Finite Element Analysis of Patch Repair in a Concrete Flat Slab

By

Samir E. Chidiac[1] and Noel P. Mailvaganam[2]

Introduction

Résumé

Many of today's ageing reinforced concrete structures have reached or exceeded their expected service life and a significant number of newer structures exposed to severe environmental conditions are showing premature deterioration within 20 years of construction (Mehta, 1991). Concrete structures deteriorate due to a number of processes such as electrochemical processes (i.e. corrosion of the steel — Photo 1), physical process (such as freeze thaw — Photo 2), chemical processes (such as chemical attack, sulphate attack, alkali-aggregate reaction, — Photo 3) and mechanical damage. These processes lead to a physical manifestation of either shrinkage or expansion of the concrete which then result in the cracking and spalling of the concrete. To date, the strategy has been repair and rehabilitation rather than replacement. However, repair not only has a more recent history, it does not have established codes from which a proper design can be done.

It is expected that the majority of structures being repaired will not survive their full design life and that in some cases the deterioration rates will be accelerated due to the deficiencies in design, specifications and quality control of the repairs (Emmons and Vaysburd, 1996). These premature failures of the repair systems are often due to misunderstanding of the causes of the problem where solutions are derived based on the symptoms. As noted by Emmons and Vaysburd (1996), a proper understanding of the interaction of the repair systems with the existing concrete substrate is required to ensure future performance of the repaired structure.

This paper presents information on the factors that influence the performance of patch repair in concrete flat slabs, namely the in-service exposure conditions, compatibility requirements and construction practices. The significance of property mismatch between the repair material and the existing reinforced concrete structure is illustrated through an analytical study that determines the performance of a patch repair. It is concluded that analytical methods could be an effective tool in the proper selection of repair material and techniques.

1. President, CHIDIAC & Associates Limited, Gloucester, ON K1J 1A3, Canada
2. Senior Research Officer, National Research Council Canada, Institute for Research in Construction, Ottawa, ON K1A 0R6, Canada

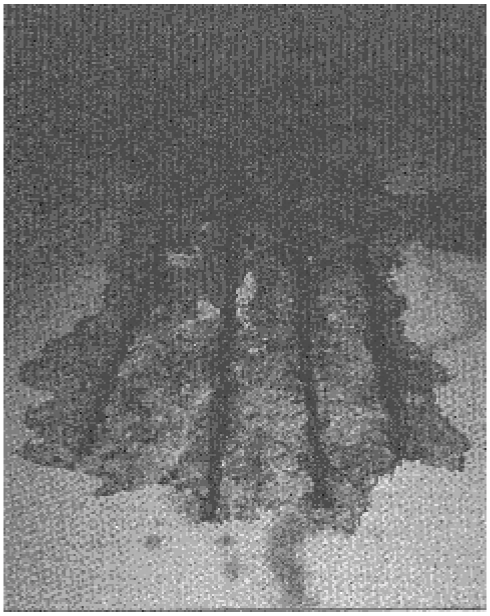

Photo 1 Corrosion of reinforcing steel

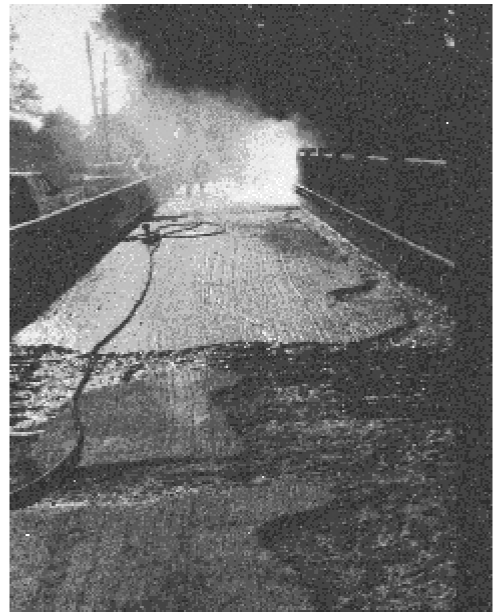

Photo 2 Gritting due to freeze-thaw action

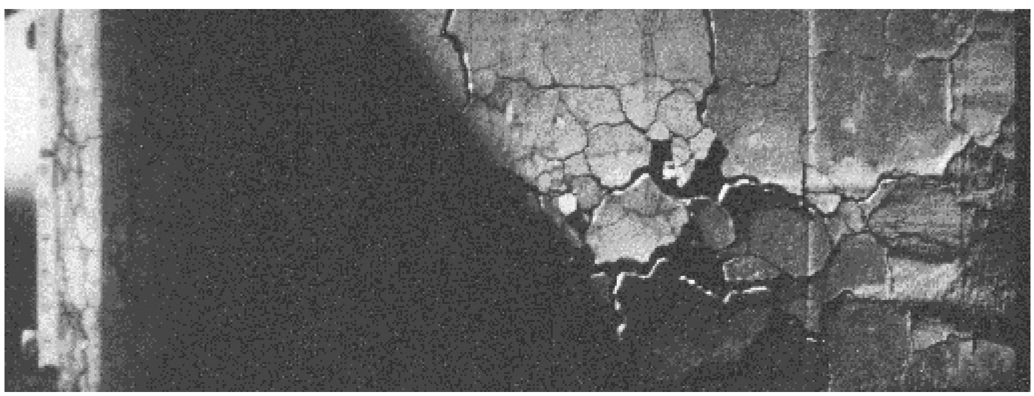

Photo 3 Cracks induced by AAR

Patch Performance Requirement

The functional requirements for concrete patches as a repair system for an existing concrete flat slab are primarily durability and serviceability. The majority of the serviceability requirements for the patch are usually addressed in the durability requirements. The exceptions are structural requirements such as vibration, deflection, etc. The durability requirements of the patch are two-fold: first, to reduce the rate of the prevailing mechanism of deterioration, and second to be compatible with the existing system so that its interaction with the substrate does not initiate another durability problem. This necessitates that the patch's mechanical, physical, chemical and electrochemical properties are similar to that of the existing reinforced concrete structure. Although meeting such requirements is not a straightforward, the design for an effective repair system can be accomplished by establishing a priority list of these requirements and being cognizant of how they influence the behaviour of the repaired structure.

Factors Influencing Patch Performance

Lack of comprehensive data and suitable guidelines for concrete repair has been identified as a leading factor in the premature failures of some current innovative techniques and materials. Thus the fundamental questions concerning the long-term performance of repair systems in a given environment cannot be predicted using current standards and specifications. The difficulties arise from the need to quantify the followings:

1. properties of the environment including the operating loads,
2. properties of the reinforced concrete substrate, and
3. properties of the repair materials.

The interaction of the patch with the environment to which the repaired structure is exposed is essential to estimate its performance. Exposure conditions, such as the macro-environment, depend largely on the geographical location of a structure (temperature, relative humidity, rainfall, snow, etc.), and the topography and demography near the structure (prevailing wind, type and concentration of pollutants, etc.). Also, they depend on the operating loads to which the structure is subjected. These actions are not easily quantifiable due to their continuous variation with time and location. However, quantification of environmental parameters is essential to design for durability.

The performance of the concrete repair system is likely to be controlled by the compatibility of the components of the system. Compatibility is typically defined as a balance of physical, chemical, electrochemical and thermal properties between the repair materials and the existing concrete substrate. Material compatibility ensures that a repair withstands all stresses induced by volume changes, chemical and electrochemical effects without distress and deterioration in a specified environment over a designed period of time. Effective material compatibility, however, is not necessarily accomplished by a match, per se, of the individual properties. Instead, the repair material properties should be appropriate for the substrate, its environment, and the design life of the repair.

Previous studies (Chidiac et al., 1997a, 1997b; Emberson and Mays, 1995; Cleland et al., 1993) have shown the following:

1. The modulus of elasticity of a patch repair material as compared with that of the substrate concrete influence the distribution of stress in the area surrounding the patch repair. It is recommended that the ratio of the modulus of elasticity of the repair material to that of the substrate lie within 0.75 and 1.25.
2. The Poisson's ratio of a patch repair material is a second order effect.

3. The tensile strength of the repair material is important to enhance the fatigue performance of concrete structures.
4. The significance of the property mismatch is dependent on the geometry of the patch.

The performance of patch repair is also influenced by the method of construction such as surface preparation, placement method and curing conditions. Cleland et al. (1993) have investigated the influence of surface condition on adhesion strength. Their results have indicated that both the grit blasting and the water jetting are effective and that the influence of surface texture on adhesion strength is not very significant. Hutchinson (1993) investigated the adhesion mechanism operating between the repair materials and concrete surfaces. Hutchinson's results indicate that the water jetting yields the highest bond strengths because of macro-rough, dust free and damp surface. The significance of partial de-bonding at the interface between the repair material and the substrate was investigated analytically by Chidiac et al. (1997b). Their results have indicated that the poor bonding of the patch is as critical as the mismatch of properties.

The placement method and the curing condition of the repair material are important factors for controlling the physical and mechanical properties (Chidiac et al. 1997c; Dhir et al, 1996). Dhir et al.'s investigation have shown that the placement method and curing conditions influence the pore structure of the concrete core. Further, Chidiac et al's experimental results have indicated that the level of vibration and type of form have a direct impact on the quality of the concrete cover. These factors lead to broader mismatch in the properties of the repair patch.

Cairns (1993a, 1993b) has evaluated experimentally and analytically the changes in the structural behaviour of reinforced concrete members caused by exposure of the reinforcement during repair. The study shows that a model can be developed to investigate the length of the bar that can be exposed without any loss in the structural capacity of the member. Further, similar analytical models can be used to estimate the residual capacity of damaged reinforced concrete slabs due to corrosion, impact, etc. (Eyre, 1992).

Analysis of Patches in a Concrete Flat Slab

Three case studies are presented to illustrate the significance of factors such as exposure conditions, compatibility of the system and flexural properties in assessing the performance of the repair system. The model consists of a concrete bridge deck with a span of 7.0 m wide and 0.3 m thick, and where the patch is located at the centre of the deck and has the following geometry, 0.5m x 0.5m x 0.1m, Figure 1. The deck is discretized using four node quadrilateral plane-strain finite elements. The material behaviour is assumed linear and elastic with the exception of the third case where a contact boundary is introduced to model a poorly bonded patch. The thermo-mechanical properties of the existing concrete substrate and the patch used in the analysis are given in Table 1.

Table 1

Mechanical and Thermal Properties used in the Analysis of the Concrete Deck

Properties	Concrete substrate	Concrete patch
Modulus of elasticity (GPa)	20	35
Poisson’s ratio	0.25	0.25
Coefficient of thermal expansion	1 E - 06	6.2 E - 06
Thermal conduction (W/mK)	1.6	1.6
Density (kg / m^3)	2000	2200

Table 2

Maximum Deflection, Effective and Bending Stresses due to Structural Loading.

	Before repairing		After repairing	
	UDL	Partial	UDL	Partial
Deflection (mm)	2.8	1.8	2.1	1.3
Max. effective stress (MPa)	5.1	2.9	4.6	2.6
Max. compressive stress (MPa)	5.8	3.3	5.2	3.0
Max. tensile stress (MPa)	1.6	1.5	1.4	1.3

Table 3

Maximum Deflection, Effective and Bending Stresses due to Structural and Thermal Loading

	Before repairing		After repairing	
	UDL	Partial	UDL	Partial
Max. effective stress (MPa)	3.31	2.2	4.39	3.7
Max. compressive stress (MPa)	4.0	2.5	4.6	3.9
Max. tensile stress (MPa)	2.3	2.2	2.1	2.1

Table 4

Maximum Deflection, Effective and Bending Stresses due to Structural & Thermal Loading with a Poorly Bonded Patch.

	Before repairing		After repairing	
	UDL	Partial	UDL	Partial
Deflection (mm)		2.0	2.4	1.6
Max. effective stress (MPa)	3.31	2.2	4.0	3.4
Max. compressive stress (MPa)	4.0	2.5	4.2	3.5
Max. tensile stress (MPa)	2.3	2.2	1.8	1.8

Concrete Patch Subjected To Structural Loads

The effects of mechanical compatibility on the performance of the patch was investigated using two loading conditions; a uniformly distributed load with a magnitude of 10 kN/m applied to the top surface of the deck; and a 50 kN/m load applied to one end of the patch as shown in Figure 1. Results obtained from the two cases are summarised in Table 2. The results show that in comparison to the unrepaired deck, the maximum effective stresses and maximum bending stresses in both tension and compression decrease with the introduction of the patch. The same pattern was observed for the maximum deflection. However, the location of the maximum tensile stresses shifts from the bottom surface of the deck to the bottom of the patch. In summary, the mechanical incompatibility of the patch due to higher values for the modulus of elasticity did not lead to higher values of bending or effective stresses.

Concrete Patch Subjected to Structural and Thermal Loads

The influence of thermal compatibility on the performance of the patch was investigated by additionally subjecting the slab to a thermal gradient of 35°C across its thickness, Figure 1. Table 3 summarises the values obtained for the case before placement and after the placement of the patch in the middle of the deck. In contrast to the previous case, the values of maximum effective stresses and compressive bending stresses increased after the introduction of the patch. This is expected to occur due to the thermal load. However, the location of the maximum values have shifted to area where the patch is located. The maximum bending stresses in tension have decreased slightly and remains in the centre and at the bottom surface of the deck.

Closer examination of the stress distribution has revealed that bending stresses in tension have been generated near the location of the patch. It should be noted that although the values are less than 1 MPa, these values form part of the loading imposed on the patch and thus add to the potential premature failure of the patch.

Poorly Bonded Patch Subjected to Structural Loads

The influence of poorly bonded patch is modeled using a contact boundary. This is modeled by creating a space between the patch and the substrate at the bottom left corner as noted in Figure 1. Similar to the first case, two loading conditions are presented. The results are summarised in Table 4. The values for maximum effective and bending stresses have increased when a cavity (due to de-bonding) is introduced to the patch. The changes in the stress values are more evident when the patch was partially loaded. In this case a maximum tensile stress previously located at the bottom surface of the deck has now shifted to the interface between the patch and the deck. The computed maximum tensile value is 1.8 MPa. This value is very near the tensile capacity of the patch near the de-bonded zone, making it prone to further cracking.

Conclusions

The following conclusions can be drawn from the analysis presented:

1. Current literature on repair of concrete structures emphasis the following requirements for selection of repair systems: a) compatible material properties between the repair material and concrete substrate, b) knowledge of in-service exposure conditions, and c) understanding of the initial causes of concrete deterioration. There is however, lack of consistent information on the influence of these factors on the interaction of the components in the repaired zone.
2. In the absence of knowledge and experience, the requirements for repair system to withstand the operating loads in a given environment for a specified design life is not straightforward. For these cases, analytical models can be used to provide insight into the performance of the repaired structure taking into consideration the properties of the existing concrete structure and the repair material, the operating loads, and the severity of the exposure conditions. However, it should be noted that existing analytical models cannot model synergistic effects and it cannot compensate for the ageing of concrete.
3. Analytical models can also be used to analyse the early age of the repair system, the effects of cracks and poor bonding between the repair material and the substrate, and the effects of operating load on the structure during repair and on the repair material shortly after its placement — traffic vibration, etc.
4. The analysis of stresses and deformations for the repaired concrete slab using patches subjected to structural and thermal loads have demonstrated the following:
    - the compatibility problems arises due to mismatch of thermo-mechanical properties,
    - the mismatch of properties between the existing concrete structure and the patch repair will most likely result in the initiation of cracks at the corner of the interfacial material, and
    - while compatibility problems can arise through a mismatch of properties, often factors involved in placing and curing of the patch have primacy in determining long term performance.

References

Cairns, J. (1993a) Behaviour of concrete beams with exposed reinforcement, Proc. Instn. Civ. Engrs Struct. Build., Vol. 99, May, 141-154.

Cairns, J. (1993b) Load relief during structural repairs to reinforced concrete beams, Proc. Instn. Civ. Engrs Struct. Build., Vol. 99, November, 417-427.

Chidiac, S.E. (1996), Covercrete - Simplified method for predicting service life of concrete, Proceedings of the Two-Day CANMET/NRC/ACI International Workshop on Developments in Repair Materials and Strategies for the Rehabilitation of Infrastructure and Buildings.

Chidiac, S.E., Noruziaan, B., and Mailvaganam, N. (1997b), Service life prediction of reinforced concrete repair system, CHIDIAC & Associates Ltd. Technical report no. DC961121.1, Ottawa, Canada.

Chidiac, S.E., Cheung, M.S. and Mailvaganam, N. (1997b), Service life of patches in concrete flat slabs, Appearing in the Proc. of the ANS Symposium, Waterloo, Canada.

Chidiac, S.E. (1997c), Investigation & validation of Covercrete concept, CHIDIAC & Associates Ltd. Technical report no. DC960326.1, Ottawa, Canada.

Cleland, D.J. et al. (1993), Concrete repairs — dependence on site conditions. Final report on SERC Grant GR/F02779, Queen's University, Belfast.

Dhir, R.K., Hewlett, P.C. and Dyer, T.D. (1996), Influence of microstructure on the physical properties of self-curing concrete, ACI Materials Journal, Vol. 93, 465-471.

Emberson, N.K. and Mays, G.C. (1996), Significance of property mismatch in the patch repair of structural concrete. Part 3: Reinforced concrete members in flexure, Magazine of Concrete Research, Vol. 48, No. 174, 45-57.

Emmons, P.E. and Vaysburd, A.M. (1995), The total system concept - Necessary for improving the performance of repaired structures, Concrete International, March, 31-36.

Eyre , J.R. and Nokhasteh, M.A. (1992), Strength assessment of corrosion damaged reinforced slabs and beams, Proc. Instn. Civ. Engrs. Struct. Build., Vol. 94, May, 197-203.

Hutchinson, A.R. (1993), Adhesion of repair materials to concrete and steel, Final report on SERC Grant GR/F88087, Brookes University, Oxford.

Mehta, P.K. (1991), Durability of concrete - Fifty years of progress?, ACI, SP-126, Editor: V.M. Malhotra, 1-32.

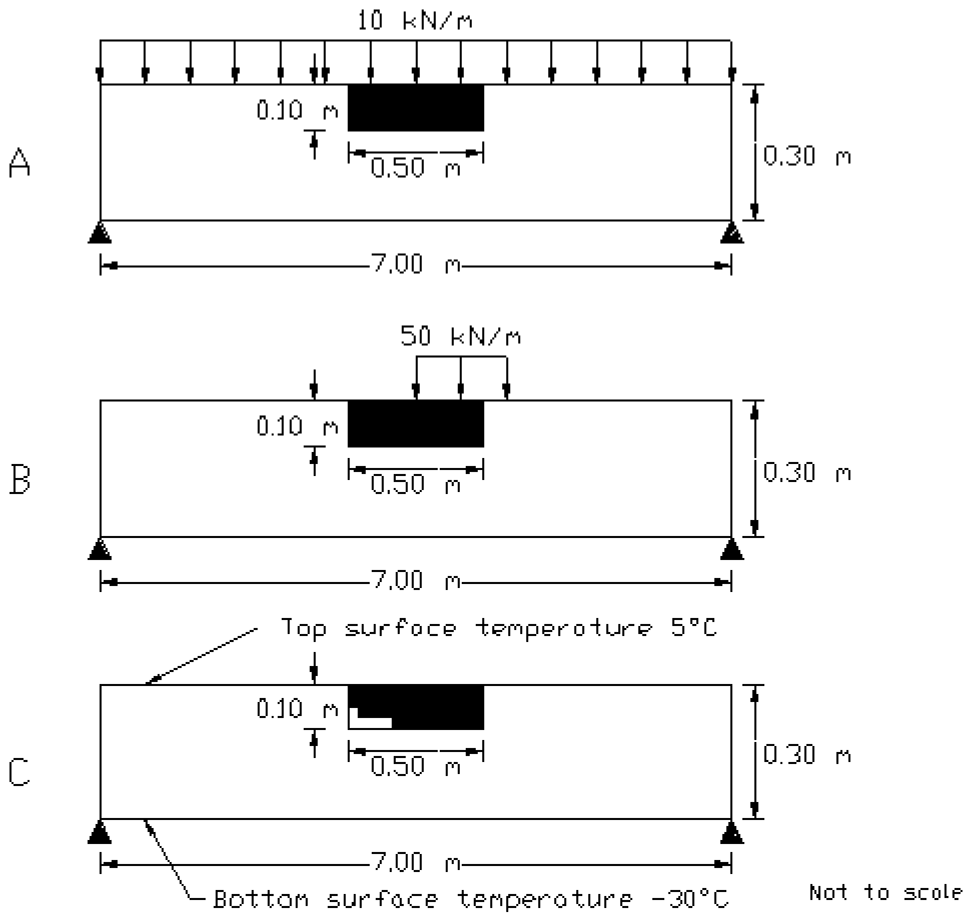

Figure 1. Model of the concrete deck —
A) subjected to uniform distributed loads,
B) subjected to partial loading,
C) subjected to thermal loading with a poorly bonded patch.