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Fiber Composites: An Economical Alternative for Retrofitting Earthquake-Damaged Precast-Concrete Walls

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A new approach for seismic retrofitting of lightly-reinforced precast-concrete walls is presented. The technique involves epoxy bonding the reinforcing material (composite fabric) to the exterior surface of the wall. The flexible light-weight fabrics are extremely strong in tension and can significantly increase the flexural and shear capacity of the member. The thin composite fabrics cause little increase in the weight and thickness of the wall, causing little change to the inertial loads and eliminating the need for strengthening of the footings. Following the January 17, 1994 Northridge earthquake, this technique was applied to a tilt-up concrete building in southern California. The method proved to be the most cost-effective alternative to repair this damaged building in a very short time. More than 20,000 ft.^{2} of wall surface area were strengthened, making this project the largest reported application of this technique. This paper discusses some of the design considerations and the strengthening of the damaged building.

INTRODUCTION

Structural engineers are frequently faced with situations where the strength or ductility of existing elements must be increased. Strengthening is required for a variety of reasons including: a) original design errors that underestimated the actual loading on the members; b) construction errors that resulted in a weaker member; c) increased loading on the member due to change in use; and d) improvements in analytical tools and codes that demonstrate the inadequate strength of the member as it was originally designed. While various codes do provide detailed guidelines for design of new structures, few provisions are available for strengthening existing structural members. As a result, the structural engineer and architect have more freedom in developing creative solutions to address the latter.

Several methods have been used to increase the flexural strength of existing structures. Among these are external post-tensioning, shotcreting that is used primarily for walls, and attaching steel plates to tension flange of the member by means of bolts, epoxy bonding, or a combination of the two. Because the method discussed in this article is closely related to external

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plating of members, some of the previous studies on this technique will be presented here. All of the following studies are on flexural or shear strengthening of reinforced concrete beams; however, these results can be readily extended to strengthening of concrete walls.

Strengthening of beams by addition of epoxy-bonded steel plates to the tension flange has been practiced for many years. The principles of this method are fairly simple. Steel plates are epoxy-bonded to the tension flange of the beam, increasing both the strength and stiffness of the girder. The shear capacity of the girders can also be increased by attaching steel plates to the web. Among the advantages of this system are the ease of application and the elimination of special anchorages that are needed in other strengthening methods such as external post-tensioning. Moreover, no measurable loss of overhead clearance will result from the addition of the plates.

Clearly, adhesives plays a significant role in the successful application of this technique. The adhesive should have sufficient strength and stiffness to ensure a complete composite action (i.e. no slip) between the plate and the concrete throughout the entire range of loading up to failure. In addition, the steel and concrete surfaces must be grit-blasted and cleaned and the epoxy should be applied in a uniform thin layer. Much of the work in the United States has been related to the bonding of steel to steel, while in other countries research has been primarily related to the bonding of steel to concrete (Klaiber, et al. 1987; Nara and Gasparini 1981).

In one study, a series of 6 x 10 in. rectangular beams with lengths varying from 11.5 ft. to 16 ft. were strengthened with epoxy bonded steel plates (Macdonald and Calder, 1982). They reported that significant improvements in the ultimate strength was observed in the strengthened beams. Several beams that had been exposed to outside environment showed a smaller ultimate strength. The reduction in the ultimate strength was attributed to corrosion at the interface of steel and epoxy.

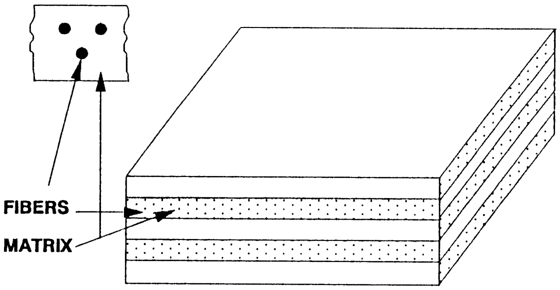
Swamy et al. (1987) conducted an extensive study and concluded that lapped plates, pre-cracking prior to plating, variable glue thickness, and the presence of stress concentrations in the adhesive had no adverse effect on the structural behavior of plated beams. In a companion study, two different types of adhesive and two grades of steel plates were used (Jones, et al. 1980). They concluded that external prestressing with steel plates resulted in enhancement of elastic range; reduction in tensile stresses; increase in strength and stiffness; and improvements in ductility at flexural failure. Others have investigated the effects of hostile environment on the durability of adhesively bonded steel-to-steel bridge connections (Hoigard and Longinow, 1986).

Epoxy bonded steel plates have been used in a large number of projects to increase the strength of girders in existing bridges and buildings (Klaiber et al. 1987). Although this technique has met some success in many countries, its major problem has been the corrosion of steel plate that adversely affects the bond strength at the epoxy-concrete interface. Moreover, the application of this technique to structural members with large surface areas, such as walls, is in most cases impractical.

An effective approach to overcome the above shortcomings is to replace the steel plate with corrosion-proof fiber-reinforced polymer (FRP) plates. In order to familiarize the reader with the advantages of FRPs, a brief introduction to these materials is provided.

FIBER-REINFORCED POLYMERS

Composite materials are made up of fibers (e.g. glass, carbon, Kevlar, etc.) bonded together with a resin matrix. For the composite materials discussed here, the fibers are long and continuous. The fibers provide the composites with their unique structural properties. The resin serves as the bonding agent to protect the fibers and to distribute the load among them. The most common type resins are polyesters and vinylesters. Composites are anisotropic materials. Depending on the type of application, the fibers can be oriented in a multitude of directions to enhance the mechanical properties of the composite in the desired direction. Figure 1 shows a typical composite laminate with fibers oriented in the 0- and 90-degree directions. Such laminates usually contain several layers of fibers; the final product can be 1/16 to 1 in. thick, resulting in a relatively stiff plate.



COMPOSITE LAMINATE

Figure 1. Composite laminate and its constituents

The use of composites for a variety of industrial applications has been rapidly increasing in recent years (ACI-440 1996). The main reasons for using composites are their superior strength-to-weight ratio, stiffness-to-weight ratios, and durability in corrosive environments as compared with conventional materials. In addition to the superior strength properties, many composites have shown much better fatigue performance than structural metals. For example, unidirectional graphite/epoxy laminates exhibit almost no sign of the conventional S-N curve (Hoskin and Baker 1986). Instead, when subjected to tension-tension cycling, a wide scatter of lifetimes ranging up to 10^7 cycles is observed, even when the maximum cyclic stress is around 80 percent of the ultimate tensile strength.

Moisture and temperature are known to have adverse effects on composites and adhesives. The change in structural behavior of composites primarily results from the effect of moisture and temperature on the resin system that bonds the fibers. Considerable effort is now being devoted to the development of resin systems and adhesives that are less prone to moisture adsorption than the epoxies in use today. The most promising of these to date seems to be PEEK (Polyether-Ether-Ketone) and Phenolic-Resin systems that are highly moisture insensitive. Even though there are still some uncertainties in the behavior of composite materials, as far as is known, no major problem has so far arisen due to either environmental effects or fatigue in composite components of aircraft in service (Hoskin and Baker 1986). Some such components have been in service for more than 25 years.

Fiber composite materials generally behave linearly elastic to failure. E-glass fiber, for example, has a tensile strength of over 300 ksi and a modulus of elasticity of about 10 million psi. However, due to the progressive fracture of fibers, it is very difficult to achieve such high stresses in sections consisting of a large number of fibers. Furthermore, in most cases, the fibers account for 60% to 70% of the volume of the composite, with resins making up the balance. Therefore, for glass-fiber-reinforced-composites, tensile strength in the range of 80 to 150 ksi and modulus of elasticity of about 6000 to 7000 ksi are common. There are, of course, other fibers such as carbon that in composite form are both stronger and stiffer than glass. However, these fibers are rather expensive and may have limited application in the construction industry where large volumes of inexpensive materials are needed. Figure 2 shows typical stress vs. strain diagrams for glass- and carbon-fiber-reinforced-polymers (GFRP and CFRP, respectively) and steel. It is important to note that although the behavior of composites is linear and elastic, their failure occurs at fairly large strains. Therefore, structural elements reinforced with these materials will fail at large deflections.

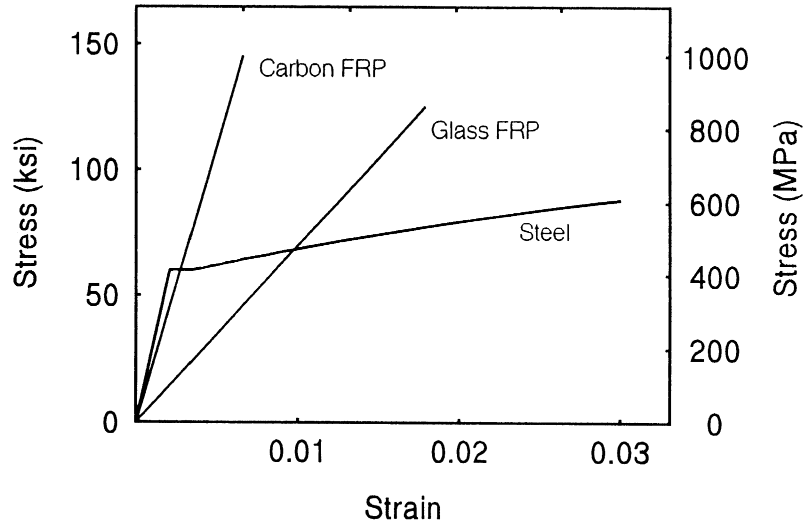


Figure 2. Stress vs. strain behavior of steel and composites

The fatigue and creep behaviors of composites are also very good. Unidirectional glass reinforced composites do not fatigue when stressed below 50 percent of their tensile strength.

Generally, composites exhibit very low creep strains. Most of the commercially available fibers, namely, glass, carbon, and boron do not creep (Mallick 1988).

Composites have been used extensively in aircraft and aerospace industries. The first recorded application of glass-fiber-composite in aircraft industry dates as far back as 1944 (Hoskin and Baker 1986). Since then, a variety of composites have been used in other industries such as ship building, chemical processing, medical, automotive, etc. Due to the large number of applications, many types of composites have been produced in mass quantities in recent years. This has substantially reduced the production cost of these materials. It is also projected that this cost will steadily decrease in the future. Therefore, the use of composites in civil engineering type structures can be economically justified. This is demonstrated in the case study that is presented in this article.

EXPERIMENTAL STUDIES

No studies have been conducted on the behavior of reinforced concrete walls strengthened with fiber composites. However, many researchers have examined concrete beams rehabilitated with FRPs. Most of those studies were initiated in an attempt to address the long-term durability of beams strengthened with steel plates reduced by the corrosion of the plate. Because of the similarities between behavior of concrete beams and walls, some of the investigations on beams are presented here to introduce the reader to the large body of information that is available on this subject.

The initial developments of this concept took place in Germany where thick glass (GFRP) plates were used and in Switzerland where thin sheets of carbon (CFRP) were utilized (Meier 1987). These studies showed the validity of strain compatibility method in the analysis of cross sections and suggested that inclined cracking may lead to premature failure by peeling-off of the strengthening sheet. Kaiser's study included the development of an analytical model for the composite plate anchoring which is in good agreement with test results (Kaiser 1989).

The writers have also conducted tests on small- and large-scale beams strengthened with GFRP plates. The small-scale tests were aimed at identifying a suitable epoxy that could be used for these applications (Saadatmanesh and Ehsani 1990). Five identical beams each having a cross-section of 3.5 x 6 in. and a length of 66 in. were constructed. Steel reinforcement for the beams consisted of one No. 3 Grade 60 bar for flexure and 3/16 in.-diameter wires placed at 3 in. for shear. The GFRP plates were 1/4 x 3 in. in cross section and they were bonded with different epoxies to four beams prior to testing. The fifth beam was the control beam. It was concluded that the success of this technique is greatly dependent on the use of a suitable epoxy and that the epoxy should have sufficient stiffness, strength and also toughness such as rubber toughened epoxies.

Upon the completion of small-scale tests, another series of tests were carried out on five rectangular beams and one T-beam (Saadatmanesh and Ehsani 1991). The rectangular beams had a cross-section of 18 x 8 in. The flange width and thickness of the T-beam were 24 in. and 3 in., respectively. The overall height was 18 in. and thickness of the web was 8 in. The overall length of each beam was 16 ft. and the beams were supported on a clear span of 15 ft. during the test. Three different reinforcement ratios were used for the beams. The GFRP plates were 6 x 1/4 in. in cross section and they were 14 ft. long. These plates were attached to the tension flange of the beams using the epoxy recommended by the pilot study. They reported significant increase in the flexural strength. The increase in the flexural strength was much greater in beams that had lower steel-reinforcement ratios. They also found that plating contributed in part to the reduced ductility. Reduction in crack sizes were observed at all load levels. A typical load-deflection curve for the large-scale beams is shown in Fig. 3. The longitudinal steel reinforcement for this beam consisted of two No. 4, Grade 60 bars. The ultimate capacity of the beam was increased by more than four fold. An analytical model was developed to predict the behavior of the retrofitted beam; as seen in the figure, there is excellent correlation between the measured and predicted responses (An et al. 1991). This beam was initially cambered prior to the bonding of the plate; therefore, a negative deflection is recorded when there is no load applied to the beam. Similar studies have been reported by others (Ritchie et al. 1991).

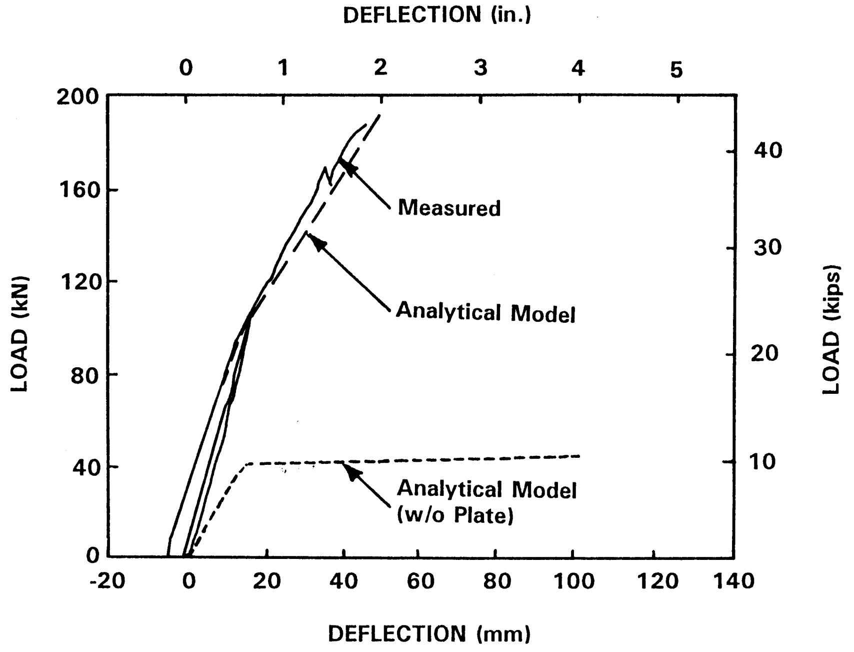


Figure 3. Load vs. deflection behavior of R/C beam strengthened with GFRP plate

Based on static short-term behavior, Plevris et al. (1995) have performed analysis of reliability of concrete beams strengthened with FRP laminates. Swiss researchers have also demonstrated that there is no loss of strength after a beam reinforced with CFRP plates is subjected to 100 freeze/thaw cycles ranging from +20 °C to -25 °C (Kaiser 1989). Triantafillou, et al. (1992) have also reported on experimental and analytical studies of beams in which the CFRP plate was prestressed before it was attached to the beam. A small number of fatigue tests have also been conducted at the Swiss Federal Testing Laboratories (EMPA). Preliminary results from these limited tests indicate good fatigue behavior of the retrofitted beams; however, the available data are very scarce and additional tests must be conducted. Finally, there are several field applications of this technique in bridges and other structures in Europe (Meier et al. 1993; ACI-440 1996).

STRENGTHENING OF WALLS WITH FRPs

Concrete walls are typically reinforced with steel reinforcing bars that are placed in one or two vertical planes. The reinforcement is comprised of horizontally- and vertically-positioned bars. In some cases, the weakness of the wall is due to the lack of reinforcing steel rather than insufficient concrete. In other words, failure of the wall is controlled by the amount of steel present. Therefore, for strengthening, additional reinforcing steel must be added to one or both faces of the wall. In the conventional approach, a new grid of reinforcing steel is placed adjacent to the wall; this grid is tied to the wall by means of closely-spaced dowels that are drilled into the wall. A layer of concrete is sprayed onto the steel reinforcement to form a thicker wall. The additional weight of the wall will of course change the dynamic loading on the structure and may require foundation adjustments; the increased thickness will also result in higher stiffness.

Due to their high tensile strength, composite materials can achieve the same objective but without the need for the additional concrete. Because most walls require small additional reinforcing material, strengthening of walls can be best achieved by using a composite fabric rather than a laminate plate such as that shown in Fig. 1; the latter would be too strong for most applications and its stiffness may make its attachment to the wall surface difficult. A sample of such fabric is shown in Fig. 4. The laminate plates discussed earlier are usually constructed with several layers of such fabrics placed on top of one another for increased strength and stiffness. In this case, the fabrics are attached to the wall by means of an epoxy; thus, here, the epoxy serves two functions. One is to fix the fabric to the wall, and the other is the same function as the resin matrix used in the laminate plate of Fig. 1. The flexibility of the fabrics makes them particularly suitable for strengthening of masonry walls, where the wall surface may not be flat or smooth; such retrofit has been carried out on a concrete masonry wall in southern California (Ehsani and Saadatmanesh, 1997).

A further significant difference exists between FRP laminates and fabrics. FRP laminates are usually produced in plants under higher quality control. The production process allows the fiber content to be fairly high, in excess of 60% by volume. Because the behavior of composites is primarily governed by the fiber rather than the resin, such laminates exhibit higher strength and stiffness. The same happens when as part of quality control in the field, samples of saturated FRP fabrics are prepared for laboratory testing. In making these coupons, the saturated fabric is placed between two flat plates and much of the resin is squeezed out, resulting in a coupon with higher volume of fiber than the actual material being placed on the structure. In the hand lay-up system used in some civil projects, for example, the fabrics are often saturated with plenty of resin, resulting in a composite which may contain only 30% fiber by volume. Thus, unless the fiber to resin ratios of the FRP are known, the specified or measured *tensile strength, modulus*, etc. are meaningless. We believe that the *tensile* *load* carried by the coupon, which is primarily a function of the strength of the fibers only, is a better parameter to be used in design.

Because the strength of composites are a function of the amount and direction of the fibers, one can design the fabric to meet the strength requirements in the vertical and horizontal directions. The approach is very similar to specifying the size and spacing of reinforcing bars. For example, a No. 4 Grade 60 bar placed at a spacing of 12 in. can provide a tensile force of 12.0 kips for a 1-ft. wide section of the wall; this is equivalent to covering the wall with a composite fabric having a tensile strength of 1 kip per inch width of the fabric. As discussed in the above paragraph, this strength will remain the same regardless of the amount of resin being used.

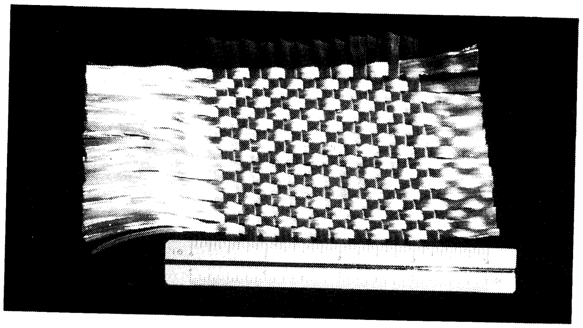


Figure 4. Sample of 0-90 degree fabric used in the field application

The success of this retrofitting technique is greatly dependant on the epoxy. The wrong type of epoxy could result in failure of the epoxy without developing the full capacity of the composite fabric (Saadatmanesh and Ehsani 1990). In the following discussion, therefore, it is assumed that failure of epoxy will not take place. As shown in Fig. 5, when a member is subjected to bending, the fibers that are perpendicular to the axis of bending, develop tensile stresses that increase the flexural resistance of the member.

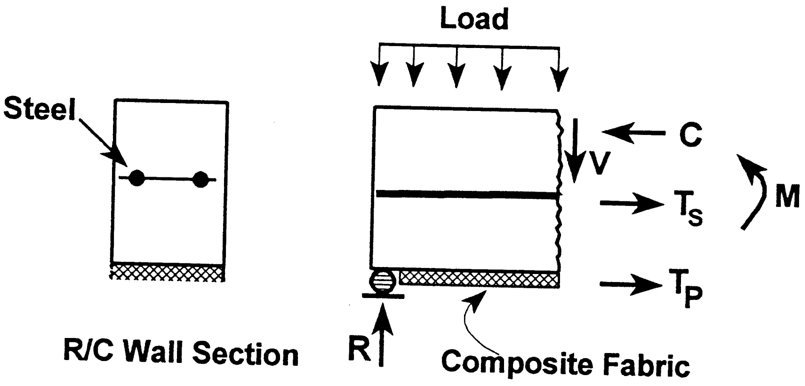


Figure 5. Mechanism of flexural resistance

Several modes of failure may occur as shown in Fig. 6. The under-reinforced unretrofitted member has a relatively low flexural strength but fails with significant ductility. When a thin fabric, t_1, is used, the stiffness and the strength of the member is increased. Failure is reached by tension failure of the fabric after the steel has yielded; the ductility of the member is also reduced. The thicker fabric, t_2, will further increase the bending capacity and stiffness. When a very thick fabric, t_3, is used, the beam may fail in one of the following two brittle modes. In one case, failure will be governed by compression failure of the concrete; in the other, the member will fail in shear in the horizontal plane passing through the longitudinal steel in the member. The latter case is more common in girders, when usually the large forces developed in a thick FRP plate have to be transferred to the beam through the small width of the flange (Fig. 7). This mode of failure can be delayed by bolting the composite material to the core of the beam. However, for most walls, the thickness of the fabric will be very small and the shear forces are transferred over a large area of concrete. Therefore, the mode of failure will resemble that corresponding to t_1 in Fig. 6.

While the above discussion and the previously-discussed test results are for members subjected to monotonic loading, similar behavior has been observed in members subjected to reversed cyclic loading. In a study currently in progress at the University of Arizona, reinforced concrete walls retrofitted on both faces with composite fabrics are being subjected to cyclic out-of-plane bending. The hysteretic response of these elements is stable and the failure envelop can be approximated with that obtained based on monotonic loading.

The mechanism for shear resistance of a wall element can be explained with the help of Fig. 8. Diagonal tensile stresses cause the inclined shear crack. The resistance of the cracked concrete is increased by the presence of the horizontal and vertical reinforcing bars that are embedded in the wall. With the composite fabric present, the fibers in the fabric add to the strength of the system. Thus, the fabric prevents the widening of the crack and complete shear failure will be delayed until all horizontal and vertical fibers crossing the crack break in tension. In a recently completed study at the Federal Highway Administration, several beams were strengthened for shear by epoxy-bonding carbon fabrics to their sides (Norris et al. 1994). The unretrofitted beams failed in a brittle manner in shear as shown in Fig. 9. With the presence of fabric, premature shear failure was eliminated and the beams failed in a ductile flexural mode.

Perhaps one of the greatest advantages of FRPs compared to conventional materials is in increasing the in-plane shear capacity of walls. This is the subject of an ongoing investigation at the University of Arizona. In a recent publication, the significant enhancements in the shear capacity of brick walls has been reported (Ehsani, et al. 1997). However, detailed discussion of shear strengthening is beyond the scope of this paper.

CONSTRUCTION PROCEDURE

The steps required in strengthening a concrete wall can be summarized in the following:

a) The wall surface is cleaned of any external coatings.
b) A thin coat of epoxy is applied to the wall surface.

c) The fiber composite fabric will be placed over the epoxied areas of the wall.
d) With the help of a roller, the fabric will be pressed onto the epoxy and if necessary, additional epoxy will be applied to the outside of the fabric so that the fabric is fully saturated in epoxy.
e) The epoxy dries in about an hour and will fully cure in 24 hours, leaving the wall with a textured finish.
f) If desired, the retrofitted wall is covered with plaster, paint, or other coatings. In addition to aesthetics, these coatings could provide protection for the epoxy against ultraviolet rays.

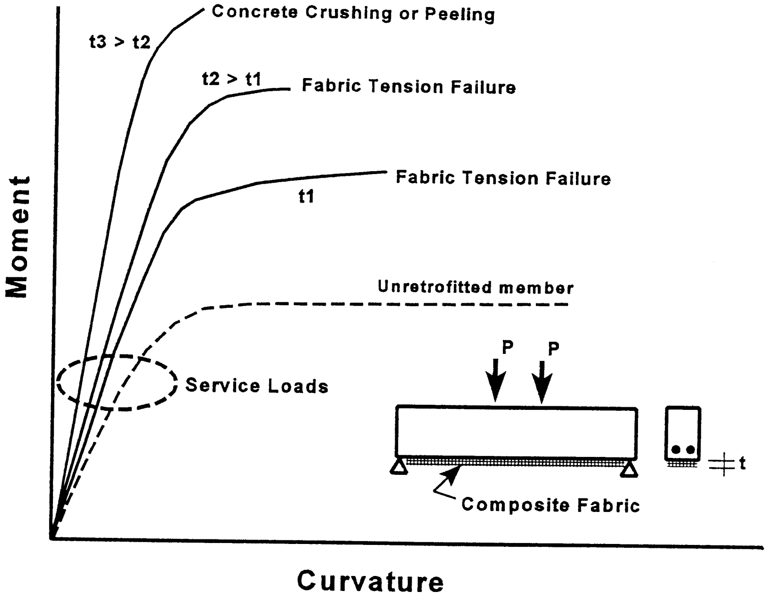


Figure 6. Behavior of flexural R/C elements with different failure modes

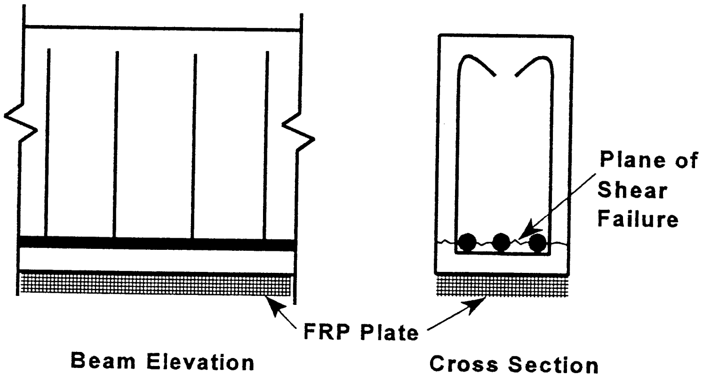


Figure 7. Failure of over-reinforced beam by peeling

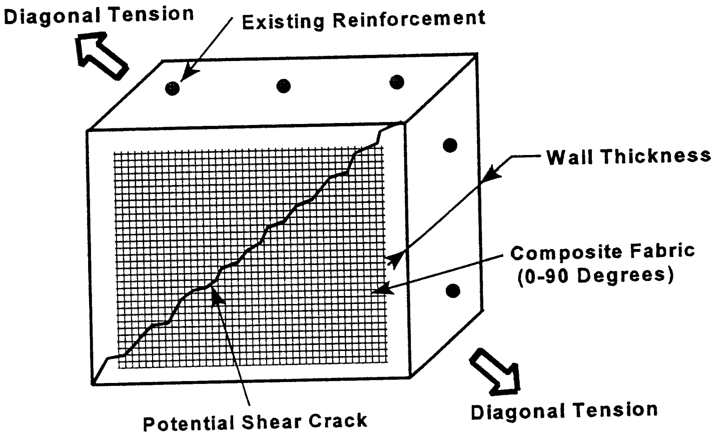


Figure 8. Mechanism of shear resistance

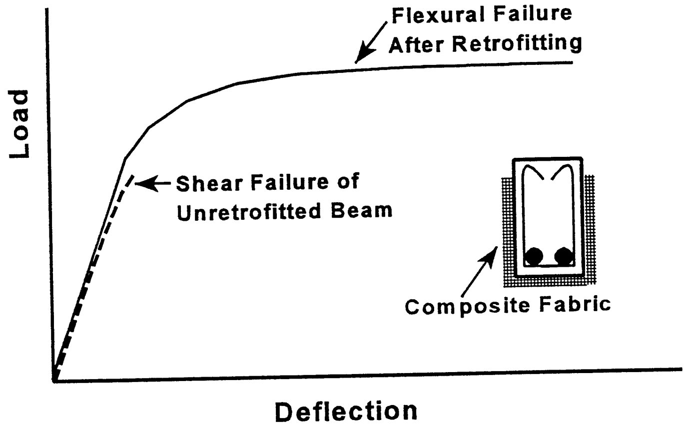


Figure 9. Behavior of R/C beams retrofitted for enhanced shear capacity

ADVANTAGES OF THE TECHNIQUE

Strengthening of concrete walls with this technique has several advantages over the use of conventional approaches. Some of the salient advantages are listed below:

a) The retrofit will provide significant out-of-plane flexural capacity for the wall.
b) The stiffness of the wall will not increase as much as it would if shotcreting were used.
c) The horizontal and vertical fibers in the fabric greatly increase the in-plane shear capacity of the wall.

d) The fiber composite fabrics will add very little weight to the wall (less than 1/4 psf) and therefore will cause negligible increases in the inertial forces caused by an earthquake.
e) The small weight added to the wall will not require any strengthening of the foundation.
f) The method will increase the wall thickness by a negligible amount (about 1/8 in.) and little valuable floor space will be lost as a result of the strengthening.
g) The fiber composite fabrics can be easily cut in the field (with an ordinary pair of scissors) to allow for openings in the wall. This will greatly simplify the construction and save labor costs.
h) The light weight of the fabrics and the simplified method will reduce construction time; this is particularly of interest in buildings that are occupied during the retrofit process.
i) The method costs lower than conventional retrofitting using shotcrete.

Glass fibers may disintegrate with time when placed in an alkaline environment such as fresh concrete. Even after the concrete is fully cured, exposure to rain and water can raise the alkalinity of concrete. Thus, when glass fibers are used, care must be taken to ensure durability of the repair. In the procedure described above, the first layer of epoxy serves as a barrier between the glass fibers and the concrete structure. Consequently, the fibers do not come in direct contact with concrete. Furthermore, the epoxy must be formulated such that it would not develop micro cracks as a result of stresses induced by temperature fluctuations. Such micro cracks could allow seepage of potentially alkaline materials to the glass fibers.

FIELD APPLICATION

The Northridge earthquake of January 17, 1994 was assessed to have a magnitude of 6.7 and caused severe damage to a large number of structures (Moehle et al. 1994). One of the structures damaged in this earthquake was a tilt-up building that was part of an industrial complex . Although some of the buildings on this site remained undamaged, portions of two structures were severely damaged during the earthquake. Of these two buildings, the one with most damage is shown in Fig. 10. The damage was concentrated in the tilt-up wall panels in the two western bays of the building. The tilt-up panels were 7 in. wide and were reinforced with Grade 40, No. 4 @18 in. in the vertical direction and No. 4 @11 in. in the horizontal direction. The walls were tied together with 15 in. x 15 in. cast-in-place columns located at 20 ft or 25 ft o.c. The wall horizontal reinforcement extended a minimum of 10 in. into the cast-in-place columns. The walls were about 30 ft. tall and were properly connected to the floor slab and the roof; no sign of distress was observed in the connection regions.

An examination of the walls after the earthquake revealed extensive horizontal cracks at about mid-height of the walls, indicating that the walls lacked adequate vertical reinforcement to resist the seismic loads (Fig. 11). Core samples indicated that the average compressive strength for the concrete was 2600 psi. The moment capacity of a 1-ft wide vertical strip of the wall is 16.3 kip-in. For a 30-ft tall wall, this is sufficient to resist 13.8% of the wall weight. The recorded ground motion accelerations in sites close to the building were much higher than 0.138 g. Moreover, the walls were not strong enough to resist the seismic forces recommended by the UBC (1991). It was clear that the flexural capacity of the walls had to be increased.

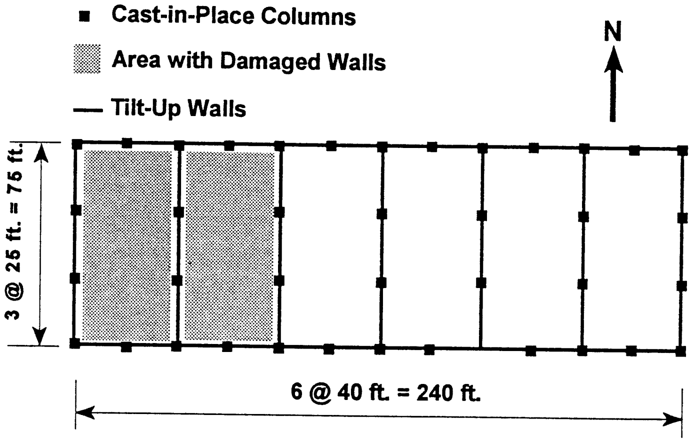


Figure 10. Plan of building damaged in the Northridge earthquake

If the walls had spanned in the horizontal direction, the existing reinforcement would have been barely sufficient to meet the demand. However, the relative stiffness of the supports were such that the wall panels spanned in the vertical direction, where the existing reinforcement was insufficient to resist the imposed loads. This is why the horizontal flexural cracks were widest near the mid-height of the wall. It is not clear if any of these cracks were formed during the construction and erection of the walls. Even if some cracks were formed at that time, the width of the cracks at mid-height of the walls clearly indicated that the vertical reinforcement in the panels had yielded.

A few different alternatives were evaluated and the merits of each system including cost, construction time, and disruptions to the daily operations of the complex were carefully evaluated. The conventional techniques included strengthening of walls with gunite, replacement of the tilt-up panels with new ones, and external post-tensioning of the walls. It was decided that the best solution would be to strengthen both faces of the walls with composite fabrics utilizing the previously-discussed technique. The fabric utilized had a tensile strength of 1 kip/in. in the longitudinal direction. Several coupons constructed with this fabric and the two-component epoxy with a fiber content of 40% by volume have been tested according to ASTM D3039. The minimum tensile strength of the coupons is 60 ksi with a modulus of elasticity ranging between 2800 and 3000 ksi. The flexural strength of a one-foot wide strip of the wall after retrofitting, assuming that the contribution of the composite fabric in compression is negligible, would be 87 k-in, capable of resisting 74% of the moment caused by the wall weight. Because the thickness of the composite materials on each face of the wall was less than 1/8 in., and considering the low specific gravity of the materials, no adjustments to the foundation were needed.

The use of new materials and methods of construction, such as the one discussed here, is possible under the provisions of Sec. 105 of the UBC (1991). The lack of previous field applications of this technique, however, led to a number of questions raised by the local building officials. Some of these questions were concerning the structural behavior of the system. Those concerns were addressed by providing the officials with laboratory test results. Other questions dealt with health, environmental, and fire safety issues of the composite system and in particular the epoxy. After all these concerns were responded to in a satisfactory manner, the city issued the permit for construction.

The walls were sand blasted to remove any paint. The two-part epoxy was mixed in the field and applied in thin layers to the wall. To ensure proper mixing of the epoxy in the field, the two components were different colors and had to be mixed until a uniform color was achieved. The 3-ft. wide fabrics were then applied to the wall in vertical strips and pressed against the epoxied wall. In a similar fashion, the subsequent strips of fabric were added with a minimum overlap of 6 inches with the adjacent strip to provide a continuous fabric on the wall. Figure 12 shows the installation of the fabrics on one of the walls. A major advantage of this system is the ease by which the fabrics can be cut in the field and placed in hard-to-reach areas; this was particularly

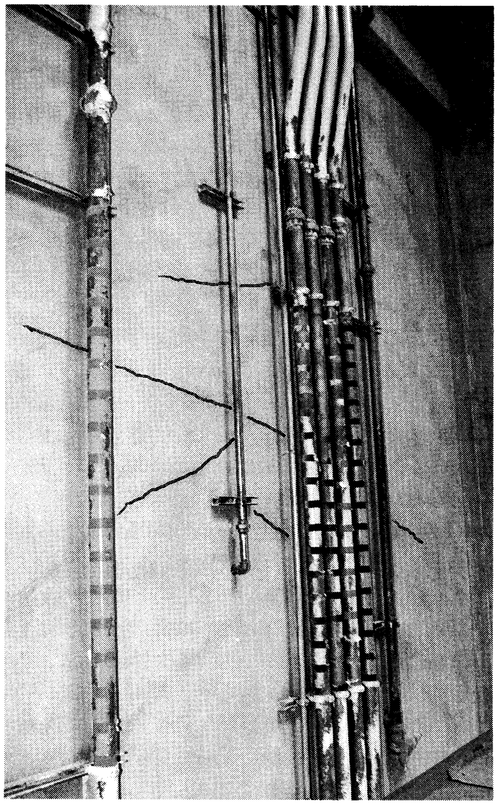


Figure 11. Typical cracked wall highlighting major cracks; the pipelines remained in place during the retrofit (*Courtesy of External Reinforcement Inc.*)

Figure 12. Application of Composite Fabrics to both faces of Tilt-Up Walls (*Courtesy of External Reinforcement Inc.*)

important in this project where at numerous locations pipes either penetrated through the walls or were positioned with a small clearance parallel to the wall surface (Fig. 11). The use of this strengthening technique did not require removal of any pipes and therefore had minimal impact on the operational activities of this industrial facility.

Once the fabric was attached to the wall, a second coating of epoxy was applied to the exterior surface so that the fabric was totally impregnated with the epoxy. Finally, the wall was painted with a special ultraviolet-protective layer of coating; the coating color was selected to match the original color of the building. The building at completion is shown in Fig. 13. Overall, more than 20,000 ft^2 of wall surface were strengthened in this project, making it the largest reported case where such technique has been used.

In design of such projects, care must be taken to ensure that the retrofitted structure fails in a ductile manner. For tiltup buildings, for example, one must ensure that brittle failures such as shear failure of the wall or failure of the connections between the wall and the adjacent elements is prevented. These factors were considered in this project. Furthermore, the design of the retrofit for the wall itself was carried out such that the failure of the wall will be by yielding of the longitudinal bars, followed by fracture of the composite fibers.

Figure 13. Western view of the building at the completion of the project (*Courtesy of External Reinforcement Inc.*)

ECONOMICAL CONSIDERATIONS

In most cases, the cost of rehabilitation is not related to the construction costs alone. Other factors, such as the potential permanent loss of leasable space and the short-term costs associated with loss of productivity and revenue generation by the occupants are major issues to be considered. In the case of the building reported here, for example, a large number of pipes passed through several damaged walls at various locations. One of the main design considerations was to ensure ongoing operation of the facility during the retrofit. The flexibility of the fabrics allowed them to be passed around the pipes at hard-to-reach locations where only small clearances were present. As a result, there was no need to separate the pipes from the walls and the retrofit activities were carried out without interrupting the operations of the plant. The cost for the project was about 70% of the lowest alternative technique and the construction was completed in two months.

CONCLUSIONS

Beam test results indicate that retrofitting of flexural reinforced concrete members with composite fabrics is a very effective technique for increasing the flexural and shear strength of these elements. Similar to steel-reinforced concrete structures where the mode of failure is governed by the amount of the reinforcement present, in these applications the amount and the strength of the fabric controls the mode of failure. Assuming that the epoxy does not fail prematurely, when lighter fabrics are used, the maximum load is that causing tension failure of the fabric. When heavier fabrics are used, the members will fail by either compression crushing of concrete or a shear failure at the plane passing through the longitudinal steel bars.

Field application of GFRP fabric in repairing this building that was severely damaged during the Northridge earthquake provided a unique economical solution for the retrofitting of the building. Considering the lower cost, the ease of application, and the improved structural behavior that will result, the technique provides a viable alternative for seismic retrofitting of reinforced concrete walls.

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