## 技術調査論文

# 복합재료를 이용한 토목·건축 구조물의 보수·보강기술

임승규* · H. Thomas Hahn**

# Composite Materials in Repair and Strengthening of Civil Engineering Structures

Seung-Gyu Lim* and H. Thomas Hahn**

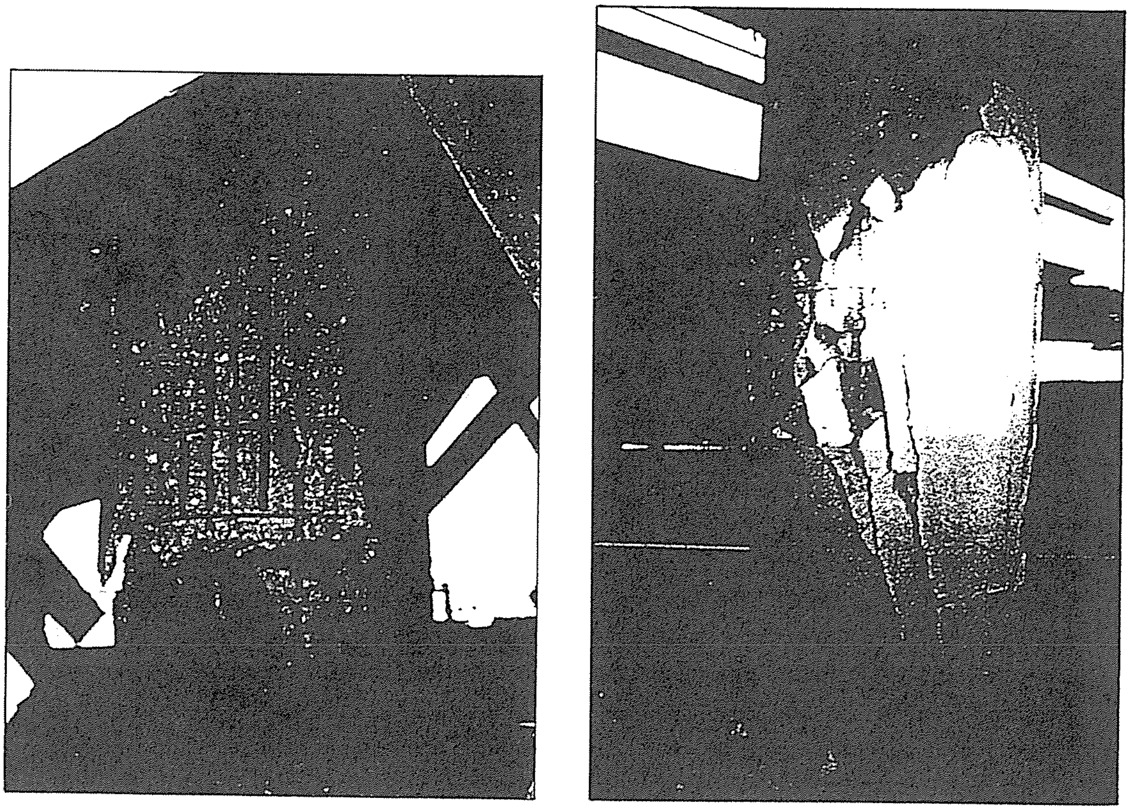

## ABSTRACT

Both deterioration due to corrosion and excessive loadings caused by over traffics or earthquakes are the major causes of loss of function of reinforced concrete structures all over the world. Thus, improved, cost effective and reliable techniques and materials are urgently needed to repair and strengthen the deteriorated and damaged concrete structures. The most conventional techniques have many limitations to be overcame. However, these techniques are much more economical than rebuilding, yet conventional methods are costly, timeconsuming, and often ineffective. Therefore, there is a need to develop new materials and techniques capable of rapidly and cost-effectively rehabilitating civil engineering structures. R&D works on the new and more economical techniques for rehabilitating reinforced concrete structure elements such as columns, beams, and walls using advanced composite materials began several years ago. The most R&D and field application projects have concentrated on concrete column repair and reinforcement. In this report, recent R&D works and commercialized techniques on concrete structure repair and strengthening using advanced composites will be reviewed.


## 1. Introduction

Deterioration of reinforced concrete due to corrosion of the reinforcing steel and environmental effects on the concrete is a long-term but almost inevitable phenomenon. Also, excessive loading caused by over traffic loads, earthquakes, or dead load may weaken even new reinforced concrete structures. Both deterioration and excessive loading are the causes of loss of function of reinforced concrete structures all over the world[1]. Moreover, it is essential that at least lifeline structures(bridge, highway, power line structure, etc.) and buildings(high rising office building, parking structure, etc.) that pose a significant hazard to the public if those would collapse must be returned to the previous safe condition.

* Principal Research Engineer, Corporate R&D Center, Sunkyong Industries Ltd.
** Professor, Hughes Aircraft Company Chair, Mechanical and Aerospace Engineering Dept, University of California, Los Angeles, USA



(a) Corrosion Damage (b) Earthquake Damage

Fig. 1. Example of Highway Column Damages

There is no question that there is not enough money available to rebuild all the deteriorated and weakened concrete structures. Thus, improved, cost effective and reliable techniques and materials are urgently needed to repair and strengthen the deteriorated concrete structures, so that those may have more longer useful service life. The most common techniques of repair and stregthening are reinforced concrete jackets, steel plate jackets, and adhesively bonded steel plates. The current methods have many limitations to be overcame as following[2~4];

Reinforced Concrete Jackets

- Additional weight and cross-sectional area.
- Additional work to remove existing concrete over steel reinforcement and attach additional steel reinforcement.

Steel Plate Jackets & Adhesively Bonded Steel Plates

- Difficult and expensive installation - Heavy plates and thick plate welding to form an integral plate.
- Need to fill annular space between steel jacket and concrete structure.
- Weight and thickness of plates result in significant stress on bonds and clearance restriction for function, respectively.

These repair and retrofitting techniques are much more economical than rebuilding, yet conventional methods are costly, timeconsuming,

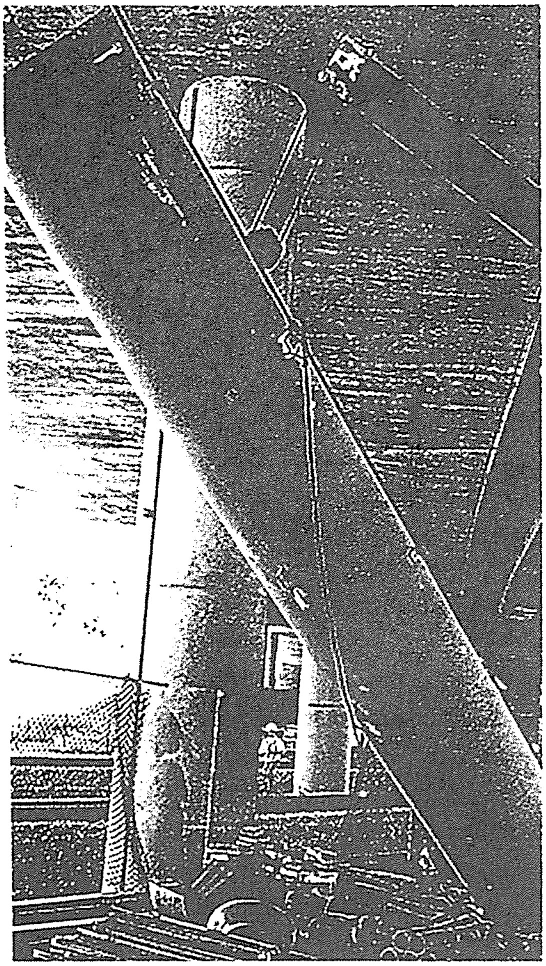


Fig. 2. Steel Jacketing Method for Column Strengthening

and often ineffective. Therefore, there is a need to develop new materials and techniques capable of rapidly and cost-effectively rehabilitating civil structures.

R&D works on the new and more economical techniques for rehabilitating reinforced concrete structure elements such as columns, beams, and walls using advanced composite materials began several years ago[5~28]. To date, most R&D and field application projects have concentrated on concrete column repair and reinforcement[5~17]. However, beam and wall strengthening applications are expanding quickly in U.S.A.[18~28]. In this report, recent R&D works and commercialized techniques on concrete structure repair and strengthening using advanced composites will be reviewed.

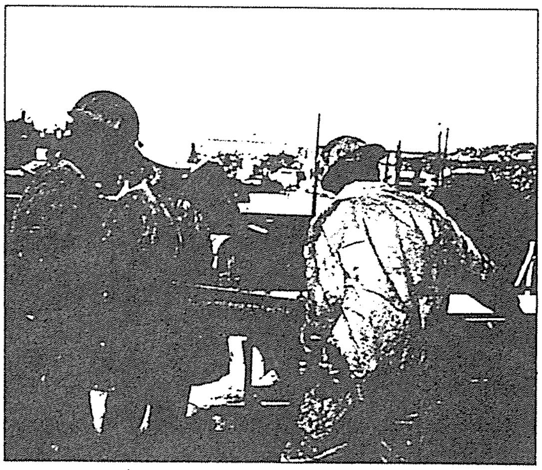
## 2. Research & Development Trend

### 2-1. Repair and Retrofitting of Reinforced Concrete Columns

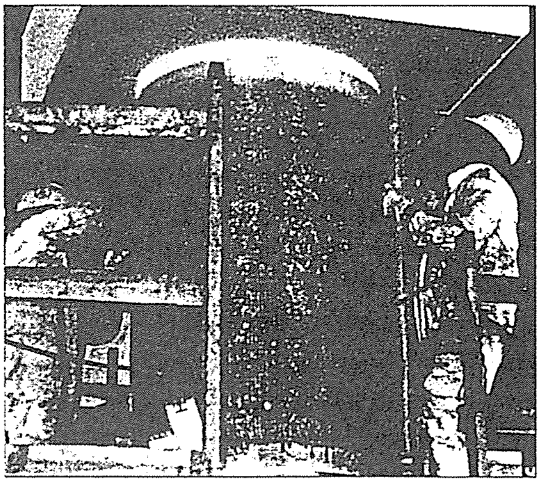
In 1992, there were 225,825(39%) U.S. bridges that were structurally deficient or obsolete. Approximately 25,000 freeway bridge columns in California need seismic retrofiiting; about half have been retrofitted to date - almost all using steel plate jacketing. Only a few have composite jacketing, primarily for demonstration and field application approval of Caltrans - The California Department of Transportation. The freeway column repair market in California alone is estimated at about $250-million[29].

Over the last three years many structure retrofit company and university research group have turned their attention to compoiste jacketing, citing their performance and economics versus steel plate jacket technique[8~17]. Now, advanced composite wraps or jackets are of high interest to Caltrans because they will not corrode and they offer the promise of costing less to install and maintain than steel plate jacket systems. Also, many building owners are applying E-glass fiber composite jackets to parking structure columns.

Hexcel Fyfe Co.[8] is the first composite fabricator to install a field demonstration for repair and strengthening of concrete columns and is also the most successful commercial retrofitter for parking structures. They developed TYFO™ S Fibrwrap™ system to add strength and ductility to existing columns and to repair the damaged



(a) On-site Impregnated Hybrid Fabric



(b) Prepreg Wrapping onto Column

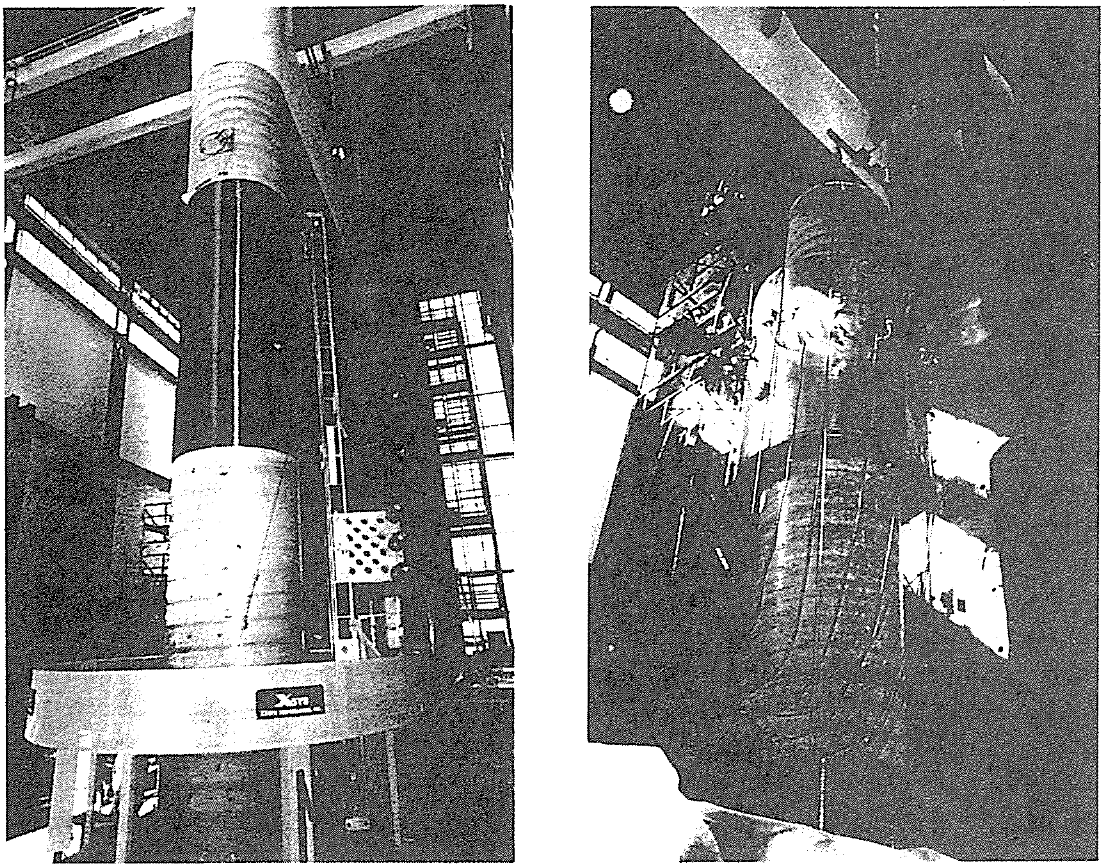
Fig. 3. TYPO™ S Fibrwrap System Installation for Column Retrofitting[8]

columns using high strength hybrid woven(E-glass in the circumferential direction around the column/Aramid in the vertical direction=90/10) /epoxy composites. Initial test results carried out on circular columns and rectangular columns built to 0.4 scale show ductility improvements to levels 10 to 14-three to five times higher than as-built columns(without composite wrapping) and equal to or better than the steel jackets[8, 13~15]. In 1992, TYFO™ S Fibrwrap™ System was applied on 15 bridge columns at an Interstate 5 freeway exit in Los Angeles. They were not damaged by the 1994 Northridge earthquake.

Based on a similar design approach Structural Rehabilitation Corp[9]. has also developed Quake Wrap™ system using glass fiber fabric/epoxy composite to provide confinement and add the ductility and strength on the concrete columns. Quake Wrap system require less time for complete installation and maintenance than conventional method. To install, any external coating are first removed, the column surface is cleaned, and two-part epoxy resin mixed in the field is applied in thin layers to the column. The 0.91m wide glass fabric is wrapped around the column and press against the epoxied column. In a similar fashion, the next layer of glass fabric is added if necessary. Finally, a thin layer of epoxy is applied over Quake Wrap. The retrofitted column could be covered with paint, plaster, or other coatings if necessary.

Carbon fiber tow sheet of Tonen(Japan) has also been applied to repair and strengthen concrete columns by Structural Preservation Systems, Inc. [10]. The installation procedure is similar to TYFO™ S Fibrwrap™ system of Hexcel Fyfe Co. [8] and Quake Wrap™ system of Structural Rehabilitation Corp. [9].

XXsys Technologies, Inc. [11] developed seamless circumferential retrofit wraps for Caltrans bridge application approval. They are challenging TYFO™ S Fibrwrap™ System of Hexcel Fyfe Co. by improving the application speed as well as stiffness using carbon/epoxy composite. XXsys uses a M10E-AS4D 12K carbon fiber(Hercules) tow prepreg produced with formulated epoxy resin (produced by Ciba Composites recently acquired by Hexcel) and has introduced a proprietary machine, called the "Robo-Wrapper" to automatically wind precise amounts of tow prepreg around the



(a) Tow Prepreg Winding Using "Robo-Wrapper" (b) Curing Oven with Radient Heat

Fig. 4. Automatic Tow Prepreg Winding for Column Retrofitting[11]

bridge column. After tow prepreg wrapping curing is done at the job site by thremally rasing the temperature to 250°F. University of California at San Diego(UCSD) conducted tests of the XXsys system on circular and rectangular columns. As built columns showed ductility numbers from 1.5 to 6 while XXsys-wrapped columns provided ductility from 8 to 14, as good as or better than steel jacketed columns[6]. Also, with a second-generation automatic winder, XXsys predicts they can wrap columns five to 10 times faster than welded steel clam-shell, cutting the average time to less than a day vs. threee to five days for 3/8-inch to 3/4-inch steel shells.

A new composite jacketing system for retrofitting reinforced columns, called Snap Tite™, has been recently developed by CMI/NCF[12] and tested at the University of Southern California[17]. The new system utilizes a series of prefabricated glass fiber reinforced composite cylindrical shells with slits. The prefabricated shell jackets are manufactured in a proprietary process around a mandrel of the diameter matching the column to be retrofitted using a multiaxial, stitched, nonwoven E-glass fabric/isophthalic polyester composites. About 90 perecnt of the E-glass is placed around the column in the hoop direction. The other 10 perecnt is in the vertical direction for easier fabric

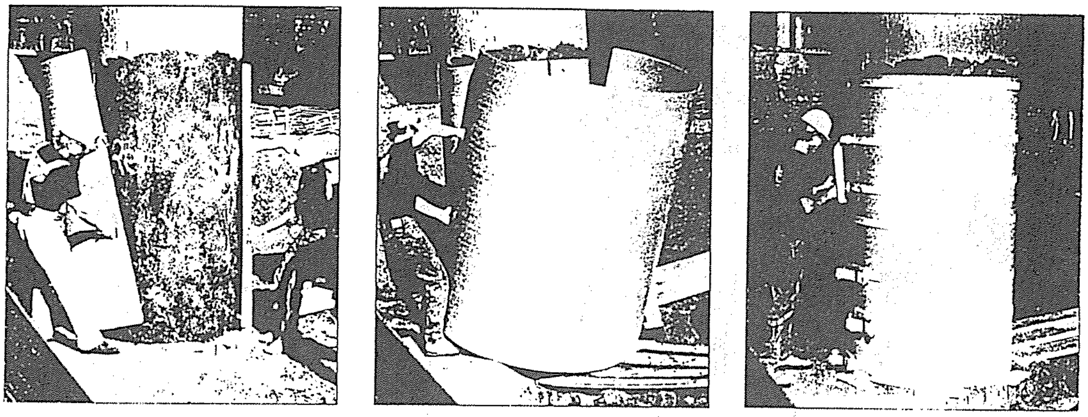


Fig. 5. Snap Tite™ Installation for Column Retrofitting[12]

handling. Field workers install Snap Tite by first spraying a urethane adhesive onto the column. Two workers can snap on a 60-lb, 48--inch tall by 48-inch diameter jacket shell. They repeat adhesive and jacket additions until they achieve design specification, usually with three to five plies of composite shell. The effectiveness of Snap Tite has been evaluated for the model columns designed based on a 1 : 2 scale of freeway columns. Retrofitted columns with 4-layer jacketing developed very stable hysteretic response up to a displacement ductility factor of 5.7. Retrofitted columns with 5-layer wrapping developed even higher load carrying capacity and a larger ductility factor[17].

Based on a similar approach Hardcore-Dupont has also developed a factory-built jacket segment approach. The multiaxial glass fiber fabric/vinyl ester composite jacket segments are manufactured using the Seemann Composite Resin Infusion

Table 1. Summary of Commercial Repair and Retrofitting Technologies of Reinforced Concrete Columns.

| Company | Method | Used Comp. Mat'ls | Remarks |
|---|---|---|---|
| Hexcel Fyfe Co.[8] | Prepreg Wrapping | Hybrid Fabric<br>Two-part Epoxy Resin | • On-site prepregging<br>• Room Temp. Curing |
| Structural Rehabilitation Corp.[9] | Dry Fabric Wrapping | Glass Fabric<br>Two-part Epoxy Resin | • Wet Lay-up Process<br>• Room Temp. Curing |
| Structural Preservation System, Inc.[10] | Dry Fiber Sheet Wrapping | Carbon Fiber Tow Sheet<br>Epoxy Resin | • Wet Lay-up Process<br>• Room Temp. Curing |
| XXsys Technologies, Inc. [11] | Tow Prepreg Winding | Carbon Fiber Tow<br>Formulated Epoxy Resin | • Factory Impregnated Tow Prepreg<br>• Automatic Robot Wrapper<br>• 250°F Curing |
| CMI/NCF[12] | Comp. Shell Jacketing | Glass Fabric<br>Isophthalic Polyester | • Prefabricated Comp. Shell<br>• Fully Overlapped Adhesive Bonding |
| Hardcore-DuPont [6] | Comp. Shell Jacketing | Glass Fabric<br>Vinyl Ester | • Prefabricated Comp. Shell by SCRIMP<br>• Slightly Overlapped Adhesive Bonding |

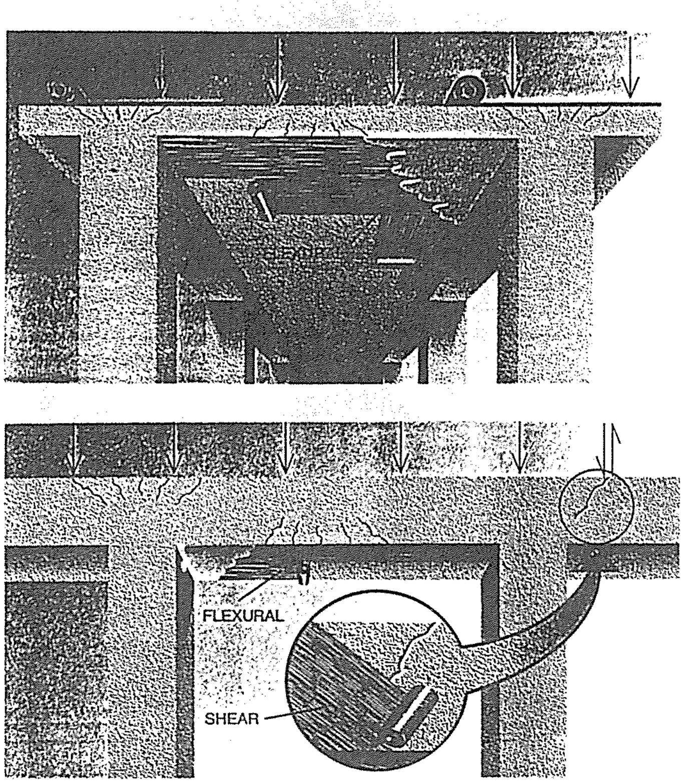
Molding Process(SCRIMP) to get the highest possible load bearing capacity. UCSD ran shear and lapsplice tests on Harcore-DuPont jacketed columns during 1995, reaching ductility levels of 10 on the lap-splice tests[6].

## 2-2. Strengthening of Concrete Beams and Walls

### 2-2-1. Flexural Strengthening of Reinforced Concrete Beams

Among the methods developed for increasing the flexural strength of concrete beams is steel plating. The earlier application of this technique involved the external attachment of a steel plate to the tension face of the beam by means of epoxy, bolts, or a combination of the two. The flexural capacity of the member is increased by a moment couple consisting of the tension force in the steel plate and an equal compression in the concrete. The advantage of this method over others such as external post-tensioning or additional supports are lower cost, ease of application and maintenance, elimination of special anchorages and the ability to strengthen the structure while it remains in use. The only drawback to this repair technique is the maintenance required to prevent the corrosion of the steel plate. Such corrosion could adversely affect the bond between the plate and the beam and cause the failure of the beam. Moreover, the heavy weight of the steel plates make their attachment more difficult, especially when the work has to be completed over head.

To overcome the above shortcommings, corrosion-proof fiber reinforced composites can be substituted for the steel plate. The light weight of composites will further simplify the construction. To install the composite plates, the first step be-



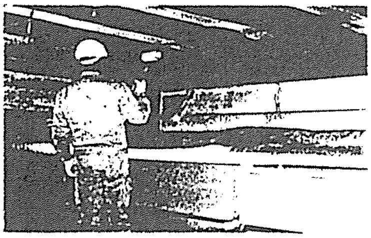



Fig. 6. Flexural Strengthening of Concrete Slab Using Carbon Fiber Tow Sheet[10]

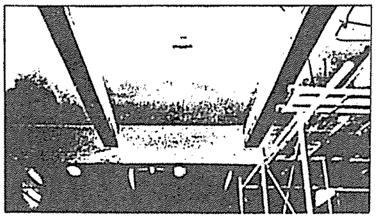


Fig. 7. Flexural Strengthening of Concrete Beam Using Carbon Fiber Two Sheet[10]

Table 2. Summary of Flexural Strengthening Methods of Reinforced Concrete Beams.

| Author(s) | Method | Used Comp. Mat'ls | Remarks |
|---|---|---|---|
| H. Saadatmanesh<br>M. Ehsani, et al.<br>[18~20] | Comp. Plate Bonding | • Cured Glass/Epoxy Plate<br>• Epoxy Adhesive | • Tested on Scale-downed Rectangular and T-section Beams |
| A.S. Crasto<br>R.Y. Kim, et al.<br>[21, 22] | Comp. Plate Bonding | • Vaccum Bag Cured Graphite/Epoxy Plate with $[0]_n$ | • Tested on Scale-downed Rectangular Beams<br>• Plate Design Test<br>• Adhesive Selection Test |
| M.J. Chajes<br>W.W. Finch, Jr.[23] | Wet Lay-up | • Carbon Fiber Tow Sheet<br>• Two-part Epoxy Resin | • Full Scale Field Demo. |
| M.J. Chajes<br>T.F. Januszka,<br>et al.[24] | Wet Lay-up | • Galss, Kevlar, Graphite Fabrics<br>• Two-part Epoxy resin | • Tested on Scale-downed T-section Beams<br>• Adhesive Selection Test |

gins with the preparing of the concrete beam surface. This involves grinding rough sections, sand blasting the entire concrete surface, epoxy injecting all cracks, and applying a surface primer. Once this process has been complete, the adhesive is applied onto the beam surface, and the composite plate is adhered to the beam soffits. The composite plate-adhesive is left to cure at ambient condition.

A limited amount of research has been conducted on flexural strengthening reinforcd concrete beams by bonding the advanced composite plates onto the tensile surface of beams[18~26]. The research works are summarized in Table 2.

### 2-2-2. Flexural and Shear Strengthening of Walls

Various methods for strengthening of lightly-reinforced concrete or Unreinforced Masonry (URM) walls have been studied in recent years. These conventional methods usually require the addition of framing elements to reduce the loads on the walls, or surface treatments such as shotcrete or gunite to increase the strength and ductility of the walls. Such retrofits often add significant mass to the structure and are time-consuming and costly to perform. The addition of the mass will increase the earth-quake-induced inertia forces and may require strengthening of the footings as well.

Fiber reinforced composites are well suited for wall repair and strengthening because the huge strength improvement could be expected by a thin

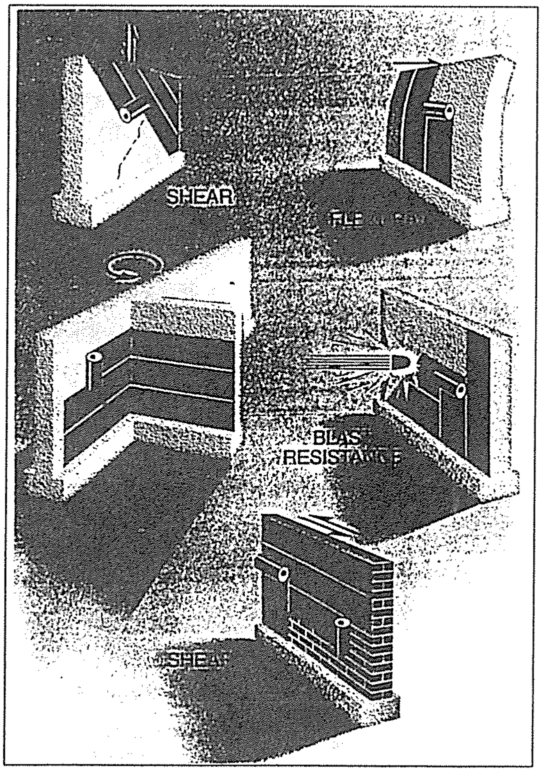



Fig. 8. Wall Strengthening Using Carbon Fiber Tow Sheet[10]

composite layer. Also, additional advantages of using composite materials include lower overall cost compared to conventional methods, simpler application and quick repair and strengthening project completion.

The steps required in strengthening an in-fill framed wall, for example, include : a) cleaning the wall surface to ensure all loose particles have been removed and if required, filling the mortar joints and resetting the loose bricks, (b) applying a thin layer of epoxy resin to the wall surface(s) and the adjacent frame elements, (c) placing the composite fabric on the epoxied surfaces and pressing it firmly against the wall, and (d) applying an additional layer of epoxy to the outer surface of the fabric to ensure that the fabric is fully saturated. If desired, the edges of fabric could be bolted to the frame using a steel angle. The surface of the wall could also be covered with coating materials to prevent environmental damages such as moisture, ultraviolet, etc. A limited amount of research has been conducted on stre-

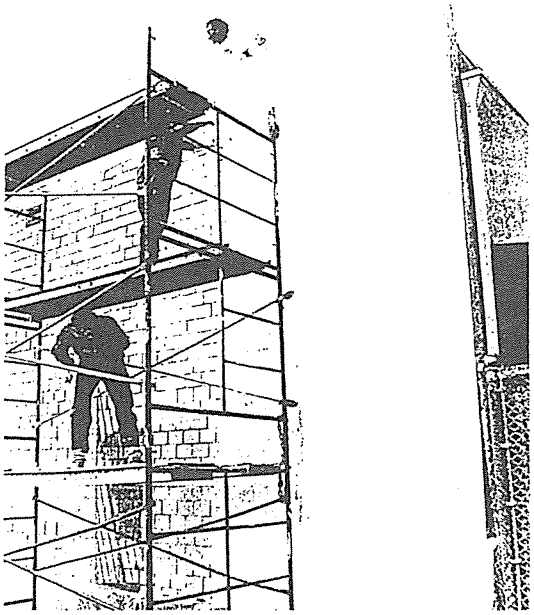


Fig. 10. Application of Composite Fabric for Wall Strengthening[28]

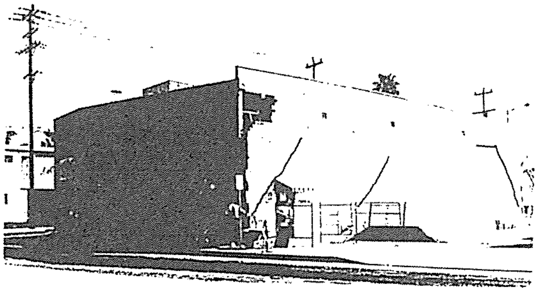


Fig. 9. Damaged Unreinforced Masonry(URM) Wall (Major Cracks are Highlighted for Identification)[28]


Fig. 11. Strengthened URM Wall[28]

Table 3. Summary of Commercial Flexural and Shear Strengthening Technologies of Walls.

| Company | Method | Used Comp. Mat'ls | Remarks |
|---|---|---|---|
| Hexcel Fyfe Co.[8] | Prepreg Lay-up | Hybrid Fabric<br>Two-part Epoxy Resin | • On-site Prepregging<br>• Room Temp. Curing |
| Structural Rehabilitation Corp. [9] | Dry Fabric Lay-up | Glass Fabric<br>Two-part Epoxy Resin | • Wet Lay-up Process<br>• Room Temp. Curing |
| Structural Preservation System, Inc.[10] | Dry Fiber Sheet Lay-up | Carbon Fiber Tow Sheet<br>Two-part Epoxy Resin | • Dry Lay-up Process<br>• Room Temp. Curing |

ngthening walls using the advanced composite materials. The commercial technologies of wall repair and strengthening are summarized in Table 3.

## 3. Conclusion

The repair and retrofit using advanced composite materials are the begining for the use of composites to upgrade civil engineering structures and could be the most effective steps to introduce composites into widespread civil engineering use. Many industrial companies and university research groups have been active in research and demonstration works to assess the performance, durability and cost of composites for repair and strengthening of reinforced concrete structues. However, there are some issues to be addressed and resolved so that advanced composite materials may be more effectively applied to civil engineering structures. These issues include :

(1) Standards and guidelines for using advanced composite materials
  - Lack of standards, codes and guidelines covering the design and fabrication of composite structural components.

(2) Familiarity of the civil engineering community with advanced composite materials
  - Lack of knowledge regrading new composites applications and future application under development.

(3) Materials system characterization
  - Lack of material property data base system

(4) Effects on the environment
  - Lack of environmental data base system such as health effects, flammability & toxicity, chemical resistance, etc.

(5) Costs
  - Lack of cost model for composite applications for civil engineering structures-need to develop the life cycle cost model.

Timely resolution of these issues will make it easier for civil engineering construction companies to more fully utilize advanced composite materials on civil engineering structures.

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