking and large deflections observed at this level.

Columns were also checked using an allowable concrete strength of f'c=75 kg/cm^2 for a level of confidence of more than 95% given the critical role played by the columns in maintaining the structural integrity of the building, and given the fact that the lowest concrete strengths were measured in the lower basement columns. A 16% overload was also observed for the columns in the basements.

The foundations did not show any overload situation.

TABLE 1 Comparison of Maximum Moments on a Typical Beam – SS4 -

ROBOT BAR #	Location in Drawings	**A**) - Max. Moment from 3D analysis (T.m)	**B**) - Max moment Capacity of Existing Beams (T.m)	**A/B** % Ratio
1185	Axis 10 (A0 – C)	43.4	40	1.09
71	Axis 10 (C – G)	42.6	40	1.07
81	Axis 10 (G – K)	16.3	21.3	0.77
82	Axis 10 (K – P)	17.8	21.3	0.84
83	Axis 10 (P – R)	17.6	9.9	1.78
84	Axis 10 (R – T)	17.2	17.4	0.99
85	Axis 10 (T – X)	19.6	12.9	1.52
1202	Axis 10 (X – X0)	12.9	8.8	1.47
68	Axis 7 (D – G)	21.38	21.32	1.0
63	Axis 7 (S – V)	24.65	21.32	1.15
64	Axis 7 (P – S)	22.42	17.41	1.28
62	Axis 5 (B – F)	24.09	21.32	1.13
58	Axis 4 (O – S)	23.43	21.32	1.09
54	Axis 1 (M – Q)	15.18	14.24	1.06
53	Axis 1 (H – L)	22.53	17.32	1.3
			Average	1.17

4-Recommendations and Concluding Remarks

Integrating the public safety issue with the financial and economic considerations of the authorities the final recommendation where as follows for an optimal strengthening strategy:
1-Check condition of all footings and reinforce those on or close to a cavity.
2-Reduce or remove all together the asymmetric earth lateral load by excavating the northern side, and anchoring or strengthening the upper eastern side.

3-Improve drainage conditions to avoid build up of water pressure against the basement walls.
4-Introduce shear walls at select locations in the building to improve the resistance against lateral loads.
5-Strengthen weakest columns by jacketing.
6-Strengthen weakest beams and lower basement slabs by the addition of structural members or by the use of carbon fiber reinforced plastic sheeting (CFRP).

A table of members to be reinforced was provided based on the structural analysis.

The recommendations for strengthening did not include any seismic loads as this is not yet required by the law in Lebanon. The resistance of this building, and others in similar condition to a seismic event remains one of the most serious hazards that our community may have to face. Whereas the Order of Engineers is currently trying to improve the public safety and the individual's professional performance for buildings being currently erected, years of chaos and poor quality control during and after the war have left us with a dangerous engineering challenge.

5-References

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