REPAIR AND RETROFITTING OF DETERIORATED REINFORCED CONCRETE STRUCTURES – THREE CASE STUDIES

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ABSTRACT

Concrete is the material most widely used in the construction of reinforced concrete structures including hydraulic structures. There are many diversified applications of reinforced concrete for storage, conveyance and collection of potable water and seawater, irrigation, and wastewater conveyance and treatment. In the Arabian Gulf, the potentially aggressive environment has resulted in premature deterioration of numerous structures in a service performance span of less than a decade. The environment characterized by high humidity and temperature and excessive air/soil borne salinity has resulted in corrosion of the reinforcement and subsequent cracking and spalling of concrete. This paper will address the issues related to repair and strengthening techniques of three reinforced concrete structures. The first case deals with the inspection, assessment and repair strategy of mosque in Dammam. Investigation of structural distress and cracking in a newly constructed seawater conveyance structure and the suggested remedial measures for mitigating the problem are presented in the second case study. Finally, strengthening and monitoring of a distressed reinforced concrete structure that supports a cylindrical tank, using carbon fiber reinforced plates (CFRP) is addressed.

Keywords: *Concrete repair, Finite element, Durability, Cracking, Chloride, Deterioration.*

الملخص

الخرسانة هي المادة الأكثر شيوعاً استخداما في عمل الهياكل الخرسانية المسلحة بما في ذلك الهياكل المائية . يوجد العديد من التطبيقات المتباينة للخرسانة المسلحة كالخزانات وحاويات مياه الشرب والماء البحري والري والنفايات الصناعية المائية . تتميز منطقة الخليج العربي البيئة العدوانية النشيطة قد تسبب تدهور وتآكل الكثير من الهياكل في فترة وجيزة قد لا تتعدى العقد من الزمن و من العوامل التي تفاقم عملية أكسدة حديد التسليح وما يتبعه من شروخ وفقدان غطاء الخرسانة البيئة ذات الرطوبة العالية والحرارة الشديدة والهواء والتربة المشبعان بالأملاح

هذه الورقة تسلط الضوء على الأمور ذات الصلة بالإصلاح وطرق التقويم المتبعة في المباني الخرسانية المسلحة . الحالة الأولى تخص معاينة وتقييم ومعالجة مسجد يعاني من التدهور الخرساني بسبب تلوث الخرسانة المسلحة الأصلية . أما الحالة الثانية فتتركز حول الأسباب التي أدت إلى ظهور وشروخ في مبنى تحت الإنشاء لتبريد ماء البحر وعمل الاقتراحات اللازمة لتفادي هذه المشكلة . أما الحالة الثالثة فتتعلق بتقوية وتدعيم هيكل خرساني يعمل لقاعدة خزان أسطواني وذلك بواسطة استخدام رقائق شعيرات الكربون المسلحة بالبوليمرات .

1. INTRODUCTION

Repair and rehabilitation work for concrete structures can broadly be classified into two categories: a) repair in which damage due to deterioration and cracking is corrected to restore the original structural shape and b) repair which is necessary to strengthen the structural capacity of members whose load carrying capacity is either inadequate or whose strength has been severely impaired due to sustained damage. While the former is essential a cosmetic restoration aimed at compliance with serviceability and structural integrity criteria, the second category deals primarily with the enhancement of strength and therefore complies predominantly with strength criteria. The mystery of the mechanism of durable repair is unfolded on publications (Emmons and Vaysburd, 1996; Pinelle, 1995; Rahman et al., 1999 and Rahman et al., 2000). A repair scheme for this category is often challenging and calls for innovative techniques (Al-Gadhib et al., 2001; Azad et al., 1998). In this paper three case studies are presented, two of which related to the first category and the third is related to the second category. The cases addressed in this paper include:

1) Inspection, assessment and repair strategy of a mosque in Dammam.
2) Investigation of structural distress and cracking in a newly constructed seawater conveyance structure.
3) Strengthening of distressed reinforced concrete structure for supporting a cylindrical tank containing liquefied gas due to excessive differential settlement via carbon fiber reinforced plates (CFRP).

2. CASE STUDY I: INSPECTION, ASSESSMENT AND REPAIR OF AL-ANOOD MOSQUE

A twenty-five-year old mosque located in Dammam has been lately suffering from serious corrosion-induced damage. The damage manifested itself in the form of vertical cracking of the ground level columns, beams supporting mezzanine floor and spalling and delamination of concrete in the roof slab.

2.1 Assessment Of The Problem

The mosque has been built at times where quality assurance was not enforced neither in the material phase nor in the construction method. The water table is high and foundations as well as slab on grade were not insulated against moisture. Consequently, salt moisture and chloride ingressed into the columns causing cracking of columns. As far as mezzanine floor slab is concerned, excessive dead load of sand was used in some areas upto 20 cm to level the slab in addition to the large number of occupants who come to conduct prayer, causing sagging and vibration of the slab. In the roof slab, damage was of sound magnitude in which spalling of concrete cover on the central part was visible due to improper installation of the moisture insulation system. A quantitative measure needs to rely on to assess the chloride level and for this different samples were taken from mezzanine, roof slab, and beams for chloride analysis. The results are summarized in Table 1.

Table 1. Chloride analysis results

Sample no.	Location	Depth from surface (mm)	Chloride by % wt. of cement
1	Mezzanine slab	3.5	0.37
2	Mezzanine slab	6.5	0.28
3	Mezzanine slab	10.5	0.05
4	Roof slab	9.5	0.36
5	Beams		0.23

The last column of the above table contains the water-soluble chloride content expressed as percentage by weight of cement. The permissible level of water-soluble chloride ions in an aggressive environment is 0.15 by weight of cement content in concrete (ACI 381-99). Samples taken at different depth levels show more or less close values, indicating that the original concrete mix was polluted.

2.2 Repair Strategy

As the columns in the ground level were severely damaged, voluminous quantities of repair materials would require high budget as repair materials are expensive. Therefore, an in-house local concrete mix is proposed combining high strength and dense internal structure as summarized in Table 2 below.

Table 2. Repair concrete mix design

Mix component	Batch weight/m^3
Cement type	365 kg
Microsilica	25 kg
Water (sweet)	155 kg
15 mm (aggregate size)	600 kg
10 mm (aggregate size)	300 kg
8 mm (aggregate size)	170 kg
Fine sand	735 kg
Superplasticizer	3.5 liter
Corrosion inhibitor	6 liter

Using the tabulated mix design, laboratory tests have yielded an f_c' = 34.5 MPa (5000 psi).

In order to close the gap between the top of the concrete column and the soffit of the slab/beams, it is recommended that the client use a pre-packed shrinkage compensated, one component, free flowing high strength concrete with a maximum aggregate size of 10 mm. Needless to say that the application of repair material has to be done in accordance with well-documented steps that can be found in MBT product guide or Fosroc product data sheets for durable repair.

As far as restoring durability and integrity of the beams is concerned, any crack ≥ 0.3 mm width should be epoxy injected. All beams in the mosque should receive protection coating to provide barrier against ingress of moisture and chloride. Further shear enhancement of the beams could be made by the use of CFRP flex wrap or by insertion of L-shaped anchors, which would be activated upon the action of live load.

3. CASE STUDY II: INVESTIGATION OF STRUCTURAL DISTRESS IN SEAWATER CONVEYANCE SYSTEM

This case study is related to a seawater conveyance and disposal channel. The structure is nearly 1.5 km long and has two portions, each having a width of 27 m between the walls. The structural system consists of slabs resting on grade. The base slabs are rigidly connected to the foundation of the side retaining walls. The base slab had no previous expansion for crack control joints over a clear span of 21 m between wall footings. The rigid connection between the slab and the wall foundation is obtained by connecting the slab steel to the long dowels projecting from the wall/footing into the slab. Transverse expansion joints have been provided at either 8 or 15 m, depending on the bay width. The height of the wall is 4.75 m above the top of the footing (Figures 1 and 2).

The base slab of the structure developed cracks shortly after construction within a time span of 7–10 days from the end of curing. The cracking pattern of slabs on grade has been seen to be random and radial. The width of crack in the base slabs varied from ¼ mm–1 mm.

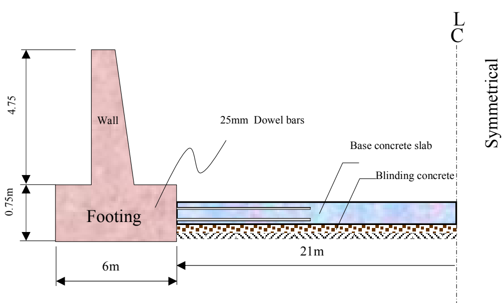

Figure 1. Typical sectional elevation of the structure

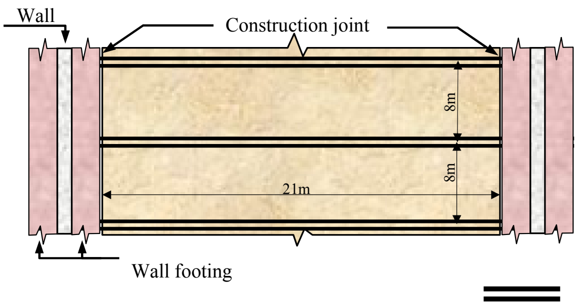

Figure 2.
Plan view of the structure

3.1 Assessment Of Causes Of Cracks

A combined experimental and numerical approach was adopted to assess the causes of cracks in the hydraulic conveyance system. Experimental investigations involving the measurement of evolution of the tensile strength, compressive strength, modulus of elasticity and free shrinkage strain was carried out on a concrete mix used in the construction of the hydraulic structure (Rahman, 1999; Baluch et al., 2000).

A finite element model of the structure was subsequently developed and the structure was analyzed for shrinkage-induced stresses in the system.

3.1.1 Experimental investigations

The tensile strength is an important index governing the failure/cracking in concrete structures subjected to tensile stresses. In the structure under consideration, the base slabs being restrained rigidly are subjected to a tensile state of stress, when the concrete shrinks due to loss of moisture (Rahman, 1999; Baluch et al., 2000). It was found experimentally that the tensile strength at 7 days at the onset of shrinkage was about 2 MPa. It increases to about 2.6 MPa at 14 days and 3.5 MPa at 28 days.

Evolution of compressive stress shows that at an age of 3 days the compressive strength is 23.5 MPa, which increases to 32 MPa at 7 days and 45 MPa at 14 days. The modulus of elasticity for this concrete mix is high. At an age of 7 days, E_c was computed to be 26.5 GPa which increased to about 32 GPa at 14 days.

The free shrinkage strain measured at the end of the testing period of 22 days was 375 μs under 23°C with RH = 55±5%. This value of 375 μs is well within the normal range of most concretes, and deemed acceptable by codes of practice of various countries.

3.1.2 Finite element analysis of the structure

In order to quantify the state of the stress in the restrained base slab, a finite element model of the structure was developed using the software STAAD-III (Research Engineer International, 1999). The computer model of the structure comprised of the base slab and vertical walls, which were modeled using, flat elements. The walls were assumed fixed at the footing.

This analysis considers 0.3 m thick slab supported on subgrade. The widths of the slab are 8 m and 15 m. The base slab is constrained not only at the walls but also from the subgrade, which offers frictional resistance to the movements due to shrinkage.

The finite element model of the structure consists of 451 nodes and 400 plate elements. Figure 3 shows the finite element discretization for the slab supported on grade. The following parameters were adopted in the analysis: A uniform volumetric shrinkage strain in the base slab elements of magnitude 200 microstrain was considered. A modulus of elasticity of 26.4 GPa as observed in the experimental investigation was adopted.

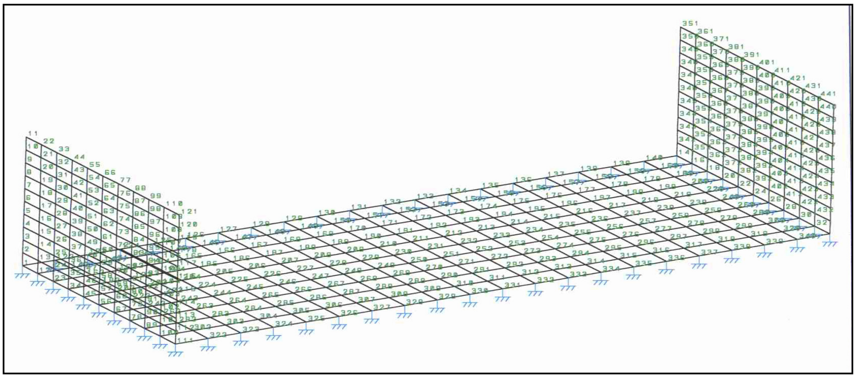

Figure 3. Finite element model of the structure

3.1.3 Results of analysis

Due to both restrained shrinkage and restraint of subgrade, the stress in the central zone of the slab increased to 7.8 MPa. It is at this location that the first crack would develop and later at other sections. Finite element analysis of the same slab in which structure was simulated to have cracked at 7 m and 14 m from edge revealed that stresses in a major portion of the base slab dropped to less than 1 MPa. These stresses are much lower than the tensile strength capacity of the concrete. This simulation essentially indicated the stress relief mechanism provided by the development of discrete cracks in the slab.

3.2 Recommended Strategy

Based on the analysis, the recommended jointing system for the discharge canal is one of *construction* joints at 7 m spacing i.e. demarcating the 21 m wide base slab into three segments (Figure 4).

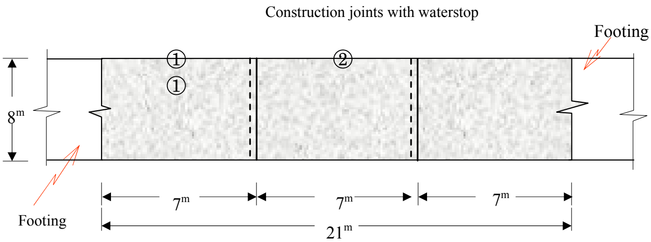

Figure 4. Recommended jointing system

4. CASE STUDY III: STRENGTHENING OF THE SUPPORTING SYSTEM OF A CYLINDRICAL LIQUID STORAGE TANK

Steel cylindrical tanks of 24 meters diameter and 18-meter height rest on an elevated support (Figure 5). The supports consist of two reinforced concrete slabs connected by columns. Following the hydro testing of the tanks, numerous cracks were observed in the top slab and columns supporting the elevated tank foundations. Significant differential settlement in the tank foundation base slabs was also observed. The foundation for each tank is constructed in reinforced concrete and takes the form of two flat slabs of octagonal shape in plan separated by a total of 25 columns of approximately 3.91 m height. The upper slab is 700 mm thick whilst the lower slab is of 800 mm thickness. The reinforced concrete columns are 800 mm by 800 mm in cross-section and contain 12 no. 22 mm diameter high yield steel reinforcement bars equally spaced around the perimeter.

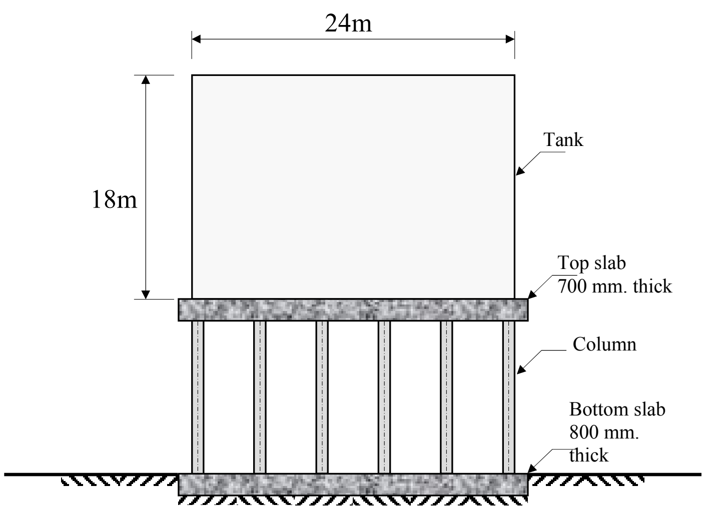

Figure 5. Elevation of liquid storage tank

4.1 Manifestation Of Distress And Cracking Patterns

With the exception of the four central columns, flexural cracking was observed within each existing reinforced concrete column. Cracking has been observed at the soffit of the upper slab. The width of these latter cracks has been estimated to be in the range of 0.3–1.0 mm. These cracks join together to form a grid pattern around the central four columns. A level survey of the base slab has been carried out. This revealed that the structure underwent significant differential settlement when loaded. Furthermore, much of this settlement remained as a permanent set when the load was removed.

4.2 Finite Element Modeling Of The Structure

The finite element modeling of the supporting structure has carried out by the original consultant using ANSYS (Version 5.6) (Ansys Manual, 2000). Each slab was modeled using 4-node shell elements whilst each column was modeled using beam elements. The soil was represented by a series of spring elements of stiffness 184.4 kN/m. The development of this three-dimensional numerical model was carried out in order to establish a detailed understanding of the behavior of the structure when subjected to the prescribed loads and the recorded differential settlements.

From the results of the finite element analysis of the tank foundation, it can be seen that the bending moment of resistance of the top and bottom slabs were exceeded in localized areas in the vicinity of the inner-most columns.

4.3 Final Assessment Of Strengthening

Out of all the options considered: (thickening the columns, or slabs), adding shear walls and using carbon fiber reinforced polymer CFRP for slab strengthening, the solution comprising of shear walls indicated a suitable method for enhancing the capacity of the structure along with, external reinforcing of top slab using CFRP was also adopted ensuring that ductility and crack serviceability requirements were met. Under serviceability state the following limits need to be satisfied: The maximum steel stress ≤ 60% of its yield (322 MPa). The maximum crack width on base slabs ≤ 0.3 mm.

The required area of carbon fiber in order to satisfy the above criteria calculated to 2430 mm^2/m width of CFRP for the central part and 1458 mm^2/m width of CFRP for the outside part of the plate. However, these quantities rendered the slab to be brittle and thus in order to form a collapse mechanism, a reduced area was recommended in order to make the system under-reinforced. The plates were embedded into the shear walls to avoid peeling failure (Khan, 2000). Presently, the two foundations have been instrumented and are under constant monitoring as the load in each tank approaches the full capacity level.

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5. CONCLUSIONS

Three case studies representing a wide spectrum of events triggering structural distress in RC structures have been documented and the importance of simulation of the structures using finite element models for consideration of various repair options has been highlighted. Although the arid and aggressive environment of the Gulf region presents a challenge to the construction industry, the tools that the consultant and practicing engineers e have in the form of computational model and innovative repair technology allows the engineering profession to meet the challenges.

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