PERFORMANCE OF CONCRETE SYSTEMS REPAIRED USING FIBER REINFORCED PLASTICS

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SUMMARY: The popularity of using fiber reinforced plastics (FRP) to repair deteriorated and deficient infrastructure is increasing around the world. However, influences of existing damage and environmental conditions on the integrity and durability of the repaired systems are not well known. These influences must be evaluated before safe, reliable, and durable repair of concrete systems with FRP is possible. This paper investigates performance of reinforced concrete systems retrofitted with FRP as influenced by existing damage parameters in the system. First, failure modes and design parameters of systems retrofitted with FRP materials are reviewed. The importance of damage conditions such as existing cracks in the concrete and deteriorated materials are discussed. Then, the influence of existing cracks in concrete beams is studied through an experimental program. The presence of cracks is shown to initiate debonding fracture well before the ultimate load of the system. A fracture mechanics based approach is used to analyze the bi-material fracture and delamination scenarios created at the concrete-adhesive-laminate interfacial region. Criteria based on energy release rate concepts are considered for the prediction of crack path and delamination process zone growth. From the testing and a numerical analysis, fracture parameters influencing the delamination process are identified and investigated. Possible influences of environmental loading conditions are examined. Finally, the influence of these issues on design and evaluation procedures of concrete systems repaired with FRP is discussed.

KEYWORDS: Composite Laminate, Retrofit, Damage, Cracking, Environmental Performance.

INTRODUCTION

The use of fiber-reinforced plastics in infrastructure rehabilitation and retrofitting offers great potential for efficient increases of load carrying capacity and restoration of system integrity in reinforced concrete structures. Consequently, the use of FRP bonded to deteriorated and damaged reinforced concrete structures is rapidly gaining popularity worldwide; high strength FRPs have been used to retrofit concrete members such as columns, slabs, beams, and girders in structures such as bridges, parking decks, smoke stacks, and buildings.

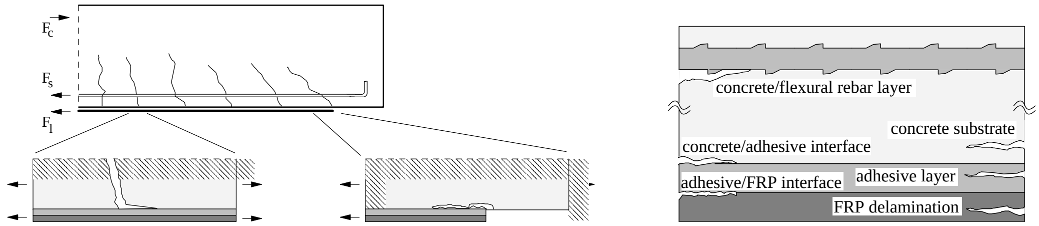
Studies of FRP composites bonded to the tension face of concrete beam elements by researchers have demonstrated that theoretical gains in flexural strength can be significant. However, new types of failure modes involving delamination of the FRP, debonding of concrete layers, and shear collapse can occur at loads significantly below the theoretical flexure strength of the system. Among these failure modes, debonding or peeling of the FRP from the concrete surface at locations of existing damage conditions is a major concern. There is a need for improved understanding of the role of delamination in system failure and techniques for using local failure criteria to evaluate the integrity of the retrofit system with respect to existing damage conditions. Additionally, information on the behavior of these processes under adverse conditions such as environmental and high intensity loading cycles is not widely available.

This paper investigates performance of reinforced concrete systems retrofitted with FRP as influenced by existing damage parameters in the system. First, the influence of damage conditions such as existing cracks in the concrete and deteriorated materials are discussed. Then, the influence of existing cracks in concrete beams on the delamination process is studied in an experimental program. An analytical procedure is then conducted to develop based on energy release rate concepts for delamination process zone growth. Finally, parameters influencing this process with respect to durability under adverse conditions are discussed.

DELAMINATION IN FRP RETROFITTED CONCRETE SYSTEMS

FRP retrofitted reinforced concrete has been observed to fail through a variety of modes, which can be grouped into distinct categories including flexural failures, shear failures, and debonding failures [1]. A common debonding mode is delamination failure of the laminate, adherent, and a thin layer of concrete substrate peeling off of the concrete structure. Delamination in rehabilitated structures and research programs has been observed [2,3]; for these reasons, interest has increased in delamination processes, criteria, and characterization methodologies.

Delamination can be caused by a number of reasons, including cyclic loading induced debonding, environmental degradation, existing damage conditions, and other application and design specific flaws. Among these damage parameters, delamination initiating from existing cracks or from the end of the laminate has been concluded to be highly influential in retrofitted beam members [3]. These failure processes are caused by local stress intensities in the concrete beam-adhesive-laminate interfacial region, as illustrated in Figure 1(a) [4,5]. These intensities can initiate microcracking in the system at early load levels, which can form in any of the constituent materials or their interfaces, as illustrated in Figure 1(b). This process was studied in an experimental program where the delamination zone was monitored with gauges, magnifying cameras, and ultrasonic evaluation [6]. It was shown that microcrack development begins well before system failure and ends when the microcracks propagate and coalesce, forming macrocracks that can result in system failure. From these studies, the constituent material’s critical fracture energy was shown to be an effective criteria for propagation of this local process zone.



(a) Local stress intensities (b) Possible microcrack locations

Figure 1 Local stress intensities and microcrack initiation scenarios

This type of knowledge offers great potential in understanding and evaluating system integrity in terms of local damage conditions including the peeling scenario from existing cracks in the concrete beam. However, quantitative information on delamination processes in these zones is limited. Additionally, the influence of the length of laminate bonded beyond the location of this damage condition must be evaluated. Thus, there exists a need for isolated study of delamination mechanisms at these local damage conditions of cracks in the concrete beam.

EXPERIMENTAL PROGRAM

In order to study the process of shear crack peeling, an initially notched shear crack laboratory specimen was developed. The objectives of the experimental program were to isolate and monitor the delamination process development from an existing crack in the concrete beam, and to investigate influences of bonded laminate length (development length) past the initial notch. To meet these objectives, concrete beam specimens containing initial shear notches were created with various lengths of bonded FRP laminate.

Specimen

To isolate the initial shear notch delamination process from other failure processes, a four-point delamination beam specimen was designed with over-reinforced shear capacity outside of the initial notch location, as shown in Figure 2. The beam specimens were designed to be retrofitted with carbon FRP (CFRP) laminate that would increase the flexural capacity by 40%. To prevent shear cracks from influencing the delamination process from the initial notch, the beams were over-reinforced in shear strength to 175% of the retrofitted capacity outside the initial notch locations. Delamination was studied by propagation from the initial notch towards the end of the laminate. Three locations of the initial notch, *c*, were studied with three lengths of laminate extending past the notch for each location, defined as the development length l_d.

Materials

The concrete beam specimens were created with 7-day normal strength concrete with 10 *mm* maximum aggregate size and a *w/c* ratio of 0.5. In addition to compressive and tensile strength testing, the fracture energy of the concrete was measured at 42.6 J/m^2 using the RILEM Technical Committee 89-FMT suggested three point testing specimen. The internal reinforcement in the beam specimens consisted of (2) #3 (ϕ=9.5 *mm*) reinforcing bars for both tensile and compressive steel. Shear stirrups were made from the same bars. The external reinforcement consisted of CFRP laminate 1 *mm* $\times$ 50 *mm* containing a fiber volume fraction of 70% with an epoxy matrix. The adhesive used was a high-strength high-modulus epoxy paste specifically designed for bonding to concrete surfaces applied with an average thickness of 1 *mm*. Properties of the materials used are listed in Table 1. Beam specimens were

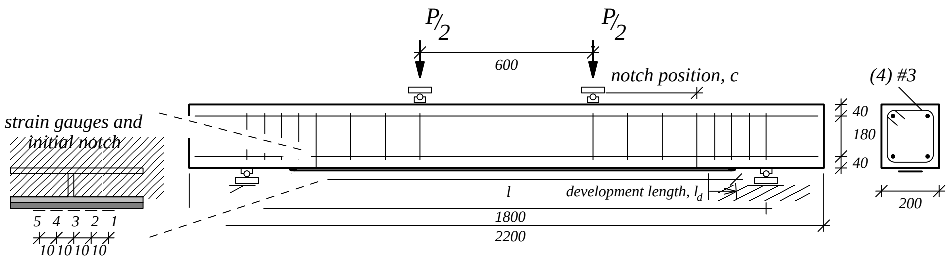


Figure 2 Initial shear notch delamination test specimen

manufactured and allowed to cure for at least 7 days. The surface to be retrofitted was roughened with a pneumatic hammer until the aggregates were exposed. The initial shear notches were created with a thin diamond saw blade to the depth of the flexural steel and filled with putty during lamination. Various lengths of laminate were applied to the beams and allowed to cure for at least 24 hours. Strain gauges were placed in the vicinity of the notch, and a magnifying camera was used to monitor the notch location.

Experimental Results

The shear notch specimens were tested in four point bending under monotonically increasing load. All specimens were observed to fail through delamination; ultimate loads are given in Table 2. In specimens with longer laminate lengths, significant shear cracking was also observed in addition to the delamination. Mid-span deflection curves, shown in Figure 3, indicate traditional nonlinearities at cracking of the concrete and plasticity of the steel. Stiffnesses and ultimate loads are shown to increase with longer laminate lengths.

Results from the strain gauges indicate an intensity in the laminate longitudinal stress in the vicinity of the initial notch. This intensity is created by the discontinuity of bonding between the beam and the plate and represents the variation in bonding stresses as force is transferred across the crack mouth. Results from the strain gauges during the load history indicate stress redistribution at loads well below the ultimate capacity, as shown in Figure 4. As the zone of bond softening around the initial notch mouth expands under increased loading, transfer of force from the concrete beam to the laminate also expands, causing the intensity to appear to widen. This process was observed to occur before the ultimate load in all the tested specimens; the load level where this process was observed to reach the first strain gauge beyond the initial notch is reported as the delamination load in Table 2. This load level can be quantitatively defined as the load stage where the rate of strain of the notch gauge increases with respect to load ($d\varepsilon/dP$) as load is transferred from the rupturing concrete to the delaminating FRP. The delamination load level is evaluated from the strain gauge loading history by estimating the initiation of the increase in the strain gauge gradient. This evaluation technique is sensitive to the location of the gauge with respect to the initial notch,

Table 1 Properties of materials used in the experimental program

Material	Tensile strength *[MPa]*	Compressive strength *[MPa]*	Elastic modulus *[Gpa]*
Concrete	2.8	20.5	25.4
Steel	418.0	-	210.0
Adhesive	24.8	-	2.7
CFRP laminate	2100.0	-	155.0

Table 2 Results of initial shear notch specimens

Notch location c *[mm]*	Development length l_d *[mm]*	Ultimate load *[kN]*	Delamination load *[kN]*	Calculated energy release *[J/m²]*
150	75	76.5	76.1	87.6
	150	94.7	62.3	61.7
	225	123.4	71.2	74.2
300	75	117.6	88.6	70.0
	225	134.3	85.9	66.3
	275	144.6	100.8	90.8
450	75	115.6	110.0	26.8
	125	135.6	123.3	33.9
unlaminated	-	48.2	-	-

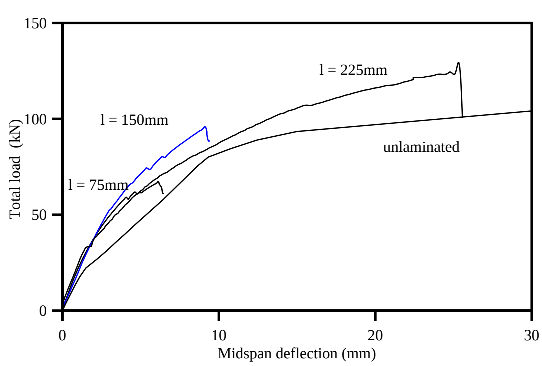
which may explain some of the scatter in the delamination load reported in Table 2. Influences on this process are examined by individual parameter.

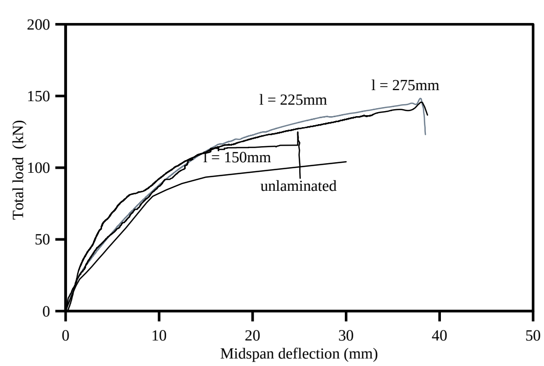
Effect of Notch Location

Three initial notch locations *c* were tested in the experimental program. Delamination loads are shown to increase with longer notch distances from the load line. This is due to the lower stresses in the notched region as the applied moment is decreased with shorter notch distances from the beam support.

Effect of Development Length

For each initial notch location, three development lengths were tested. Figure 5 shows the ultimate loads of the beams plotted with respect to the laminate development length. Similar trends are observed regardless of the initial notch location; the ultimate load of the beam increases with the development length. From this, it can be concluded that increasing development lengths might provide greater ductility and extend the duration of the delaminating process before the ultimate load. This process was further studied in an analytical procedure.





(a) *c = 150* (b) *c = 300*

Figure 3 Experimental mid-span deflection curves

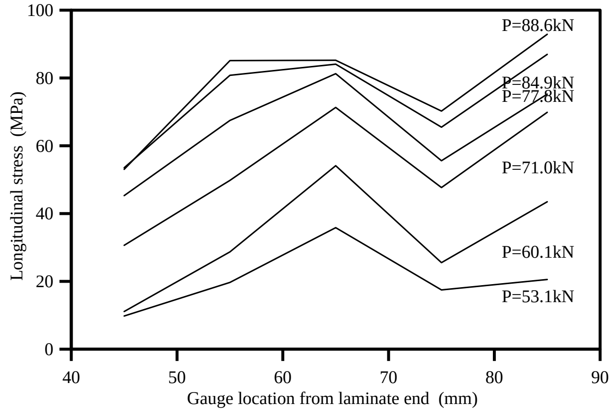


Figure 4 Laminate stresses with load history for the beam with *c=150, l=150*

ANALYTICAL PROCEDURE

In plate strengthened reinforced concrete members, bond action has been grouped into three distinct zones including (i) anchorage of plate end, (ii) shear force and moderate bending, and (iii) high bending moment with low shear [4]. The initial notches studied in this experimental program all lie within the second zone, with shear force and moderate bending moments. This analysis will be limited to this zone, where bond stresses are caused by the variation of bending moments along the beam and by force transfer at cracks. First, the elastic stress distribution of the force transfer zone at the location of notches will be examined. Then, the use of an energy based criteria for delamination from these crack damage zones will be developed.

Microcrack Strength Criteria

Researchers have investigated the force transfer at locations of cracks in the concrete beam and have presented closed form solutions to the elastic shear and normal interfacial stresses near a crack [5,8]. The solution to the differential equation governing the laminate longitudinal stress is in the general form dependent on the initial crack location. The constants of integration in the differential equation can be solved by assuming the axial stress in the laminate at the crack location ($x=0$) and at a location outside the transfer zone ($x=l_{tz}$) are known. Substituting these boundary conditions into the closed form solution yields, for small x within the transition zone

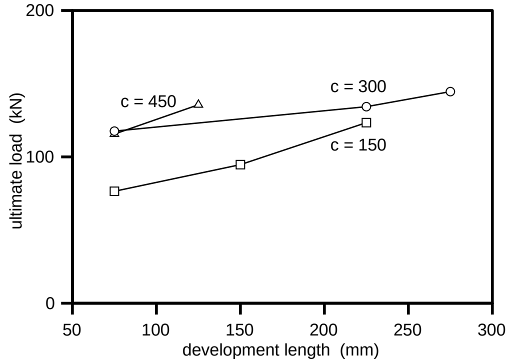


Figure 5 Ultimate load versus development length for various initial notch locations

$$\sigma_l(x) = \left[\sigma_{l_1} - \tfrac{E_l}{E_c}\sigma_c(x=0)\right]e^{-\omega x} + \tfrac{E_l}{E_c} f_c(x) \tag{1}$$

where σ_l is the longitudinal stress in the laminate, σ_{l1} is the known stress at the crack location,

$$\omega^2 = \frac{\mu_a}{t_a t_l E_l} \tag{2}$$

where μ_a is the shear modulus of the adhesive, E_l is the elastic modulus of the laminate, and t is the thickness of these layers. The stress in the concrete $\sigma_c(x)$ can be estimated with elastic flexure formula

$$\sigma_c(x) = \frac{My}{I_{tr}} = \frac{P(C-x)y}{2I_{tr}} \tag{3}$$

where the terms $P(C\text{-}x)/2$ describe the applied moment on the section as a function of the notch distance from the reaction C, the distance from the section neutral axis to the bottom concrete fiber y, and the transformed moment of inertia of the section I_{tr}.

From elementary momentum balance and from assuming constant shear stress in the laminate, the bond stress is given by

$$\tau(x) = \frac{\partial\sigma_l(x)}{\partial x}t_l = t_l\left[\left(\frac{E_l}{E_c}\frac{PCy}{2I_{tr}} - \sigma_{l_1}\right)\omega e^{-\omega x} - \frac{E_l}{E_c}\frac{Py}{2I_{tr}}\right] \tag{4}$$

These results indicate the shear intensity at the notch can be related to the axial stresses in the laminate at the shear notch location. When subjected to a monotonically increasing load, this intensity causes cracking in the concrete at low load levels because the shear strength of the concrete ($\tau_{max} = 0.166 f'^{\,1/2}_c = 0.9MPa$) is exceeded early. Equation (4) can be solved in terms of concrete shear capacity (τ_{max}) at the notch location $x=0$

$$\sigma_l = \frac{E_l}{E_c}\frac{Py}{2I_{tr}}\left[C - \frac{1}{\omega}\right] - \frac{\tau_{\max}}{t_l\omega} \tag{5}$$

For the system studied in this paper, the first term in Equation (5) evaluated at $c = 300mm$ becomes negligible at low loads and can be reduced to terms of a maximum allowable laminate stress intensity

$$\sigma_{l_{\max}} = 4.61\tau_{\max} \tag{6}$$

which occurs below $P = 5kN$ and indicates the initiation of the microcracking, which will occur in the concrete for the system tested in this section and initiate the bond softening zone. However, once the microcracking has initiated, this elastic stress solution is no longer valid and energy methods must be applied to assess the integrity of the system.

Energy Based Criteria

The applied crack driving force at the initial notch can be evaluated using energy methods [6]. The elastic energy contained in a beam structure under bending and shear forces M and V can be estimated by integrating the normal and shear stresses over the cross sectional area. The beams tested in this investigation can be discretized into divisions of similar cross sections and applied loading. The delamination process in the tested beams is simulated by advancing the delamination location of a by da, and transforming the laminated section (EI_l and GA_l) to equivalent unadhered, delaminated section (EI_u and GA_u) where EI_i and GA_i are the discrete section bending and shearing stiffnesses dependent on the integral load level, respectively

$$\frac{dW}{da} = \frac{M_a^2}{2b}\left(\frac{1}{EI_u} - \frac{1}{EI_l}\right) + \frac{V_a^2}{2b}\left(\frac{k_u}{GA_u} - \frac{k_l}{GA_l}\right) \tag{7}$$

where k_u and k_l are constants in the calculation of shearing stresses of the cross section and b is the width of the beam [8,9]. The unadhered section EI_u at the initial notch can be estimated by taking moments of areas about the neutral axis ch

$$EI_u = \frac{E_c b_c (ch)^3}{3} + A_s E_s (d_s - ch)^2 + E_l A_l h^2 (1-c)^2 \tag{9}$$

where E_i is the elastic modulus of material i (=c for concrete, s for steel, and l for laminate), b_c is the width of the concrete, A_s and A_{FRP} are the areas of the reinforcing steel and FRP laminate, and d_s is the depth to the reinforcing steel. Strain compatibility and force equilibrium methods can be used to find neutral axis depth ratio c of beam height h

$$c^2[h] + c[h\eta_s\rho_s' + 2h\eta_s\rho_s + h\eta_l\rho_l] - 2[d'\eta_s\rho_s' + d\eta_s\rho_s + h\eta_l\rho_l] = 0 \tag{8}$$

where η_s and η_l are stiffness ratios of the reinforcing steel and laminate to the concrete and ρ_s, ρ'_s, and ρ_l are reinforcement ratios of the tensile steel, compressive steel, and laminate, respectively. The adhered section EI_l can also be evaluated using these conventional methods and by assuming the full concrete section is intact and able to transfer shear to the laminate ($c = h/2$)

$$EI_l = \frac{E_c b_c h^6}{24} + A_s E_s (d_s - \tfrac{h}{2})^2 + E_l A_l h^2 (1 - \tfrac{h}{2})^2 \tag{10}$$

This assumption is supported by the concept of minimum crack spacing and the implicit supposition of whole section between cracks.

Applied crack driving forces for the system at load levels corresponding to fracture initiation at the notch strain gauge were calculated using this analytical procedure, as shown in Table 2. It is shown that the energy released in the experimental program at the initiation of

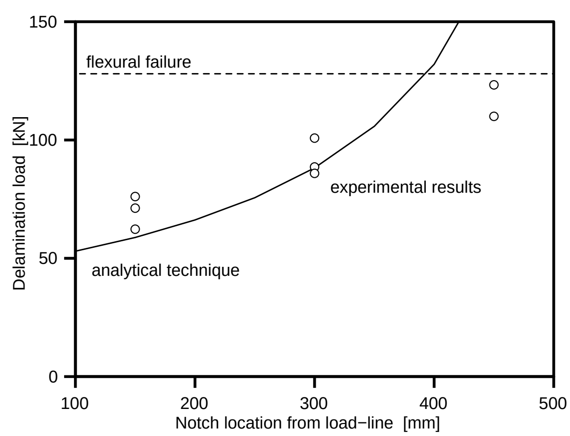


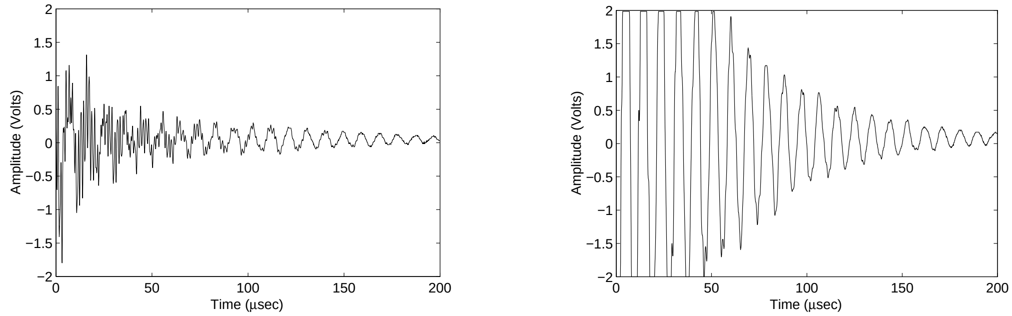
Figure 6 Comparison of analytical procedure to experimental results

delamination at the location of the notch strain gauge remained relatively independent of both notch location and laminate development length. The values for the notch located at *c=150mm* may be lower than average due to shear cracking also observed in these specimens at the point of delamination.

Since the energy release rate derived from the experimental program remained relatively constant and independent of the experimental parameters, the use of the critical energy release rate as a delamination criteria was investigated. The analytical procedure for calculating the energy release rate from the applied loading was conducted in reverse through an iterative computational routine. Because failure in the experimental program was observed to occur in the concrete substrate, the fracture energy of the concrete (G_f = 42.6 J/m^2) as the delamination criteria dW/da. An incremental load loop was repeated using increasing load levels in Equations (8) through (10) until the applied moment and moments of inertia exceeded the concrete's fracture energy through Equation (7). These calculated delamination loads are plotted in Figure 6 with the results from the experimental program. It is shown that this procedure approximates the delamination load trend reasonably well, and that the load increases as the location of the initial notch approaches the support.

DURABILITY AND INSPECTION OF FRP RETROFITTED CONCRETE SYSTEMS

An important advantage of FRP composites that make them suitable for retrofitting applications is their durability against environmental exposure. The FRP laminate and the epoxy adhesive used in retrofitting applications have excellent corrosion resistance compared to conventional construction materials. However, certain environmental parameters can jeopardize the durability of the retrofitted system at the material interfaces due to different mechanical and physical characteristics of the materials involved. Integrity and durability of the bond between concrete and the composite laminate is of utmost importance in a retrofitted system. Long-term environmental exposure may result in gradual and cumulative degradation of material properties and can play an important role in load capacity and failure mechanisms of retrofitted systems. Moisture and humidity, along with attacks by other aggressive liquids may pose a significant threat to the integrity of a bonded retrofit. Liquids may enter the interface by diffusion through the adhesive, transport along the interface, capillary action through cracks and crazes in the adhesive, or through the damaged concrete substrate. When entered the interface, the bond strength may be reduced through plasticisation, hydrolisis, cracking, or crazing of the adhesive, displacement of the adhesive at the adhesive/adherent interface, and by inducing swelling stresses in the interface [11]. Internal hydrostatic pressure due to freezing of pore water or recrystallization of salts may result in mechanical damaging and weakening of the interface. Elevated temperatures and presence of an applied stress



(a) response from sound bond (b) response from debonded area

Figure 7 Detection of debonding by ultrasonic inspection accelerate the rate of bond degradation. Thus, there is a need for research on degradation rates and mechanisms of bond in retrofitted systems for proper design and inspections.

Inspection of the bond at the concrete-FRP interface is an essential part of safe operation of retrofitted systems. Several advanced NDT techniques including ultrasonic inspection, infrared thermography and radar can potentially be used for this task. Among these methods, ultrasonic inspection have gained popularity due to its relative ease and inexpensive equipment. Figure 7 illustrates the potential of ultrasonic inspection for detecting debonding at the concrete-FRP interface. The figure shows the response obtained from ultrasonic measurement of (a) sound bond and (b) complete debonding. Any response in between can be interpreted as an indication of the bond quality.

CONCLUSION

Use of FRP composites as a means for repair and retrofitting of concrete structures is likely to provide an effective and cost-efficient way of maintaining aging concrete infrastructure. However, in order to ensure safety of retrofitted structures, several performance and durability related issues must be addressed, and design, application, and inspection procedures must be standardized. There is need for accurate models that predict failure behavior of retrofitted systems with special emphasis on debonding failures emanating from laminate ends and shear crack locations. These models must be able to predict debonding failures which often take place at load levels well below that based on failure by rupture of FRP laminate. Also, deterioration models are needed to assess and predict durability characteristics of retrofitted systems, as well accurate inspection techniques for condition assessment.

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