Performance of Retrofitted Concrete Using FRP

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ABSTRACT

Fiber reinforced plastics (FRP) have become a popular choice of materials for improving the load capacity and stiffness of existing concrete structures worldwide. However, failures of the retrofitted systems may become brittle and the bonded plastic sheets are susceptible to delamination from the concrete substrate. The influence of design and existing damage parameters on the failure processes of retrofitted concrete needs to be fully understood for reliable solutions to infrastructure renewal. This paper investigates performance and failure issues of retrofitted reinforced concrete beams through combined experimental and analytical studies. First, failure modes and design parameters of FRP retrofitted concrete structures are reviewed, and it is concluded that retrofitted concrete beams can be susceptible to delamination failures. For this reason, delamination is studied through an experimental program involving retrofitted reinforced concrete laboratory beam specimens. The addition of the laminate to the concrete beams is shown to increase load capacity and stiffness, but the specimens are observed to fail through debonding in the concrete substrate. Finally, durability issues concerning the reliability of FRP retrofit systems under environmental conditions is discussed.

KEYWORDS

FRP Composite Laminate; Retrofit; Damage; Cracking; Concrete; Environmental performance.

INTRODUCTION

The use of fiber-reinforced plastics (FRP) bonded to deteriorated, deficient, and damaged reinforced concrete structures has gained popularity in Europe, Japan, and North America. High-strength FRPs offer great potential for lightweight, cost-effective retrofitting of concrete infrastructure through external bonding to concrete members to increase strengths and stiffnesses. Fiber reinforced plastics have been used to retrofit concrete members such as columns, slabs, beams, and girders in structures including bridges, parking decks, smoke stacks, and buildings.

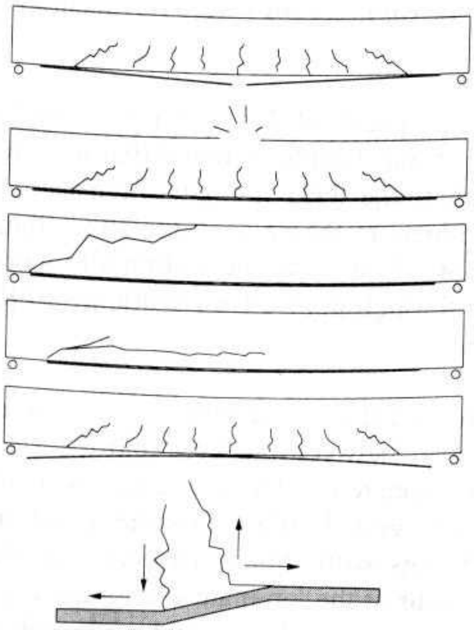
Theoretical gains in flexural strength using this method can be significant; however, researchers have also observed new types of failures that can limit these gains. These failures are often brittle, involving delamination of the FRP, debonding of concrete layers, and shear collapse, and can occur at loads significatly lower than the theoretical strength of the retrofit system. Among these failure modes, debonding or peeling of the FRP from the concrete surface is a major concern, yet little is known about the fracture processes and characteristics of these mechanisms. Thus, there is a need for improved knowledge of the delamination and peeling failure processes.

Researchers have indicated that failure criteria for laminated systems need to be established before confident application of FRP to strengthening concrete systems is possible (Meier, 1992). For this, a fundamental understanding of mechanics and failure mechanisms of the retrofit system is necessary. This paper investigates performance of retrofitted reinforced concrete beams through experimental and analytical studies on laboratory beam specimens retrofitted with FRP laminate. First, available information on applications and failure modes of FRP retrofitted concrete systems are reviewed. Then, an experimental program conducted to investigate the local delamination process using laboratory specimens is presented. Finally, durability issues effecting the performance of retrofitted concrete systems is discussed.

USE OF FRP IN RETROFITTING REINFORCED CONCRETE

Fiber-reinforced plastics exploit the advantages of high tensile strength fibers and are characterized by excellent corrosion resistance, fatigue resistance, low densities, and high specific stiffness and strength. Commonly used fibers include E-glass, Kevlar/aramid, and carbon; these can be pre-impregnated in matrices, lined unidirectionally in tow sheets, or woven into bidirectional fabrics. The implementation of these materials in strengthening existing reinforced concrete infrastructure has been demonstrated around the world. First applications of FRP to concrete structures include the use of carbon fiber reinforced plastic (CFRP) to strengthen a bridge with a damaged prestressing tendon (Meier, 1992); a mobile platform was used at night to restore the integrity of the bridge. GFRP tow sheets have been used on a bridge to increase the bending moment capacity (Nanni, 1995); tow sheets have also been used on a prestressed box beam bridge (Finch et al., 1994).

Considerable research has been conducted to study the implications of retrofitting reinforced concrete beams with FRP. Early research has demonstrated that the addition of CFRP laminate to reinforced concrete T-beams can increase ultimate strengths by 22% and also increase stiffnesses of the beams; additionally, prestressed CFRP laminates can be used to further increase the stiffness of the system (Kaiser, 1989). The strain in the CFRP in different beams was shown to exhibit three distinct stages of beam behavior under loading, corresponding to the uncracked section of the beam, the cracked section with elastic steel, and finally the section with plastic steel, ending when the FRP failed in tension (Meier and Kaiser, 1991). Increases in strengths over 40% and increases in stiffnesses were also reported with the use of glass and Kevlar based FRP (Rostasy et al., 1992; Chajes et al., 1994) where shear failures of the concrete beams were observed in addition to laminate tension rupture. In some cases, strength increases of up to 200% have been achieved through the use of external clamps to prevent debonding of the FRP (Saadatmanesh and Ehsani, 1989). Additionally, prestressing the FRP laminate before application has been investigated (Plevris and Triantafillou, 1994); it was found that high



(a) Steel yield and FRP rupture

(b) Concrete compression failure

(c) Shear failure

(d) Debond of layer along rebar

(e) Delamination of FRP plate

(f) Peeling due to shear crack

Figure 1. Failure modes in FRP retrofitted concrete beams

levels of prestress can result in shear failure in the concrete at the anchorage zone. These early studies, among others, have investigated a variety of retrofit systems and presented their responses under loading; many researchers have concluded that failure processes and their governing criteria need further study.

FAILURE MODES OF FRP RETROFITTED REINFORCED CONCRETE

Researchers have concluded that failure criteria for laminated systems need to be established (Ziraba et al., 1994). For this, however, a thorough understanding of the behavior of these systems is necessary. Many studies have presented a wide variety of failure modes observed in retrofit concrete beams (Meier, 1992; Chajes et al., 1994); these failure types can be grouped into six distinct categories, illustrated in Figure 1. The criteria for each of these failures are affected by various parameters in the design of a FRP retrofit concrete beam. For example, it has been recommended that failure of these systems should occur with yielding of steel and ultimately rupture of the laminate before compressive concrete failures, shown in Figure 1(a) (Meier, 1992). This can be accomplished by optimizing the FRP and the steel reinforcement ratio through traditional reinforced concrete design methods. Some other modes of failure, such as shear and debonding failures, can depend on other parameters such as existing shear reinforcement, crack configuration prior to strengthening, laminate length, and relative laminate/adherent/concrete stiffnesses. Recently, exploratory studies investigating the influence of these and other parameters on the failure behavior of laminated reinforced concrete beams were performed (Buyukozturk and Hearing, 1998).

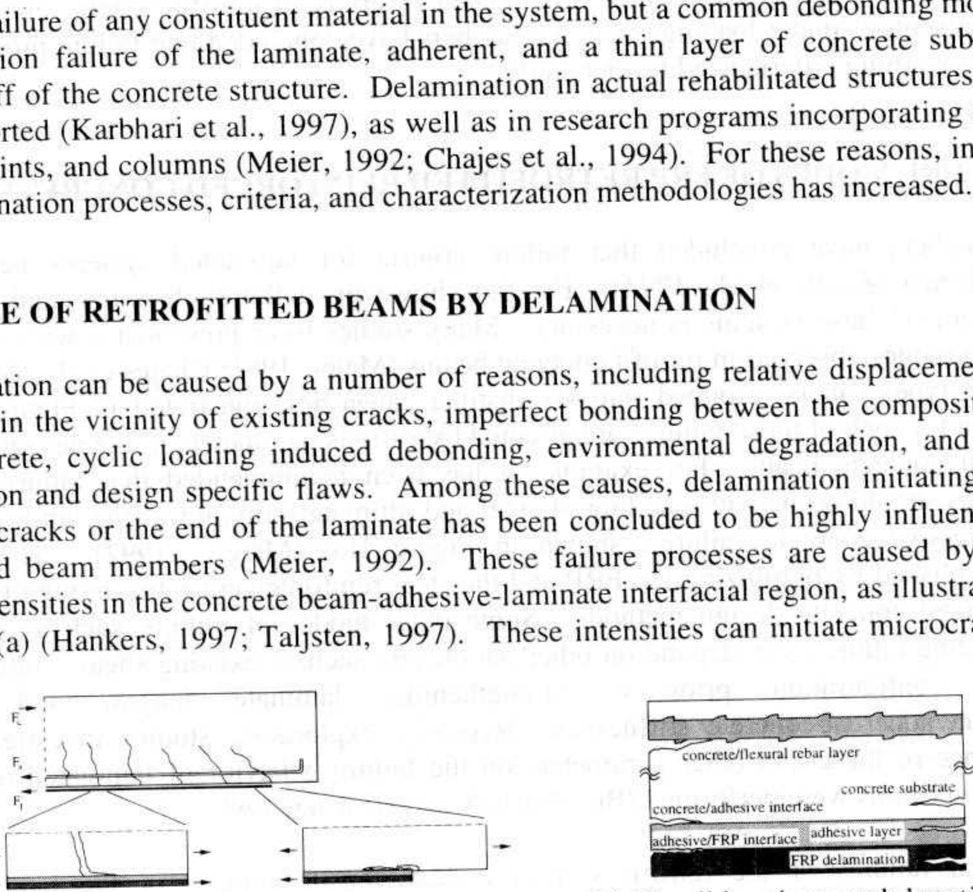
Flexural failures of the retrofit section include tensile rupture of the laminate and compression failure of the concrete. Both failures occur in a brittle manner with a sharp, explosive fracture. Strengths can be theoretically increased up to 200% have been reported (Saadatmanesh and Ehsani, 1989; Meier, 1992). Deflections are reduced compared to the unretrofit section, and the beam stiffness is increased. The ultimate strengths and stiffnesses of the beams with these flexural failures can be accurately predicted using strain- or stress-compatiblity theories.

Shear failures of retrofit sections occur when the shear capacity of the section is exceeded prior to the load level reaching the flexural strength. It has been concluded that the FRP along the bottom of the beam does not significantly add to the shear strength of the section. Shear cracks typically extend from the end of the laminate to the point of loading. Shear failure occurs at loads agreeing with traditional reinforced concrete shear strength theory. Research into improving the shear capacity of beams through innovative retrofit with FRP is increasing (Sharif et al., 1994; Chajes et al., 1994).

Other types of failures in FRP retrofit concrete involve a variety of debonding mechanisms; these include failure of the concrete layer between the FRP and the steel, and delamination or ''peeling" of the FRP from the concrete. These failures typically occur in beams with greater shear resistance but are very brittle. Debonding of the concrete layer at the rebar has been observed in beams with shorter laminate lengths, indicating that significant stress concentrations can occur at the laminate anchorage zone. Shear crack ''peeling" of the laminate can occur with longer laminate lengths where significant shear cracks have formed. These debonding failures have been reported by a number of research teams (Saadatmanesh and Ehsani, 1989; Sharif et al., 1994), and the laminate-concrete interfaces have been concluded to be susceptible to relative vertical displacements of shear cracks in the concrete beam (Meier, 1992). Debonding can occur through failure of any constituent material in the system, but 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 actual rehabilitated structures have been reported (Karbhari et al., 1997), as well as in research programs incorporating slabs, beams, joints, and columns (Meier, 1992; Chajes et al., 1994). For these reasons, interest in delamination processes, criteria, and characterization methodologies has increased.

FAILURE OF RETROFITTED BEAMS BY DELAMINATION

Delamination can be caused by a number of reasons, including relative displacements of concrete in the vicinity of existing cracks, imperfect bonding between the composite and the concrete, cyclic loading induced debonding, environmental degradation, and other application and design specific flaws. Among these causes, delamination initiating from existing cracks or the end of the laminate has been concluded to be highly influential in retrofitted beam members (Meier, 1992). These failure processes are caused by local stress intensities in the concrete beam-adhesive-laminate interfacial region, as illustrated in Figure 2(a) (Hankers, 1997; Taljsten, 1997). These intensities can initiate microcracking



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

Figure 2. Local stress intensities and microcrack initiation scenarios

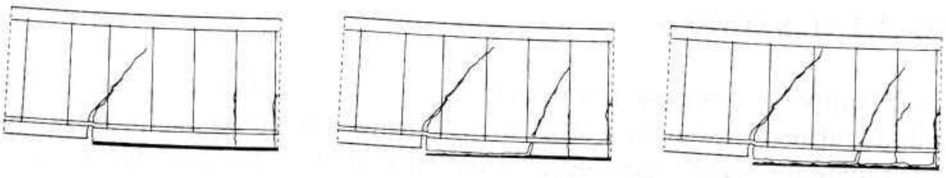


Figure 3. High speed video clips of plate end zone failures, after (Holzenkampfer, 1995)

in the system at early load levels. Microcracks can form in any of the constituent materials or their interfaces, such as the laminate/adhesive interface, the adhesive/concrete interface, or the concrete/flexural steel layer, as shown in Figure 2(b). Upon further loading these microcracks propagate and coalesce, ultimately forming macrocracks that can result in system failure.

This process has been studied by researchers using a variety of retrofitted system models. Studies using reinforced concrete beams retrofitted with externally bonded plates have been used to investigate global beam behavior during delamination failures. Theoretical peeling stresses in the adhesive layer of a beam with a bonded strengthening plate were derived by neglecting damage and cracks in the beam (Taljsten, 1997). However, high speed video clips of plate end zone failures clearly show that cracks in the existing beam play a critical role in the peeling process, as shown in Figure 3 (Holzenkampfer, 1997). Even with the aid of high speed video, though, the exact local failure mechanism and direction of peeling of the steel plate delaminating is still unclear. The presence of shear cracks near the end of the laminate make it difficult to determine if local debonding initiated at the crack mouths or the end of the laminate. Peeling failures of this type have also been observed in studies on the behavior of the retrofitted system with different bonded steel plate lengths (Jansze, 1997); it was concluded that unplated length influenced the peeling mechanisms. Again, however, the direction of peeling and exact local mechanism responsible for the system failure is indeterminable due to the flexural and shear cracks observed in the laboratory specimens. These and other reasons have lead researchers to use other specimens and scenarios to study the delamination process.

A variety of simplified models have been used to isolate the peeling failure process and study the bonding interaction between the concrete surface and external reinforcement. Experimental observations during lap shear pull-off tests have indicated that progressive bond failure is initiated by microcracks in the substrate at peak bonding stress followed by coalescence into debonding macrocracks (Hankers, 1997). Other studies have included theoretical models of unreinforced open sandwich specimens (Hamoush and Ahmad, 1990) and peel tests (Karbhari, et al. 1997) where local fracture under varying external peel loadings was studied through inclined lap-type specimens. Changes in peeling angles were concluded to affect the fracture morphology; higher angles of FRP peeling off the stationary slab were shown to shift the delamination process deeper into the mortar substrate. However, the application of this knowledge to laminated reinforced concrete flexural members is limited; the conditions of the concrete substrate in these studies may not have developed the complete microcrack initiation and propagation process found in components with conventional reinforcement subjected to generalized flexure and shear loadings. Thus, there exists a need for isolated study of local delamination mechanisms of reinforced members under flexural beam loading.

EXPERIMENTAL STUDIES

A two-part experimental program has been conducted to investigate the local delamination process and the influence of initial cracks in the concrete beam on that process. In the first series, delamination beam specimens were tested to monitor local delamination machanisms. The second series involved initially cracked retrofitted beams to investigate the influence of initial cracks on the delamination process.

Tests with Initial Delamination Specimens

Specialized delamination beam specimens were developed and tested in an experimental program to study local delamination fracture processes. The objectives of the program were to isolate and monitor local delamination crack development and propagation, and to investigate influences of bonded laminate length on the delamination process. To meet these objectives, delamination specimens containing initial delamination notches were created with various lengths of bonded FRP laminate, as shown in Figure 4. The beam specimens were designed to be retrofitted with carbon FRP (CFRP) laminate that would theoretically increase the flexural capacity by 40% through tensile laminate rupture. To reduce the influence of shear cracks on the delamination process, the beams were over-reinforced with closely spaced stirrups that increased the shear strength to 175% of the flexural retrofitted capacity. Delamination was studied by propagation from the end of the laminate towards the center of the specimen. To simulate steady-state conditions, initial delamination cracks were introduced with a thin sheet of plastic placed between the adhesive and concrete as the beam was retrofitted.

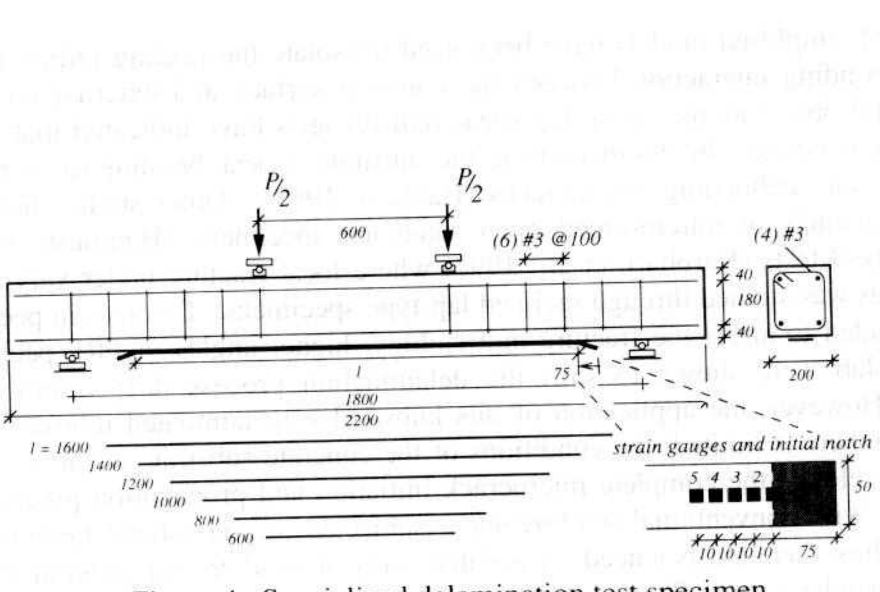


Figure 4. Specialized delamination test specimen

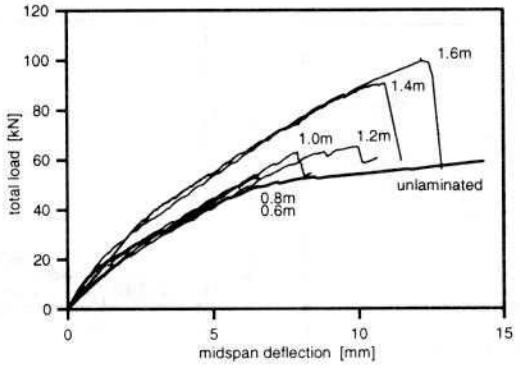


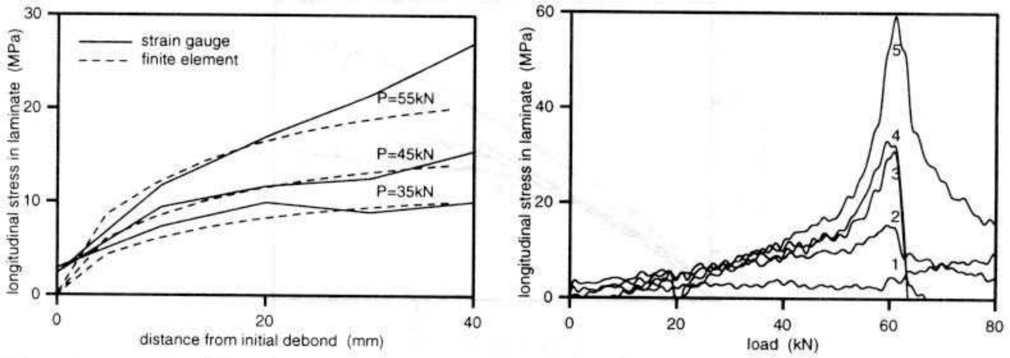
Figure 5. Midspan deflection curves for initially notched delamination specimen

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*. Beam specimens were 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. Various lengths of laminate were applied to the beams and allowed to cure for at least 24 hours. Six lengths of laminate were tested in the program, from 33% to 89% of the total span, as shown in Figure 4. Ten strain gauges (five on each end) were applied to selected specimens at the anchorage zone, also illustrated in Figure 4.

The specimens were loaded in four point bending in load steps of 4.5 *kN* until system failure. Midspan deflections and strain gauge signals were monitored continuously. The anchorage zones were inspected for delamination initiation at each load level using a magnifying scope.

Table 1. Results of the experimental program

Laminated length [*m*]	Delamination intiation [*kN*]	Ultimate load [*kN*]	Calculated energy release rate [J/m^2]	Failure mode
Unlaminated	-	48.2	-	steel yield
0.6	27.8	52.3	62.3	debonding
0.8	35.2	53.8	39.8	debonding
1.0	31.1	62.1	36.3	debonding
1.2	39.6	63.2	34.4	debonding
1.4	60.0	90.6	35.9	debonding
1.6	97.3	100.4	24.2	debonding



(a) Development of laminate stresses in anchorage zone

(b) Laminate stresses with load history

Figure 6. Results from the strain gauges on the beam with 1.4m bonded length

Delamination Series Results

First, unlaminated control beams were tested. The midspan deflection curves demonstrate traditional nonlinearities at cracking of the concrete and plasticity of the steel, as shown in Figure 5. Then, laminated beams were tested; midspan deflection curves are also shown in Figure 5. Ultimate loads from the testing program are presented in Table 1. The beams exhibited concrete cracking at levels higher than the unlaminated beams, with flexural cracking confined mostly to the constant moment span. Stiffnesses were observed to increase with the addition of the laminate. Strain gauge results indicated a development of laminate stresses in the anchorage region, as illustrated with different load levels in Figure 6(a).

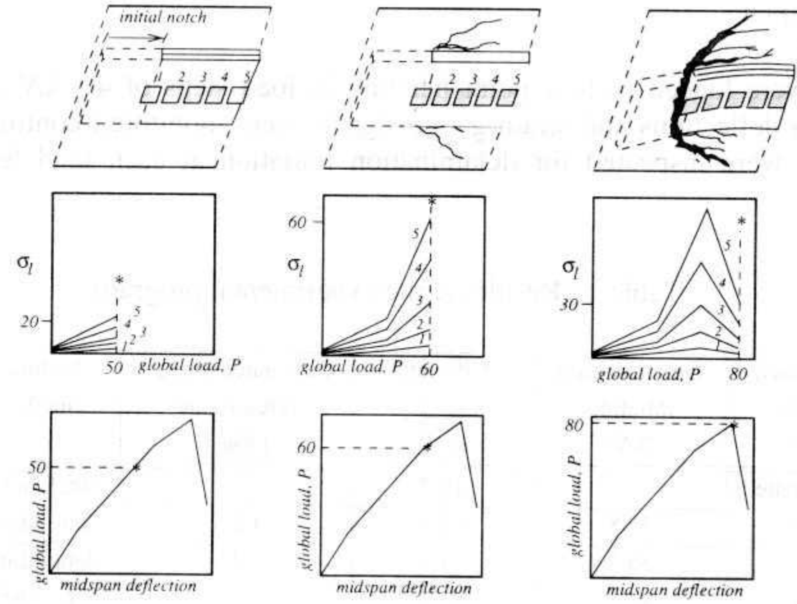


Figure 7. Delamination process zone development with idealizations of Figures 6(b) and 5 for the 1.4 m laminate length beam

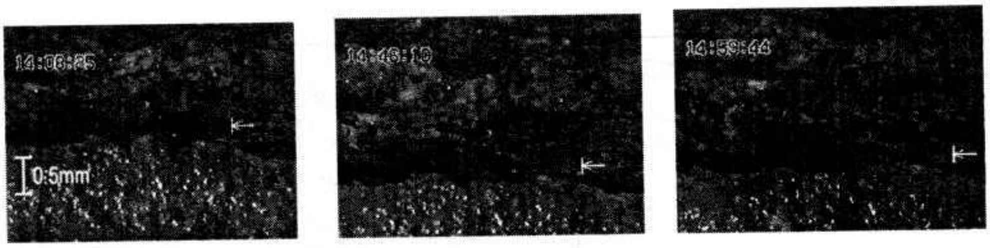


Figure 8. Images of process zone development obtained with magnifying camera

All retrofitted specimens failed through delamination in the concrete, leaving a thin layer of concrete substrate bonded to the delaminated FRP. Initial cracking in the concrete substrate at the delamination/anchorage zone was typically observed after flexural cracking, and before yielding of the steel or final delamination. These initial cracks were often accompanied by audible noises, and changes in stiffness were also observed in the midspan deflection curve. The strain gauge readings indicated that strains in the laminate reached their peak at crack initiation, and decreased upon further loading, as shown for the beam with 1.4 *m* bonded length in Figure 6(b). This indicates the initiation of the delamination process (at 60 *kN* for the beam shown), even though in this case the beam continued to resist more load. Upon additional loading the initial crack continued to widen until the ultimate load of the beam was reached (at 90 *kN* for the beam shown), where unstable delamination occurred resulting in peeling of the laminate, adhesive, and a thin layer of concrete. This process, illustrated in Figure 8, is idealized in Figure 7 with simplifications of behavior demonstrated in Figure 6(b) and 5.

Tests with Initial Shear Crack

A second test series has been initiated involving concrete beam specimens containing single sets of initially notched shear cracks. The objectives of this program are to isolate and monitor the delamination process development from existing cracks in the concrete beam, and to investigate influences of bonded laminate length (development length) past the initial crack. To meet these objectives, concrete beam specimens, similar to the first study, containing initial shear crack notches were created with various lengths of bonded

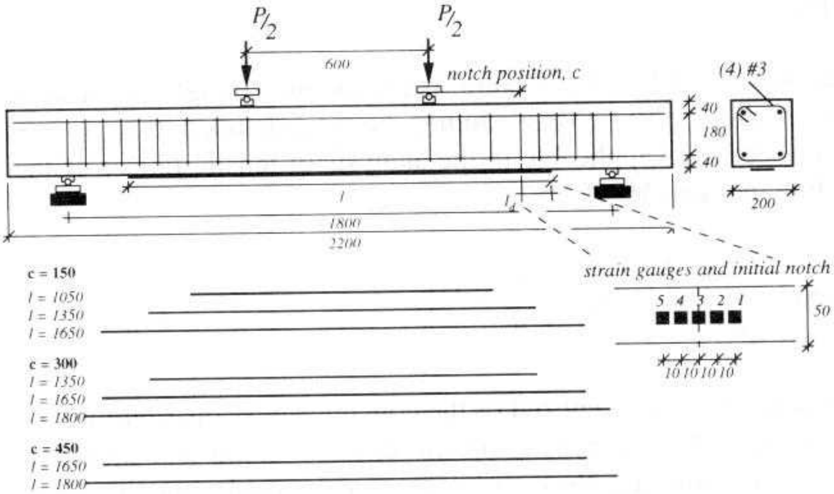


Figure 9. Delamination specimen with initial shear notches

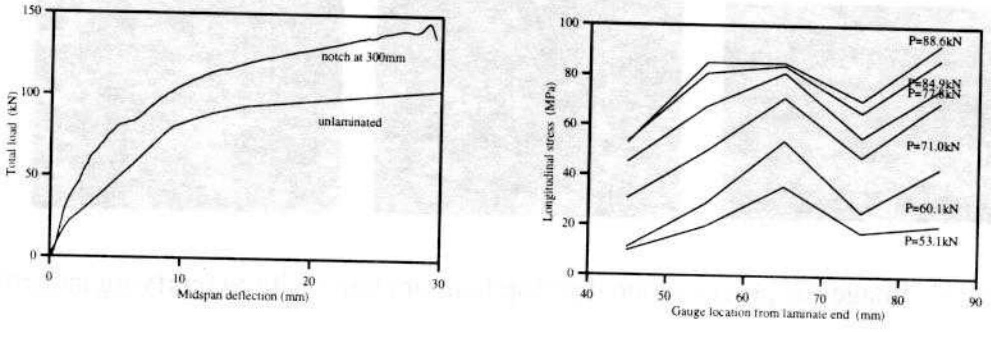


Figure 10. Load line deflection and strain gauge history for shear notched delamination specimen

FRP laminate, as shown in Figure 9. To reduce the influence of shear cracks other than the initial notch, the beams were over-reinforced in shear outside of the location of the initial notch. Delamination was studied by propagation from the initial notch towards the end of the laminate. The same materials were used as in the first study, and the initial notch was created with a thin diamond saw blade and filled with putty during lamination. Three locations of initial cracks were tested with three development lengths beyond each notch, as illustrated in Figure 9. Initial results indicate the existence of a stress intensity at the crack mouth which initiates a delamination process before the ultimate load of the beam, as shown in Figure 10. The strain gauge history shows the process as the intensity shifts outward from the initial notch towards the end of the laminate.

ANALYTICAL PROCEDURES

Considerable research has been conducted into the analysis of failure mechanisms of laminated reinforced concrete beams. These analyses usually consider short-term behavior of singly reinforced concrete members with rectangular cross sections strengthened with FRP on the bottom face of the member; in principle, similar approaches may apply for other geometric configurations.

Flexural Failures

Many researchers have analyzed the flexural behavior and strength of the composite cross section (Plevris et al., 1990). Most studies have concluded that a stress or strain equilibrium of the section is applicable in the analysis of tensile failure of the laminate at an ultimate bending moment M_u of

$$\frac{M_u}{bd^2 f_c^{'}} = \frac{f_y}{f_c^{'}} \rho_s \left(1 - \frac{\overline{y}}{d}\right) + \frac{E_{f_c} \varepsilon_{f_c}^{*}}{f_c^{'}} \rho_{f_c} \left(\frac{h_p}{d} - \frac{\overline{y}}{d}\right) \qquad [1]$$

where y is the distance from the centroid of the concrete stress distribution to the top fiber, h_p is the depth to the FRP, ε^{*}_{fc} and E_{fc} are the ultimate strain and modulus of the fiber composite, and other terms are those used in conventional concrete analysis. Using similiar arguments, these studies have also concluded that the section will fail in