Application of Composites in Infrastructure – Part III
(a brief report on research and development)

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Abstract:

Composites have been in application for the past 3 – 4 decades, but only in the last decade that engineers have been given any serious consideration for its application in civil Infrastructure: such as bridges, roads, earthquake retrofitting of buildings etc. In this paper the growth of application of composites in civil infrastructures and some of its implications are discussed. This paper is divided into 3 parts: Part-I) Materials aspect - fundamentals of composite materials, the matrix and fibers used, Part-II) Composites industry viewpoint: outlook of an engineer of the Australian branch of a worldwide composites manufacturing company towards infrastructure applications **(part-I and part-II are in the previous paper),** and Part-III) a Structural engineer's observation on the increased application of composites in civil infrastructure.

Part III: "Concrete/Steel/Wood v Composite: A Structural engineering viewpoint on the beginning and growth of the application of composites in Infrastructure".

Although the design and analysis principles of composite structures are based on the same basic principles that are used for the design of so called traditional civil engineering structures, the actual application of composites in civil engineering projects started very late, in late 1980 to be precise. In the beginning, the FRP applications to civil infrastructure, was in the form of marine structures, piers, tanks and pilings for military requirement. Rapid use of any new material in civil infrastructure is difficult because of local code restrictions. Even now, very little research has been done for the application of composites in the infrastructures. The early application of composites in the civil infrastructures can be found in the form of repair and retrofit of buildings and bridges. California Transportation Agency started to use composite jacketing for the seismic retrofitting of bridge piers in the late 1980. Since then FRP materials have gained popularity in various seismic repair and retrofitting applications, both for bridges and buildings. Non-seismic repair and retrofit in the eastern part of the USA has gained momentum in the last ten years. In the area of new civil-structural work with 100% composites, the progress is relatively less. At present some light structures, prefabricated frames, light bridges, transmission poles, and various building parts are getting built commercially **[1].** In this paper an attempt is made to explain some of the work that has been done for new infrastructure and for repair and retrofit of existing structures using composite materials.

Infrastructure:

During the developmental stage of prestressed concrete, some of the early structures were storage tanks for liquids. Today, most of the concrete storage tanks are built by using circular prestressing, because it provides leak proof containers. Where corrosive chemicals are used metal alloy linings are provided. In recent days corrosion and solvent resistant raisins are increasingly being used in FRP composites. Not only the tanks made of these materials are easy to install and are more economical than the conventional materials, but also they have better service life. However, because of lack of awareness, lack of research data, and lack of marketing, the visibility of FRP tank constructions are low. Chemical and fuel storage tanks made with FRP have many advantages: high strength, corrosion resistance, design flexibility, easy to bond with steel and concrete, and low cost are some of them. Special expertise is required for the resin selection and structural design, which at the moment is delaying the widespread use of these materials. It is not very difficult to visualize that within a few years large number of tanks and its supports, starting from municipal water tanks to large petrochemical tanks, will be built with FRP composites **[2].** Many years ago, cooling towers were built in Nahorkatia, Assam, India, for Assam oil Company, using precast concrete structural members. The maximum length of any one beam, or wall, or slab was 6'-0" (a patent British design). It was a very difficult task to manufacture and assemble those units and keep a quality control. These types of structures can be built very easily today, using same or even slightly larger sizes of manufactured FRP units. The labor cost will be substantially low. Quality control will be much better. However, selection of FRP materials and proper resins will need modern expertise. Material cost is another item, which has to be investigated.

In Europe prestressed concrete structures are very common. Prestressed concrete wires, bars, and strands are typically made of high strength steel. The ultimate strength varies from 100 MPa (145 ksi) to 1862 MPa (270 ksi). Prestressed concrete is heavily used in civil infrastructure and for repair and retrofit **[2a, 2b]**. If sufficient concrete cover is not maintained the high strength steel can corrode causing failure of the structures. In some cases the problems become very acute, when the structures or structural components are exposed to weather (constant cyclic thermal loading), and sufficient concrete covers are not provided. On the other hand, very thick concrete covers will increase the weight of the component. If the members get too heavy they create erection problems. CFRP wire, bars and strands have been used successfully to solve these problems. They are light and they do not corrode. Recently engineers in Switzerland have reported the use of High-Strength Prestressed Hollow Circular Poles for the transmission of High-Voltage Electricity. Spun concrete has been used for creating the prototype poles and the prototypes were load tested. High strength concrete and CFRP high-strength bars were used for making 27 m (88.6 ft) high poles for 110 kV power lines in the northeastern part of Switzerland. The outer diameter was 820 mm (32.3 in) and the inner diameter was 740 mm (29.1 in) at the base. The section was prestressed with 40 CFRP rods with 5-mm (0.196 in) diameter. Not enough research data existed on the usage of CFRP bars for pretensioning. The Swiss engineers made extensive testing on the particular CFRP rods they used, and found that they need 250 mm (9.8 in) to 450 mm (17.7 in) bond length for 5-mm diameter CFRP bars. It took them four years to complete all the other tests on the prototype, which includes: Outdoor Bending Creep Test, Freeze Thaw Temperature Behavior, Short term Torsion test, and Long term compression Tests. It was observed that the thermal compatibility of the CFEP rods with concrete matrix could be a problem and had to be considered in the design. The prototypes were successfully tested in the autumn of 2000 **[3].** Application of CFRP reinforcements and prestresing wires, rods and strands have been steadily increasing. Several light footbridges have been constructed in Denmark and other

European countries using CFRP prestressing tendons **[4]**. However, it will take some time to build complete consumer confidence, before the widespread usage can be seen.

Structural shapes, plates, angles and tubes made of FRP materials are now available in the market. Most of the applications are in light structures and frames. In one of the recent projects of US Federal Aviation Agency, pultrudede fiberglass square tubing was utilized to build a disposable Antenna Tower within the airfield. The FAA criteria was – " Low Impact Resistant Structures shall be designed to withstand the static and operational / survival wind / jet blast loads with a suitable factor of safety, but fail readily when subjected to sudden collision forces of a 26.7 kN (6000 lb) light weight aircraft travelling at 139 km/h (75 knots)." The tower was 7-m (23-ft) tall and 0.9 m (3 ft wide). The engineers designed the tower as a truss. It was analyzed by finite element method considering the material as isotropic in the transverse directions. Dynamic analysis was done for the impact load. The structure was completed in the early 1990. The material cost was only $2000. It was a simple structure and did not involve any city or state building code. Similar smaller structures are getting built and consumer confidence is building up gradually **[5].** In the USA it took almost 50 years before prestressed concrete got its full entry in the construction market. In the late fifties and early sixties, even in a big city like New York, builders and developers were reluctant to invest their money on prestressed structures. Composite, as a building construction material, is going through that phase. However, composite is in a more advantageous situation, because several other industries, like aviation and auto have given it a successful early start.

In the beginning the composite structural shapes looked very much like structural steel shapes built according to AISC specification. The structural members were manufactured as I, H, L, O and other tube shapes. The process for making any FRP structural shape, by pultrusion process, is not as elaborate as making steel shapes. Very soon engineers developed other FRP structural shapes, which turned out to be more efficient and economical. In some cases modular units were fabricated. Laurel Lick Bridge, a short span all composite bridge, was constructed in West Virginia in 1997. The abutments were made of FRP columns/piles and multi-cellular panels with a reinforced concrete cap beam. The super structure was completely made of FRP materials. The deck modules were specially designed with a honeycomb shaped cross section. The typical deck modules looked like a hollow slab 6.10 m (20 ft) span and 4.88 m (16 ft) wide. The top and bottom flanges were slightly thicker than the webs. The webs formed the honeycomb shape. FRP wide flange beams spaced uniformly supported the deck-slabs. The size, weight and the shape of the decks were optimized and were designed to carry specific highway loads. The decks were fabricated using pultrusion process having multi-axial fabric architecture. Extensive laboratory testing was done on the high strength high performance adhesives, blind fasteners and the completed deck modules. Wick wire Run Bridge, a similar bridge, was built in the same area, in 1997, where supports were steel beams. These bridges are much lighter than the conventional concrete bridges. Similar developments are happening elsewhere. These projects were made successful with a well-planned systems approach **[6].**

A 20-m (65.6 ft) cable stay pedestrian bridge was constructed entirely by FRP materials, in Japan in 1998. The bridge center span was 11 m (36.1 ft) and the end spans were 4.5 m (14.8 ft). Rectangular hollow floor panels were supported by the longitudinal girders, which were supported by the stay cables. The two towers, floor panels and longitudinal girders were made of Pultruded GFRP materials. The stay cables and the cable anchorages were made of CFRP materials. The anchorage receptors bolts, and the splice plates were made of GRFP materials.

The bridge was load tested. The deflections and the member stresses were within the limits. However, the engineers stated that, improvement of member properties, structural shape and its rigidity and connection designs have to be improved **[7].** Several pedestrian bridges have been built in Europe for load testing purposes and for the observation of long-term behaviour. It will take some time before all the test results get compiled.

The design of civil infrastructure with steel, concrete or prestressed concrete is more or less a systematic matter. There are many textbooks, published design standards and guidelines. Composites are very special materials. They are very light, they can carry extremely high stresses and construction can be very simple. However, infrastructure design with composite materials is in its infant stage. Building design standards have not developed yet. The other difficulties are: structural materials are non-isotropic, and non homogeneous, some structural materials are laminates with different properties in each direction, there are no clear cut plastic yielding and the materials, in general, are brittle. At this moment there are not enough engineers in the general civil engineering market who are knowledgeable enough to design structures with composite materials. It is still a specialty item. However, finite element methods can be used for stress analysis and some simplified design methods as suggested by some of the authors can be used for the time being. Modern engineers may take comfort by recognizing that, when the Empire State Building was built (1929), there were no computers, not even calculators **[8].**

Repair and Retrofit:

In the civil infrastructure field composite materials have received sufficient recognition in the repair and retrofit market. The FRP-fabric and FRP-plates with high strength adhesives have been successfully used for the repair and retrofit work in many buildings and bridges. Although much research is necessary to perfect the methodologies, some reports of model testing in the laboratory and prototype testing in the fields are available. Hollaway and Leeming in “Strengthening of Reinforced Concrete Structures”, have discussed several repair and retrofit work (laboratory and field-testing) very systematically. In one case, in the early 1990, test beams were taken from an old deteriorated highway bridge in England. The beams were 18 m (59 ft) long, 310mm (12.2 in) x 710mm (28 in) in cross section and prestressed with 60 wires. CFRP composite plates were bonded to the bottom surface with Sikadur 31 or Sikadur 30 high strength adhesives. Plates of various lengths were used and in some cases some of the prestressing wires were removed. The beams were load tested before and after the placement of the CFRP plates and the results were compared with the theoretical values. The general observations were: 1) the CFRP plates provided significant improvement in crack control and increased beam stiffness in flexure. 2) No anchorage failure were noticed, 3) When tendons were removed loads were carried by the retrofitted beams successfully and 4) Retrofitting of concrete and prestressed concrete beams with bonded CFRP plates could be a viable system **[9].** Sika Ltd of UK has developed a standard strengthening system for concrete and masonry structures, using carbon fiber/epoxy polymer laminates and advanced epoxy adhesives for a number of years. In the matrix fiber volume content is generally > 68%. The thickness laminates varies from 1.2 to 1.4 mm (0.05 to 0.06 inch) and width varies from 50 to 150 mm (2 to 6 inches). Saw and Drewett have reported the case histories of several retrofit works in Europe and UK that happened in last twenty years, using Sika system. The common items in all of the above repair works were: 1) complete cleaning of the substrate, 2) Fabrication of the Carbadur laminates to proper size and length, 3) Application of the adhesives according to specification, 4) Using rubber rollers for removal of excess adhesives and air bubbles, 5) In some cases, drilling of bolts in the end anchorage zones to reduce the possibility of peeling. Using these procedures one 1963 bridge across river Rhine, in Switzerland was retrofitted. The carbon laminates, 1.2mm x 80mm (0.05 in x 3.15.in), were placed at the bottom of reinforced concrete bridge deck, in the transverse direction at 75 cm (3.0 inch) spacing. The reinforced concrete joists of the roof of Kings College Hospital of London were repaired with SIKA CarboDur laminas. The laminas were placed at the bottom of 400-mm (15.75 inch) deep joists. The un-reinforced masonry walls of an office building in Switzerland were retrofitted using the same methods. Three closely spaced 1.2mm x

100mm (0.05 in x 4 in) Carbadur laminas were placed in the walls to form an x-shape between the floors. The X-shape, acted like a tension only bracing system. The adjacent columns were used for anchoring the ends of the laminas. Many retrofitting jobs of wood bridges, concrete slabs, historical buildings and waffle slabs have been done in Europe **[10].** Recently CFRP strengthening of a large railroad bridge (145m (375.7 ft) long mid-span and 91m (298.6 ft) end-span) in Lulea, Sweden, and full scale testing was reported. Entire work was done without stopping the traffic. Load testing indicated significant reduction of deflection after retrofitting. **[11].**

Strengthening concrete and masonry structures with FRP jackets, plates, and fabrics and high strength adhesives has become very common in the USA since the early 1990. The usage of FRP is increasing every year. Almost 30 % of the US bridges have been classified as deficient. Since the early 1970 various repair methods have been tried in the colder part of the country. Since the beginning of 1990, industrial and marine structures were routinely retrofitted using high strength fiber composites (HSFC), in Wisconsin, Vermont, Kansas, Ontario, New York, Illinois, Indiana and Pennsylvania **[12].** As the FRP repair methods became popular, fiber wraps were tried in the old bridge piers and smoke stacks. The bridge decks, and slabs in the industrial and commercial buildings got repaired with FRP laminates. However, because of limited research data and lack of experience, usages of FRP in the infrastructures were limited. In the seismic areas, like California, the necessity of widespread seismic retrofit work was always discussed, because of financial reasons it never got momentum. Since the 1907 Long Beach earthquake engineers have been discussing the items like, redundancy, ductility and confinement. The repairs and some retrofit works were done using conventional methods with concrete, prestressed concrete, gunniting, and steel-plates. After the 1985 Mexico City Earthquake (many building collapsed), followed by 1987 Whittier Earthquake (many URM walls collapsed), engineers and particularly the legislators understood the necessity of seismic retrofit work in California. They realized that in the long run seismic retrofitting would be cheaper than going through the lengthy legal process after the structures collapse. Through legislation, retrofitting of un-reinforced masonry walls was made compulsory. After the 1989 Loma Prieta Earthquake, seeing the failures of buildings and bridges, the legislators and the California Transportation Authority (CAL Tran) became more serious on retrofitting of old buildings and bridges. Cal-Tran started collaborative research with the University of San Diego on bridge pier retrofitting by using FRP jacketing. Just about the same time, as the tension due to cold the war started to relax, the US defense and aerospace industry started to reduce in size. The industries and experts who were heavily engaged in the application of composites started to divert their attention to other industries. Civil infrastructures, particularly the repair and retrofit jobs became the direct beneficiary. Many universities diverted their research work to repair and retrofit with FRP. Saadatmanesh and Ehsani started research on strengthening of RC beams in the late 1980’s and they concluded that FRP and high strength adhesives could be effectively used for strengthening RC beams. **[13, 14]** They also have worked on the experimental and design development of URM retrofit jobs. **[15, 16]** Since the mid 1990’s Nani and others have done some work on the strengthening prestressed slabs. An existing prestressed parking structure slabs were successfully retrofitted using CFRP materials and subsequently it was load tested. They concluded that the CFRP placement was easy and it had increased the ultimate load carrying capacity of the slabs significantly **[17].** Although the FRP repair and retrofit systems are still developing and no definite building codes like steel and concrete codes exists yet, the repair and retrofit works are not standing still. Manufactures and suppliers managed to publish their own manuals based on the limited research to help the material selection process and design. Two large US suppliers/contractors, SIKA and Master Builders have their own manuals. **[18, 19]**

Steel jacketing of building and bridge columns was very expensive. It was heavy and it changed the stiffness of the columns. As an alternate to steel jacketing, FRP jacketing soon became very popular. Cal Tran did the application of FRP materials in seismic retrofit of the bridges and bridge piers in a very systemic manner. Cal Tran sponsored large-scale research work at UC San Diego. At present significant number of bridge columns have been retrofitted in California, with FRP materials (typical systems are, fiber wrap, prefab shell and full height prefab shell) **[20, 21, 22].**

Northridge Earthquake of 1994, caused several bridge failures in California. As a result bridge retrofit programs, both research and actual retrofitting jobs, increased significantly. The FRP retrofitting systems have taken a lion's share of the market, along with the conventional retrofitting systems like, steel jacketing, gunniting with reinforcements and external prestressing. The FRP materials, although well defined by the aerospace industries, are revalued for its applicability in the civil infrastructure **[23].**

The 1994 Northridge Earthquake caused extensive losses in California. It was close to $30 billion. From newly built prestressed parking structures to old wood residential buildings, severe damages were noticed in large number of structures. Seismologists reported that the magnitude of the earthquake was 6.8, however, unlike other earthquakes, this one had a strong vertical acceleration component. Public questioned the adequacy of the codes. In the first one month, there was no report of any damages of steel buildings. Then reports started to appear that there were many beam-column joint failures in the steel moment frames. Engineers were very nervous when the news appeared that the beam-column joints of many ductile moment resisting frames had also cracked. These well-designed frames and the joints were supposed to survive such earthquakes. Many beam-column joints of the concrete moment frames were also damaged. In 1995, at Cal-State Fullerton a pilot research project (funded) was started to see the feasibility of repairing and retrofitting of steel beam-column moment connections using conventional and FRP repair systems. The half scale models (six) were subjected to incremental cyclic loading till the ultimate loads were reached. Two of the defective specimens were repaired by using prefabricated braided epoxy graphite connectors connected with high strength epoxy adhesives or by bolts. The specimens did not reach the same ultimate load as the control specimen but they satisfied the ductility criteria. The connectors failed at the knee. It was recognized that with a stiffer connector the ultimate load carrying capacity could be reached. In another case, steel connector was adhesively bonded to the defective beam-column joint. The repaired specimen reached higher than the theoretical load, however, ductility was low. This pilot testing was probably the first ever attempted to repair steel beam-column joint with composite material. Much research is necessary in this area **[24].** In another research project, concrete beam column joints (six) were repaired and /or retrofitted with carbon-epoxy laminates and E-glass-epoxy laminates and high strength adhesives. The repaired and retrofitted joints were subjected to progressively increasing cyclic loading **[25].** The repaired and retrofitted specimens exceeded the ultimate load carrying capacity of the control specimens. Between the two repair materials (Carbon and E-glass) ductility was much better in the specimens with E-glass repair system. It was concluded that while Carbon system could provide sufficient strength, if ductility was a requirement E-glass system would be preferable. The figure 1 and 2 are the load deflection plots of the control and E-glass repaired specimens. The repaired specimen had more strength and ductility than the control specimen. The specimen with E-glass retrofit, after the cyclic load testing, is shown in the photograph-1 **[26].** At present, we are working on seismic retrofitting of unbonded prestressed concrete beams using e-glass and carbon composites. Our Initial, findings are very encouraging. The cracked control specimens, when repaired with only one layer of composite material, carried more that 160% of the original failure load.

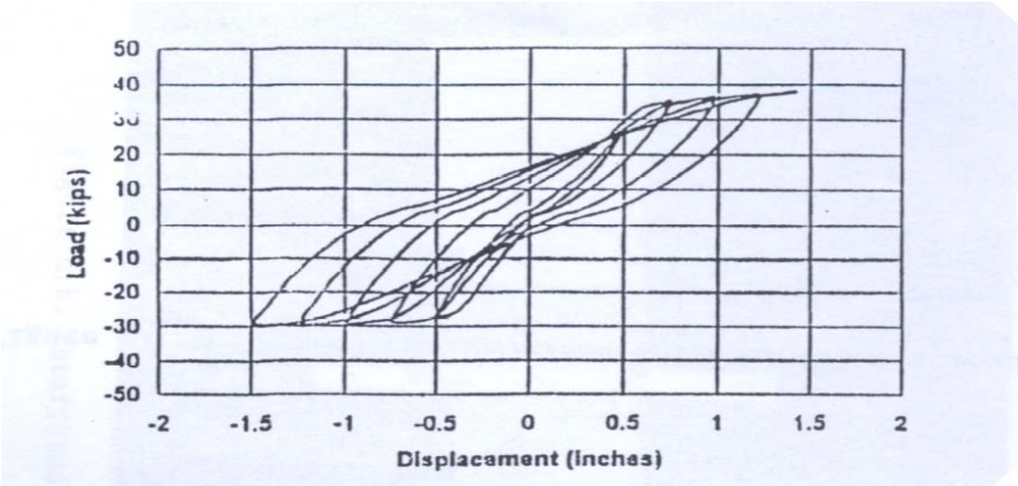


Figure-1 **Load-Deflection plot for the control specimen SP-1**

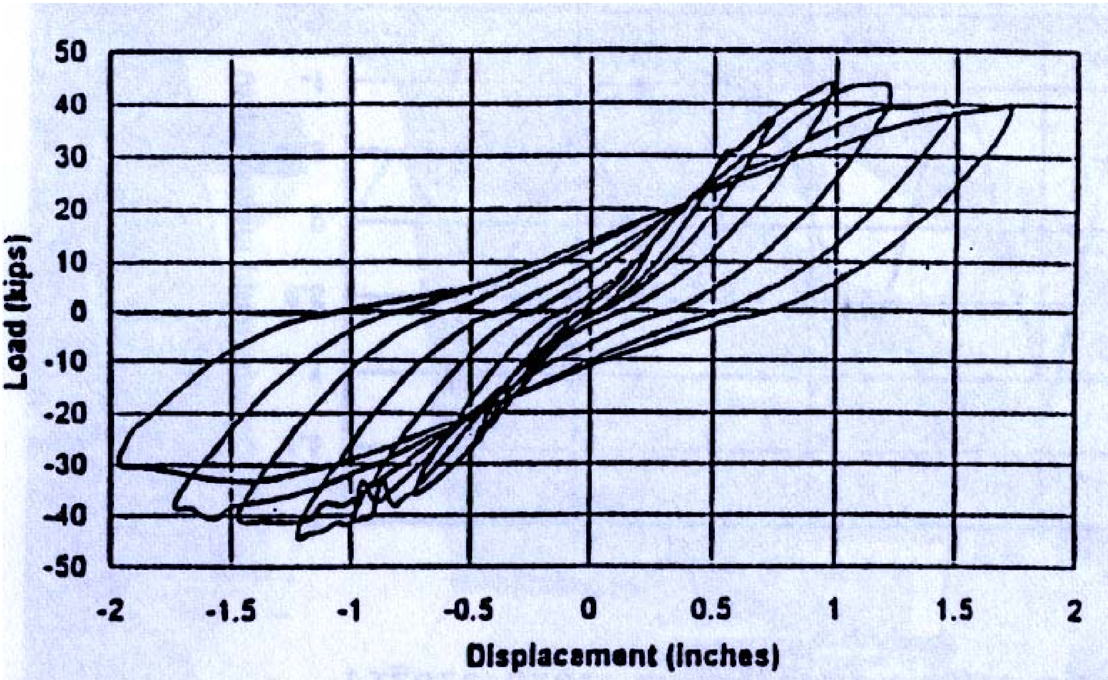
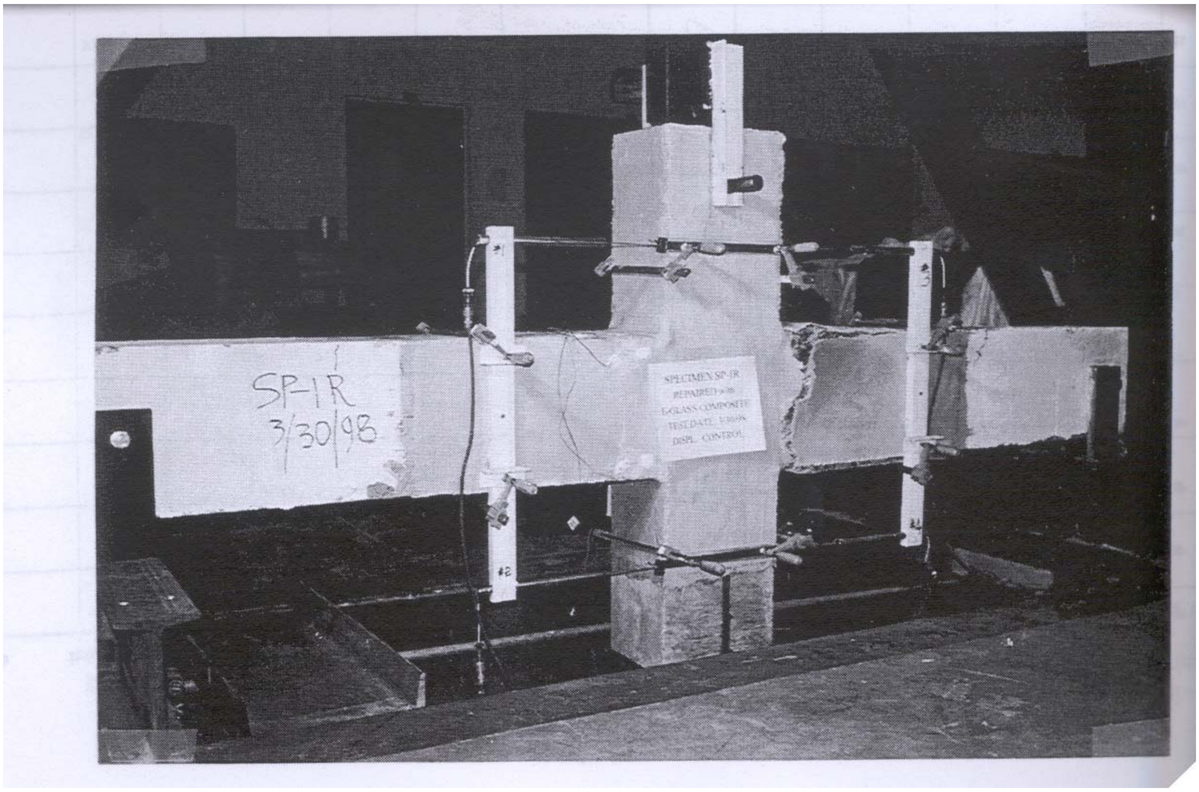


Figure 2 Load-Deflection plot for the repaired control specimen with E-glass SP-1R



Photograph-1
Repaired specimen SP-1R with E -Glass at ultimate stage of loading

Conclusion:

Currently, large amount of seismic and non-seismic repair and retrofit work of civil infrastructure, using FRP materials and high-strength and high performance adhesives, are going on in the USA. It is very clear that the volume of repair and retrofit works with composites will increase substantially in the future. The application of FRP materials for the new structures will depend on the ability of FRP to compete with the conventional materials. Lightness, strength and easy workability are three very positive aspects of FRP material. The FRP materials are now well accepted for repair and retrofit job. However, there are other items to consider. To market FRP materials for new structures, effect of environment, UV, chemical attack, high temperature, radiation, structural vibration, creep and shrinkage, and last but not least public acceptance and cost have to be considered.

Recommendation:

Extensive model and prototype testing under various conditions has to be done. A comprehensive design procedure for civil infrastructure has to be developed. All theoretical design methods must have experimental support. The applicability of the FRP materials, and the design and construction methods in civil infrastructures, has to be classified based on strength and durability.

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