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Structural Rehabilitation with Advanced Composites

Réhabilitation des structures porteuses avec des matériaux composites d'avant-garde

Sanierung von Tragwerken mit modernen Verbundwerkstoffen

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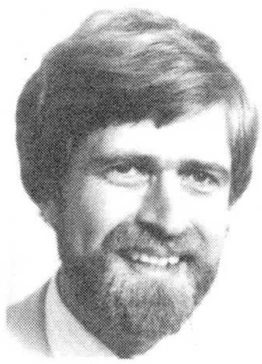

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SUMMARY

The paper provides an overview of the use of advanced composites in the repair, strengthening and seismic retrofit of existing concrete structures. The structural effectiveness of these rehabilitation measures is documented by large-scale experimental data in direct comparison to tested "as-built" behaviour and conventional rehabilitation measures. Advantages of and concerns with the uses of these new materials in civil engineering applications are addressed.

RÉSUMÉ

Cette communication donne une vue synoptique sur l'utilisation de matériaux composites d'avant-garde et hautement performants, pour renforcer et réhabiliter les ouvrages en béton. L'efficacité structurale de ces mesures de rénovation repose sur d'innombrables données résultant d'essais réalisés à grande échelle; ces données sont comparées aux résultats expérimentaux effectués sur des ouvrages existants et aux méthodes de réhabilitation classiques. Les avantages et les incertitudes découlant de l'emploi de ces nouveaux matériaux dans le domaine des constructions civiles sont présentés.

ZUSAMMENFASSUNG

Der Beitrag enthält einen Überblick über die Anwendung von hochfesten Kunstfasern in der Reparatur, Verstärkung und Erdbebensicherung bestehender Betonbauten. Die konstruktive Wirksamkeit dieser Erneuerungsmassnahmen ist mit Grossversuchsergebnissen dokumentiert und mit Versuchsdaten von bestehenden Bauten und konventionellen Sanierungsmethoden verglichen worden. Die Vorteile und Bedenken, die aus der Anwendung dieser neuen Materialien im Bauingenieurbereich erwachsen, werden erörtert.

1. INTRODUCTION

Advanced composite materials, predominantly developed for use in the aerospace industry, have shown a great potential for strengthening, retrofitting and repair of existing buildings and bridge structures to extend their service life well into the 21st century. With the broader availability of glass, aramid and carbon fibers, as well as automation in the manufacturing process, PMCs (Polymer Matrix Composites) can be affordable and competitive with conventional structural rehabilitation materials and processes.

The structural effectiveness of PMCs in rehabilitating existing structural systems has repeatedly been demonstrated with full or large-scale structural tests at the University of California, San Diego. Carbon fabric overlays have been used to retrofit reinforced and unreinforced masonry walls for seismic loads and to restore and more than double the displacement capacity in the repair of a full-scale 5-story reinforced masonry building tested under simulated seismic loads to failure. Bridge columns were seismically retrofitted and repaired with fiberglass, carbon and hybrid composite jackets and composite retrofits were shown to be just as effective as conventional steel jacket column retrofit technology.

While the low density and the high mechanical characteristics of advanced composite materials were long recognized, applications in the civil engineering sector were limited to date due to (1) high materials and manufacturing costs, and (2) the component by component replacement of existing structural members rather than a comprehensive design approach with these new materials. This paper provides an overview of the use of advanced composites in the repair, strengthening and retrofit of existing civil structures.

2. ADVANCED COMPOSITES FOR CIVIL ENGINEERING APPLICATIONS

The most common advanced composites fibers used in PMC structural applications are carbon, aramid and glass, and the most commonly used matrices are epoxies and esters. While a detailed discussion of materials, and manufacturing processes of these PMCs can be found elsewhere [1], only their key characteristics, including cost, will be summarized here with direct reference to civil engineering applications. In order to compete with conventional civil engineering materials, often referred to high performance fibers developed and used in the aerospace industry are cost prohibitive in the civil sector, limiting the choice to advanced composite materials referred to under the low to medium performance category.

The range of realistic properties can be summarized as follows:

<u>strength</u>: For quasi-isotropic material considerations or design assumptions strength values comparable to high strength structural steels can be achieved. However, due to the non-ductile failure characteristics only a limited range of these capacities can be utilized. Uni-directional fiber geometry can result in strength characteristics similar to high strength prestressing wires and strands.

<u>strain</u>: Failure strains are low and typically limited to the 1 to 3% range with carbon fibers at the lower and glass and aramids at the upper end of the range.

<u>modulus</u>: Moduli for quasi-isotropic assumptions range from 10% to 30% of steel and for uni-directional fiber applications from 1/3 to 2/3 of the structural steel modulus.

<u>cost</u>: Cost is dominated by the price of the fiber material, ranging currently per pound from $1-3 for glass to $10-14 for carbon (T300, AS4). Typical resins are $1-2 per pound.

With a 40 to 60% typical fiber volume fraction and automated manufacturing techniques, PMC structural component costs in place can range from $3-12 per pound, with glass at the lower and carbon at the upper end of the range.

It should be noted that both strength and modulus decrease rapidly with deviation of the fiber orientation from the loading direction which is largely a function of a very low shear modulus of the matrix or resin system, typically 1% or less of Young's Modulus for steel. For rehabilitation of existing concrete structures, the reduced weight of these advanced composite materials is not an issue since the application consists of thin overlays, as will be discussed in the following.

While the chemical resistance of these PMCs to acid or corrosive environments is very good in general, durability aspects such as ultra violet degradation of the matrix, alkaline reactions between glass and concrete, and water absorption by the resin system typically require a form of protective external coating. Furthermore, only limited information on the creep and relaxation characteristics of affordable PMCs in the civil engineering environment exist to date and require comprehensive evaluations. Also, significant differences in thermal characteristics between the existing concrete substrate and the PMC overlays need to be addressed. In the following only the short term structural effectiveness of PMC rehabilitation of existing concrete structures is discussed.

3. REHABILITATION OF EXISTING CONCRETE STRUCTURES

Rehabilitation of existing concrete structures with PMCs can be accomplished in three ways, namely by (1) external post-tensioning with PMC systems, (2) by linear application of strips of PMCs bonded and anchored to the concrete members, and (3) by thin surface overlays.

The first two general applications have been successfully implemented e.g. Meier, et al [2], but require the transfer of localized forces from the composite system to the existing structure. This need for special anchorage devices and local concentrated force transfer can largely be eliminated through the use of distributed surface overlays. Over the past five years these structural surface overlays have been systematically developed at UCSD and applied to (1) the seismic retrofit and repair of bridge columns, (2) the seismic retrofit and strengthening of reinforced and unreinforced concrete and masonry walls, and (3) the strengthening of bridge structures for increased superstructure capacity. Due to increasing concerns with the alkaline reaction between concrete and glass, the research described in the following has primarily focused on carbon overlays which are chemically and environmentally more resilient and stable.

3.1 Seismic Retrofit and Strengthening of Columns

One of the primary deficiencies of older reinforced concrete columns both in bridges and buildings is the insufficient amount of transverse reinforcement. Problems arising from this deficiency are (1) low ductility in unconfined concrete with low ultimate strength and strain, (2) premature buckling of longitudinal column reinforcement, (3) shear failures, and (4) bond and development failures of lap spliced reinforcement.

All of the above deficiencies can be removed by jacketing of the existing concrete column preferably with a circular or oval jacket providing distributed confining forces which result from the jacket curvature once membrane action in the jacket is activated by column dilation. For shear, which is not so much a confinement but rather a strength issue, also jackets of rectangular

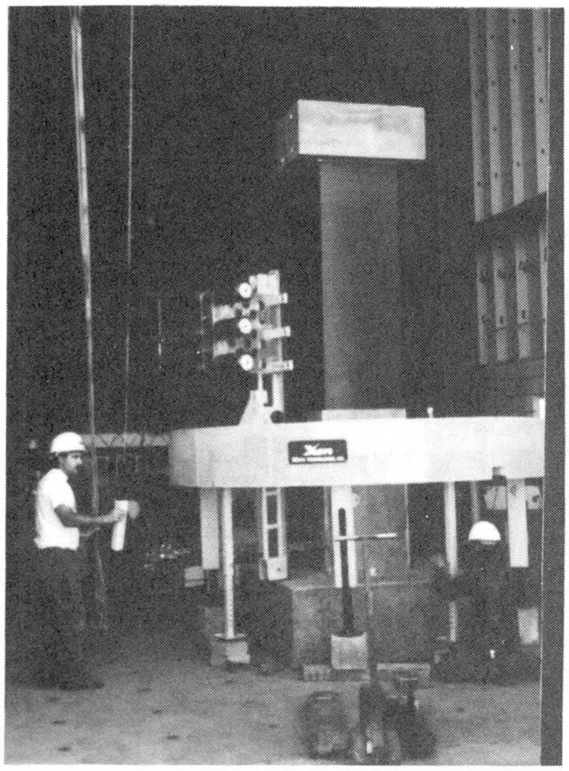
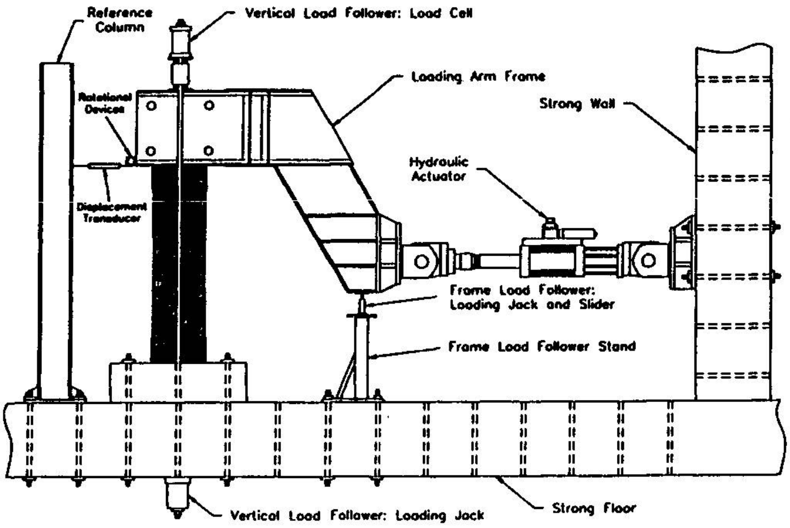
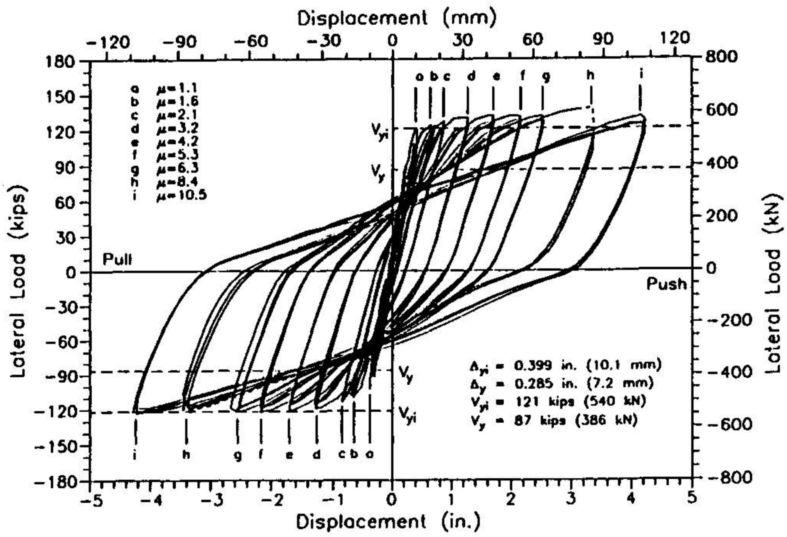


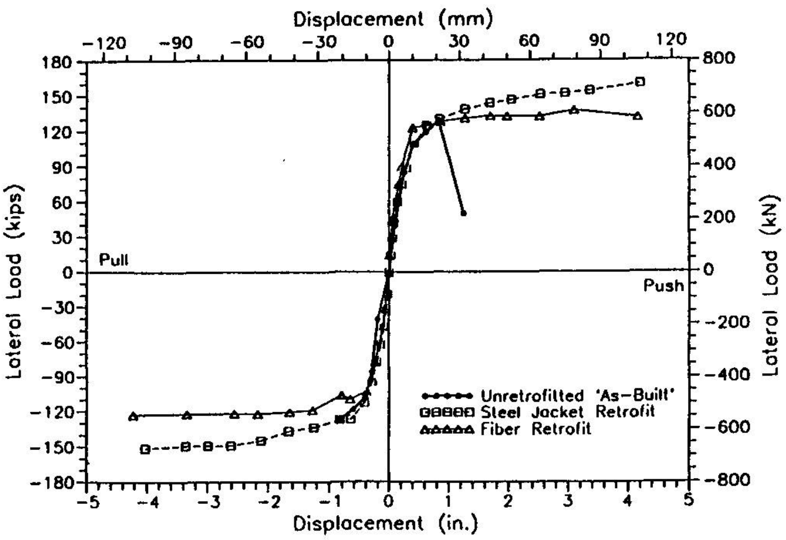
Fig. 1 Automated Carbon Jacket System



a) Test Setup



b) Load-Displacement Hysteresis



c) Load-Displacement Envelope Comparison

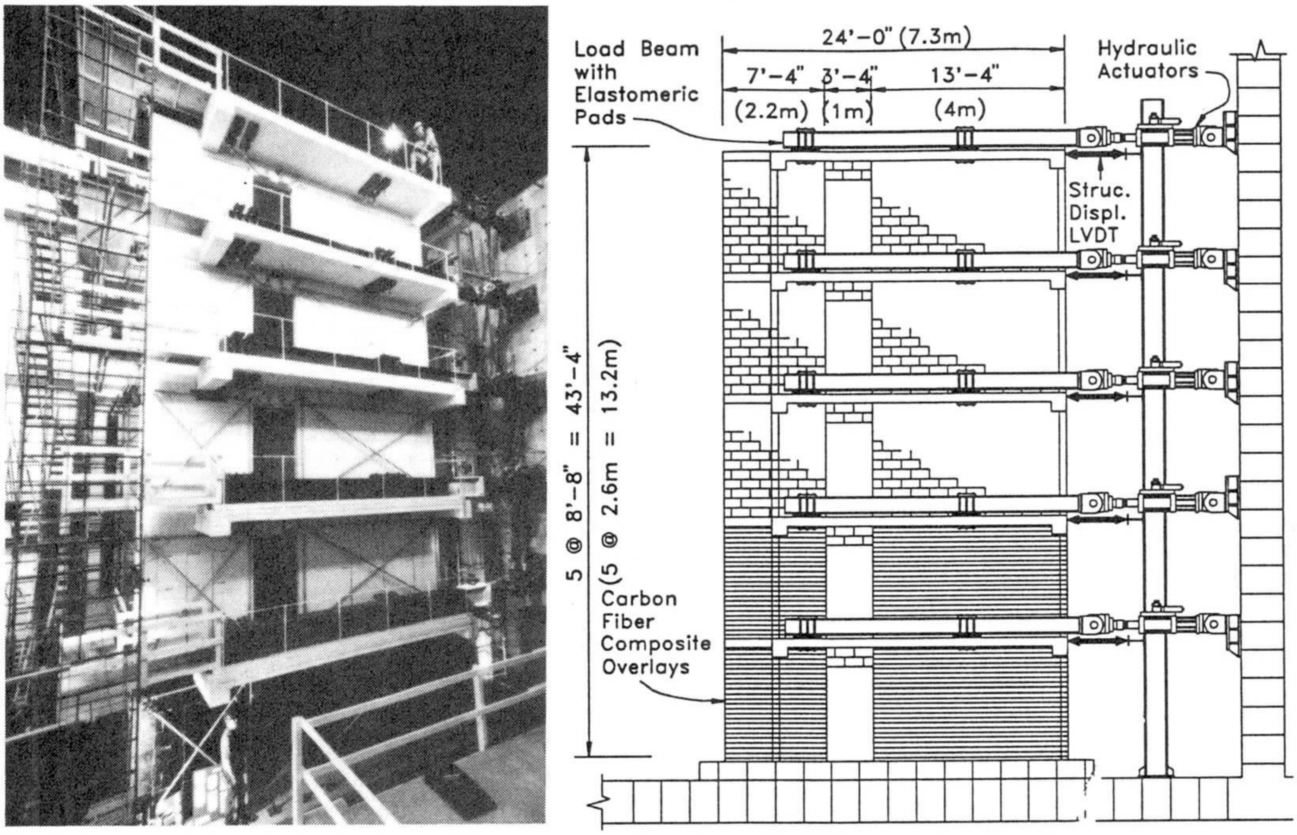
Fig. 2 Carbon Jacket Retrofitted Shear Column Test

geometry can be very effective. General repair and retrofit principles developed by Priestley, et al [3] apply and can directly be used to design carbon jackets. In order to compete with widely used steel jacketing, an automated winding system with 12k prepreg carbon tows was developed and tested under an Advanced Research Projects Agency (ARPA) technology reinvestment project by the Advanced Composite Technology Transfer Consortium to retrofit prismatic columns of circular, oval or rectangular cross-section. The automated winding system is depicted in Fig. 1, during the jacket installation on a rectangular bridge column model. The effectiveness of the carbon jacket system is demonstrated in Fig. 2 with the example of a circular shear column tested in double bending as shown in Fig. 2a to a displacement ductility of over ten with stable hysteretic behavior, see Fig. 2b. A direct comparison of the load-deflection envelope with tests of a corresponding unretrofitted "as-built" column and a steel jacket retrofitted column is presented in Fig. 2c and shows that not only the same ductility provided by the steel jacket was reached, but that this ductility was achieved without strength or stiffness increase which are phenomena to be avoided during seismic column retrofit [4]. The first prototype field demonstrations of this retrofit technology are currently in progress in cooperation with Caltrans in Los Angeles and San Diego.

3.2 Structural Wall Overlays

Seismic repair and retrofitting of structural walls can be accomplished very economically with thin advanced composite wall overlays. Tests have focused to date on (1) reduction of shear deformations in seismically damaged structural walls, (2) retrofitting of shear walls to achieve ductile flexural in-plane behavior, (3) increase in flexural ductility of structural walls, as well as (4) retrofitting of out-of-plane unreinforced structural walls.

A series of seven single-story structural wall panel tests were



a) Overview b) Carbon Overlay Areas

Fig. 3 Five-Story Full-Scale Building Test

performed on fully grouted hollow core concrete masonry walls at full-scale. Subsequent to sandblasting and filling of voids with epoxy or polymer concrete, advanced composite overlays are applied to the wall surface either single or double-sided in the form of mats or woven fabrics saturated with resin in an impregnator.

Especially for in-plane wall response or shear, very thin overlays (only one or two layers $t_i = 0.5$ *to 1.0 mm*) can show significant seismic improvements. Composite fibers are oriented horizontally to cross diagonal or shear cracks, while allowing horizontal or flexural cracks to open. Forces to be transferred in the composite overlays are limited by the laminar shear or principal tensile strength of the existing structural wall material since the polymer resin typically features significantly higher tensile capacities than the concrete or masonry substrate.

To improve shear capacities of structural walls of length d with advanced composite overlays of thickness t_o and a conservative diagonal tension crack angle assumption of 45°, the resulting shear capacity increase can be determined as

$$V_o = f_o \, t_o \, d \qquad (1)$$

where the allowable overlay stress level f_o is based on a maximum allowable strain of 0.004 above which aggregated interlock is assumed to be lost.

However, for typical structural wall aspect ratios, i.e. height and length of approximately the same dimensions, the above strain criteria inherently assumes large shear deformations, namely 0.4% drift due to shear alone in order for the composite overlay to become effective. Thus, additional limitations on the total allowable shear deformations can be imposed by reducing the allowable overlay stress level f_o. Alternatively, stiffness criteria can be employed in the wall overlay design, limiting shear deformations to deformation levels which can be expected in concrete walls with conventional horizontal reinforcement $A_{sh}^{req.}$ (determined based on conventional design requirements), by scaling the amount of horizontal overlay fabric A_{oh} from the required horizontal reinforcement as

$$A_{oh} = A_{sh}^{req.} \frac{E_s}{E_o} \qquad (2)$$

which will also ensure equal participation of the already existing conventional horizontal wall reinforcement.

Since the bond between the composite overlays or the resin matrix and the concrete substrate is at least as good as the bond capacity between individual reinforcing bars and unconfined concrete, upper limits to the total improvement of shear capacity can also be taken as those encountered in conventional concrete design codes.

The seismic deformation limitations of many structural walls are controlled by compression toe crushing or lateral stability of the compression toe region. A nominal level of compression toe confinement can be provided by wrapping additional layers of composite overlay material around the toe region if access is available.

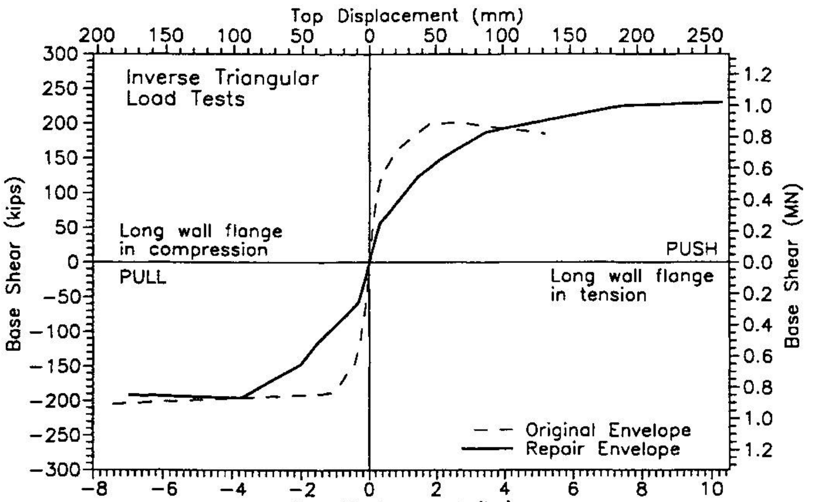


Fig. 4 Load-Displacement Envelope Comparison for Carbon Overlay Repair Test

For out-of-plane wall retrofitting the key design aspects are (1) the development of the overlay material in regions of high moment gradients, and (2) the potential for buckling and delamination of the thin and stiff overlays on the compression side of the flexural member. Detailed research data and corresponding design guidelines for both of these areas are currently being developed, reviewed, and experimentally validated.

The effectiveness of the application of advanced composite wall overlays for seismic repair and retrofitting of structural wall systems can best be demonstrated by the example of a full-scale five-story reinforced masonry building, see Fig. 3, which was tested under pseudo-dynamic simulated seismic loads to failure [5]. Subsequent to the original testing, the building was repaired by means of structural carbon overlays to the first two stories of the structural walls, (see Fig. 3b), subsequent to reconstruction of the crushed wall toes with polymer concrete.

The load-deflection envelopes for the original and the retest of the five-story building, (see Fig. 4), show that a single layer of carbon fabric overlay [t = 1.25 mm, predominately horizontal woven carbon fabric, (12 k toe AS4), with epoxy resin matrix], applied on each side of the structural walls with two layers in the toe regions, contributed significantly to doubling the inelastic deformation capacity. Measured shear deformations in the overlayed wall panels were reduced to half the shear deformations in the original five-story building test. Detailed information of the repair and retrofit installation and seismic response data can be found in [5].

3.3 Bridge Superstructure Strengthening

Bridge superstructure capacity deficiencies have been encountered both for increasing traffic loads and permit overload vehicles, as well as for longitudinal seismic resistance, where current seismic design philosophy requires that sufficient superstructure capacity exists to force plastic hinging into the column. Column hinging is desirable since in the column the plastic hinge region can be (1) confined by spiral reinforcement, and (2) inspected and repaired following an earthquake without superstructure closure or traffic interruptions.

On a 1/3 scale prooftest model of the San Francisco Terminal Separation replacement structure design following the 1989 Loma Prieta earthquake, the concept of carbon fabric soffit overlays was explored [6], see Fig. 5.

Only two layers of each nominally 0.56 mm thick carbon overlays with fibers along the bridge axis were applied. The effectiveness of strain transfer from the soffit reinforcement to the carbon overlay is depicted in Fig. 6, which shows for the indicated soffit location both, the reinforcement strains before and after the overlay application, as well as the recorded strains in the carbon fabric overlay. Premature joint failure of the cap/column connection prevented a full development of a plastic column hinge and with it a complete verification of the carbon overlay strengthening concept.

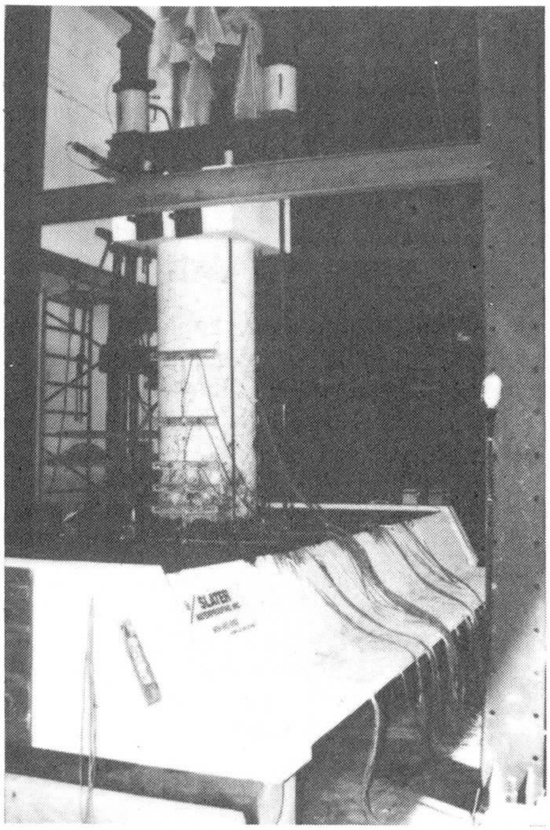


Fig. 5 Bridge Superstructure Strengthening with Soffit Carbon Overlay

However, the strain transfer shown in Fig. 6, as well as measured carbon overlay strains of over 1500 $\mu\varepsilon$ at other locations clearly showed the contribution of the advanced composite overlay strengthening to the superstructure capacity. Buckling of the thin carbon overlay in front of the compression toe of the column, installation and quality assurance procedures, as well as design guidelines, still need to be developed prior to field applications.

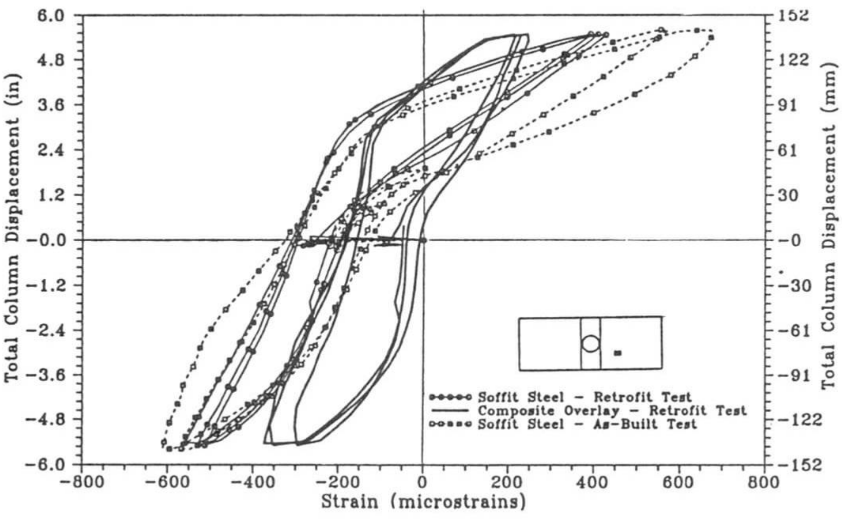


Fig. 6 Strain Comparison of Soffit Strains With and Without Carbon Overlay

In general, in all of the above described tests where hand lay-up installation of advanced composite overlays was used, significant variability in overlay thickness was observed. Thus, for a strength or stiffness based design approach nominal and not measured thicknesses and mechanical properties as verified by coupon tests need to be employed. Alternatively, the resin or matrix system with its low mechanical characteristics is only used to locate the fiber, and the entire design is strictly based on fiber properties and number of layers of woven or stitched composite fabric without reference to the matrix or overlay thickness.

4. CONCLUSIONS

Aging and deterioration, design and detailing of existing concrete structures, as well as substandard seismic designed and detailed structures, require the rapid development of new rehabilitation technologies. Polymer matrix composites or advanced composite materials have shown high potential for structural effectiveness in rehabilitating existing concrete structures by means of thin jackets or overlays. The structural effectiveness in terms of strengthening and/or seismic retrofitting was demonstrated on numerous large or full-scale laboratory tests on building and bridge systems.

For some of these rehabilitation applications for advanced composites such as column retrofitting and in-plane structural wall strengthening, complete structural design guidelines have been developed, whereas other applications such as flexural strengthening of unreinforced walls and bridge superstructure strengthening with soffit overlays have been demonstrated in principle but detailed design guidelines do not yet exist.

In general, additional research and development is needed to address quality control issues for the application and curing of in-situ composite applications, as well as aging and durability characteristics in the civil environment. Furthermore, accidental loads such as fire, impact and subsequent repairability need to be addressed prior to the formulation of general advanced composites rehabilitation technology guidelines. All of the above issues are currently addressed under an Advanced Research Projects Agency (ARPA) Technology Reinvestment Project (TRP) research program in coordination with Caltrans and the Federal Highway Administration to provide the scientific basis for the application of advanced composites rehabilitation technology of existing concrete structures.

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