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DEVELOPMENT OF ADVANCED COMPOSITE CARBON SHELL SYSTEMS FOR CONCRETE COLUMNS IN SEISMIC ZONES

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ABSTRACT

Advanced composite materials, developed originally for aerospace and defense applications, have shown great potential for applications in the civil engineering and construction industry, based on their outstanding mechanical and chemical characteristics. The paper summarizes and highlights recent research developments into a new structural concept and system for bridge and building columns in seismic zones. The system consists of carbon tubes filled with concrete, where the carbon tubes have the dual function of formwork and reinforcement for the concrete columns. Due to the light weight of the carbon shells, fast and easy field assembly and erection without the need for heavy lifting equipment are possible. The concrete is directly placed in the carbon tubes, eliminating the need for special formwork, rebar cages, and formwork removal. Pilot lateral load tests on two concrete filled carbon shell columns with different connection details have shown the great potential of this innovative application for the development of new seismic framing systems.

KEYWORDS

advanced composite materials, polymer matrix composites, bridge columns, building columns, seismic design, concrete filled carbon tubes, tailored design

INTRODUCTION

Advanced composite materials such as carbon, aramid, or glass fibers in polymer matrices, such as epoxies or esters, have shown outstanding mechanical and chemical characteristics to be of great interests to civil engineering design and construction. Only the high material costs and high costs in the manufacturing, due to the predominant hand lay-up techniques, have kept these materials largely in the higher priced aerospace and defense industries and out of the civil engineering sector. Recent developments in manufacturing technologies and the need for new and more durable materials for rehabilitation of existing civil structural systems and renewal requirements of the aging building and bridge inventory have shown that the light weight of these polymer matrix composites (PMCs) in combination with their high strength and chemical inertness can be cost-effectively employed, particularly in the seismic retrofitting of buildings and bridges, as long as the manufacturing/installation process can be automated and the design fully integrates these new materials with conventional civil structural materials such as concrete and steel (Seible, *et al.*, 1995a)

A concept which emerges from this combination of conventional civil construction materials and, for the civil engineering sector, new polymer matrix composites (PMCs), is that of the concrete filled Carbon Shell System (CSS), where the concrete takes on the compression force transfer and the carbon shell the functions of (1) formwork for the concrete, (2) confinement of the concrete, and (3) tension force transfer in both longitudinal bending and shear.

While the concrete filled Carbon Shell System (CSS) concept is rather simple and similar to conventional Concrete Filled steel Tube (CFT) systems, the advantages of this new system of (1) light weight (no heavy lifting equipment required for assembly), (2) tailorable fiber orientation for best mechanical properties, and (3) durability due to the high chemical inertness of the carbon fibers, can only be fully utilized when appropriate connections systems and concepts can be developed and proven. In particular, for columns in seismic zones a clear seismic design philosophy needs to be developed which addresses either (1) ductility, or (2) strength design principles. Since the carbon shells are inherently not very ductile but strong in tension, the research effort has to focus on the connections for both ductility and strength.

This new concept is schematically depicted in Fig. 1. The carbon tubes have a ribbed inner surface for bond and force transfer to the concrete core. A model for the confined stress state of the concrete filled carbon tube system is also shown in Fig. 1 and will serve as the basis for the subsequent characterization of the new system.

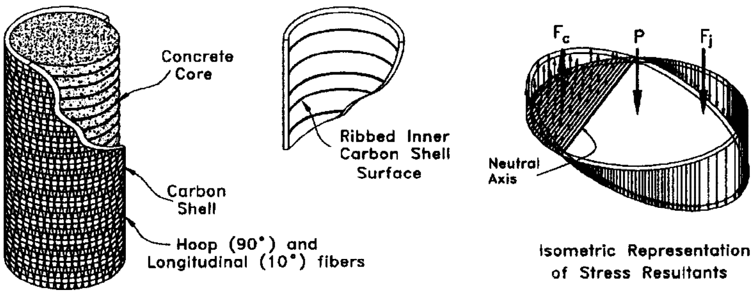


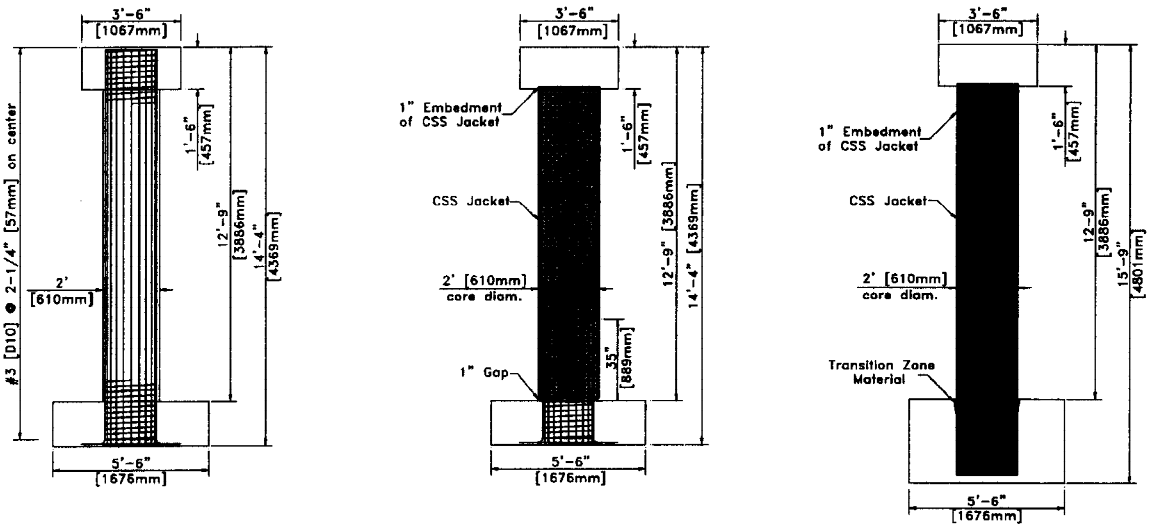
Fig. 1. Schematic of Concrete Filled Carbon Shell System

The presented research aims to systematically develop the basis for such a system for columns in seismic zones made of filament wound carbon shells and filled on-site with concrete. The research focusses on three areas namely, (1) the analytical modeling and characterization of the concrete filled carbon shell system and the proposed connections, (2) the development of appropriate design models for seismic design, and (3) the experimental large scale validation of the system to characterize both strength and inelastic deformation capacity potential.

DESIGN PHILOSOPHY AND DESIGN MODELS

The development of a concrete filled carbon shell system for seismic zones demands that the lateral response of the new system be comparable to or better than that of conventionally reinforced concrete columns. As with the development of any new system, the possibilities of obtaining a wide array of structural response with different design details is an important factor to consider. The preliminary research focus was aimed at bounding the expected spectrum of structural response by considering two different design concepts for seismic response, namely one based on ductility and the other one on strength. For direct comparison, a conventionally reinforced "as-built" concrete column lateral load test was used. The three pilot test specimens are graphically depicted on Fig. 2.

Carbon Shell System 1 (CSS-1) utilized starter bars that extend from the footing into the column providing a conventional ductile anchorage mechanism into the footing. A force transfer mechanism is therefore envisioned to take place from the carbon shell system to the anchorage bars on their way down to the footing. The presence of steel starter bars and the carbon jacket confinement ensures the development of a conventional plastic hinge mechanism. Uncertainties in mechanical material properties were accounted for by setting a design limit state of $0.5f_u$ for the carbon shell. The expected failure mode of CSS-1 is ductile plastic hinging with starter bar fracture due to low cycle fatigue at large inelastic deformations.



a) "As-Built": conventional steel reinforced column

b) CSS-1: carbon shell system with steel starter bars

c) CSS-2: carbon shell system without steel for anchorage

Fig. 2. Pilot Test Unit Geometries

Carbon Shell System 2 (CSS-2), the strength design concept, continues the carbon shell jacket into the footing, completely eliminating the use of steel for anchorage. The anchorage force mechanism consists then of the reaction moment due to the compression force couple generated inside the footing and the friction between the carbon shell and the concrete. Therefore the response of the laminated composite and thus the overall shell behavior is expected to be essentially linear-elastic up to failure. For this reason, an equal energy design approach was used for this design concept, where a design limit state of f_u with a strength reduction factor of 0.85 (or a reduction of three times the standard deviation) due to material properties variation was adopted. In the equal energy design approach the target design moment was found by equating the area under the inelastic force-deformation curve for the conventionally reinforced concrete column with the area under the elastic force-deformation curve for the carbon shell system column with equal initial stiffness. The expected failure mode of CSS-2 is in the form of brittle shell failure at the footing-column interface at high lateral loads.

While detailed analysis and design models exist in the civil engineering community for concrete and reinforced concrete seismic response, and in the aerospace industry for the characterization of polymer matrix composite tubes, appropriate models need to be developed which can characterize the interaction between the concrete core and the carbon shell for all possible serviceability and limit states. A simple but rational approach was developed with the purpose of allowing rapid experimental investigation and providing the basis for further, more rigorous, analytical modeling. The models focus on the determination of the required design reinforcement levels for flexure, shear and confinement (Seible, *et al.*, 1995b). The following design considerations were made:

Flexure Design. The flexure design of the carbon shell system was controlled by the objective of matching or exceeding the flexural strength capacity of the "as-built" column. The developed analytical model for flexural design and assessment is based on the evaluation of the carbon shell thickness required to maintain force and moment equilibrium at a given cross section at a given limit state condition, see Fig. 1. The following relevant assumptions were made for the flexural design criteria (Seible, et al., 1995b; Burgueño, *et al.*, 1995a):

a) Full bond is assumed between the shell and the concrete core.
b) The moment contribution of the shell in compression is considered.
c) Based on the corresponding fiber orientation, orthotropic properties are assumed for the carbon shell, using equivalent moduli in both the longitudinal and transverse directions.
d) The equivalent elastic moduli of the carbon shell for compression and tension are considered equal.
e) Section capacity limit states are defined as $0.5f_u$ for CSS-1 and $[f_u - 3\sigma]$ for CSS-2.
f) Enhanced behavior of the concrete core due to confinement is considered.
g) A Bernoulli-Euler approach is used to represent the strain field of the composite cross-section.

Shear Design. The design and assessment of shear strength for the carbon shell systems are based on the predictive UCSD shear strength model (Priestley, *et al.*, 1994; Priestley, *et al.*, 1996). In this model, the shear strength of the column member is considered to consist of three independent components: a concrete component whose magnitude depends on the level of member ductility, an axial load component whose magnitude depends on the column aspect ratio, and a modified truss component whose magnitude depends here on the effective shell reinforcement content (Seible, *et al.*, 1995b). Both flexural and confinement reinforcement are considered to contribute to the strength of the truss mechanism.

Confinement Design. The design and evaluation of confinement capacity considered three different cases. The confinement requirements of the starter bar region for CSS-1 were based on a bond failure mechanism. An expression for the required confinement was developed based on well accepted approaches for the confinement of lap-splices (Priestley, *et al.*, 1992). Within the potential plastic hinge regions requiring confinement, an appropriate volumetric confinement ratio is provided based on an experimentally derived expression that relates the confinement effect with the ultimate compression strain in the section for retrofit measures with advanced material jackets (Priestley, *et al.*, 1996). For non plastic hinge regions, and outside of the starter bar transition zone, minimum recommended levels of passive flexural confinement are provided.

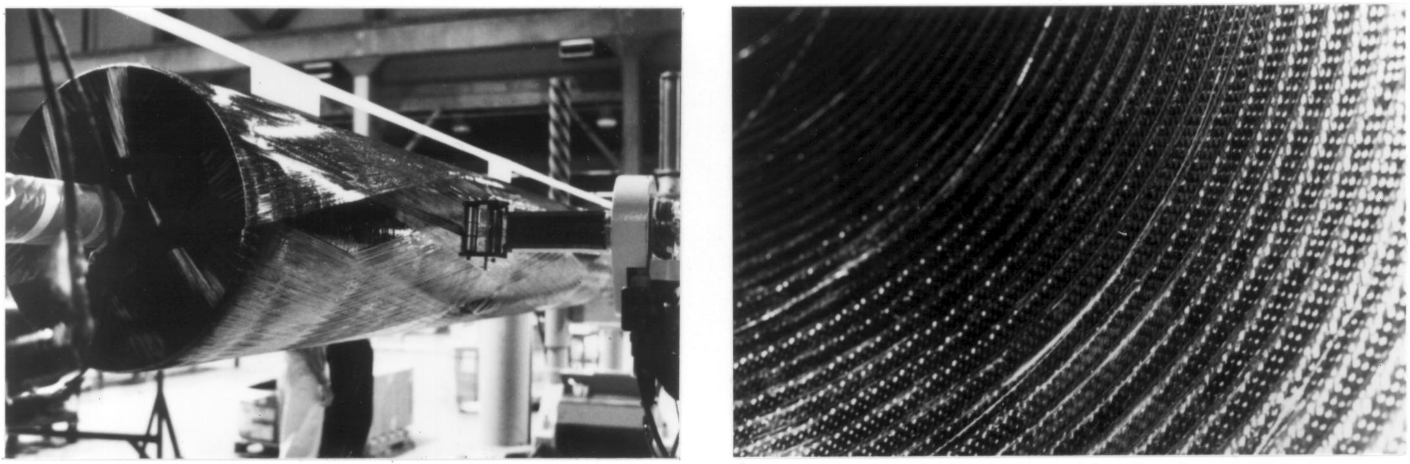
Manufacturing of Carbon Shells

Much of the success and cost effectiveness of an advanced composite component is controlled greatly by the manufacturing processes and tooling. Therefore, they are considered an integral part of the design process. Filament winding with automatic placement of the carbon tows onto a mandrel in accordance with a given pattern is a proven method for the production of low cost composite structures, see Fig. 3. In this process, bundles of fibers (tows) are impregnated with the matrix material (resin) and are wet wound onto a rotating mandrel over its whole length by means of a carriage that moves back and forth on a linear track. The winding of multiple layers of unidirectional fibers at different chosen orientations on the mandrel results in the desired strength and stiffness characteristics. In general, the shell will possess orthotropic properties, that is, the strength and stiffness of the shell will be different in different directions.

The carbon shells were manufactured to prescribed thicknesses of circumferential and helical windings to meet the design guidelines outlined above. The shell systems were fabricated at the filament winding facilities of Alliant Techsystems (Abdallah, 1995). Hercules AS4D-GP (12K) carbon fibers and Hercules HBRF-55A epoxy resin system was used. The layup sequence was determined to meet the prescribed thickness requirements of the hoop and helical layers, ensure quality control of the laminated shell (provide a uniform relatively void free structure), and optimize the manufacturing process. The manufactured shell layup consisted of a combination of $\pm 10^{\circ}$ helicals and 90° hoops for total thicknesses of 0.2 to 0.5 in. (5 to 10mm), see Fig. 3a. A summary of the average mechanical properties of the manufactured carbon shells is presented in Table I.

Table I. Average Mechanical Properties of Manufactured Carbon Shell Systems (CSS)

PROPERTY	CSS
Fiber Volume Ratio	53.4 %
Resin Volume Ratio	42.2 %
Void Volume Ratio	4.4 %
Axial Tension Modulus	15030 ksi (103.6 GPa)
Axial Tension Strength	86.58 ksi (596.9 MPa)
Axial Compression Modulus	13410 ksi (92.46 GPa)
Axial Compression Strength	70.19 ksi (483.9 MPa)
Shear Strength (R-θ dir.)	6.23 ksi (42.9 MPa)
Shear Strength (R-Z dir.)	2.77 ksi (19.1 MPa)



a) Filament Winding of CSS ±10° helicals

b) Internal Ribs in Transition Region of CSS-1

Fig. 3. Carbon Shell System (CSS) Manufacturing Process and Details

EXPERIMENTAL PROGRAM

Test Units and Test Setup

The selected pilot test unit configuration consisted of a 40% scale model of a typical prototype circular bridge column. A column aspect ratio (height to diameter) susceptible to flexure dominated response was chosen, and an axial load level representing what is considered to be a practical upper bound expected in single column bridge bents was provided. The typical geometry of the test units consists of a circular cantilever column with an effective height of 12 ft (3.66m), and a concrete core diameter of 2 ft (0.61m).

The conventional steel reinforced concrete column test unit, or "as-built" column, see Fig. 2a, contained 20 #7 G60 bars of continuous reinforcement, corresponding to a longitudinal steel ratio of 2.66% with a 1 in. (25.4mm) cover to main bars. Transverse reinforcement was provided by #3 G60 spirals with a pith of 2.25 in. (57mm), or a 0.82% volumetric reinforcement ratio.

As mentioned before, Carbon Shell System 1 (CSS-1), see Fig. 2b, relies on the use of steel starter bars for anchorage into the footing. With the purpose of maintaining the same moment capacity of the "as-built" column at the critical section, the starter bar details also consist of 20 #7 G60 steel bars but without any transverse steel reinforcement, which is provided by the carbon shell jacket. The required starter bar length was assumed at forty times the longitudinal starter bar diameter, thus obtaining a 35 in. (889mm) starter bar length. An anchorage, or transition region, in the carbon shell was identified to be 36 in. in length (914mm) from the bottom of the shell to accommodate the starter bar length. The carbon shell thickness in the anchorage region was 0.375 in. (10mm), while the thickness in the regular region was 0.20 in. (5mm). The inside surface of the carbon shell along this transition region was manufactured with internal ribs to aid in the force transfer mechanism to the starter bars by multiple compression strut development, see Fig. 3b. A 1 in. (25.4mm) gap was provided between the bottom of the shell and the top of the footing to avoid crushing of the carbon shell at the compression toe of the column under large deformations and allow plastic hinge rotations without added strength of stiffness from the carbon shell jacket.

Carbon Shell System 2 (CSS-2), see Fig. 2c, continues the carbon shell into the footing for anchorage, avoiding the use of steel starter bars. The carbon shell tube had a constant thickness of 0.46 in. (12mm). The reaction moment at the footing connection depends only on the compression force couple developed inside the footing. This situation gives rise to high joint shear stresses in the footing at ultimate response. Careful consideration was given to this issue, and without any guidelines for joint shear strength assessment for this new system, it was decided to minimize the joint shear stress levels to the allowable levels in conventionally reinforced concrete systems. The footing depth was increased to a height of 36 in. (914mm) and postentioned to reduce the joint shear stress levels. The configuration of this design concept also brought concerns regarding normal stress concentrations on the carbon shell at the column-footing interface. Detailed finite element analysis showed the need to provide a transition zone inside the joint to alleviate the stress concentrations generated on the compression side of the column. The geometry and material properties for this region were determined by performing parameter studies. A transition zone distributed vertically along the top 6 in. of the footing connection, and tapering down linearly from a 0.5 in. (13mm) thickness at the top was provided. The selected material for this interface region was a structural adhesive with a compression elastic modulus of approximately half that of concrete.

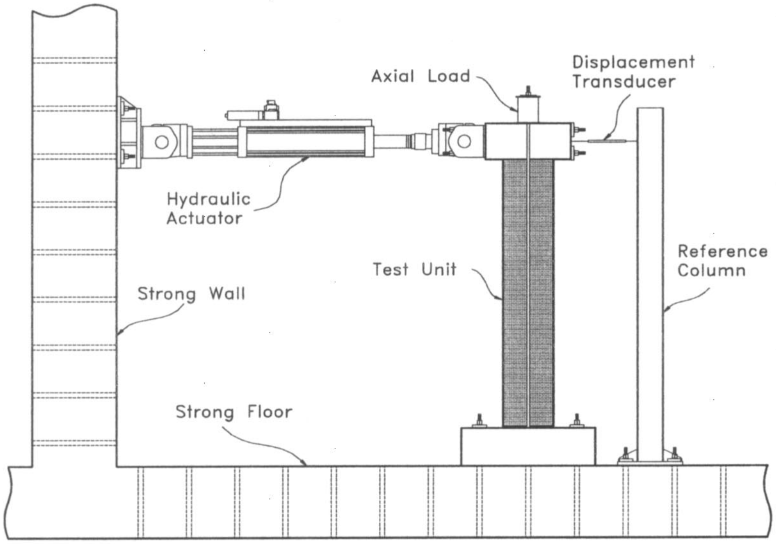
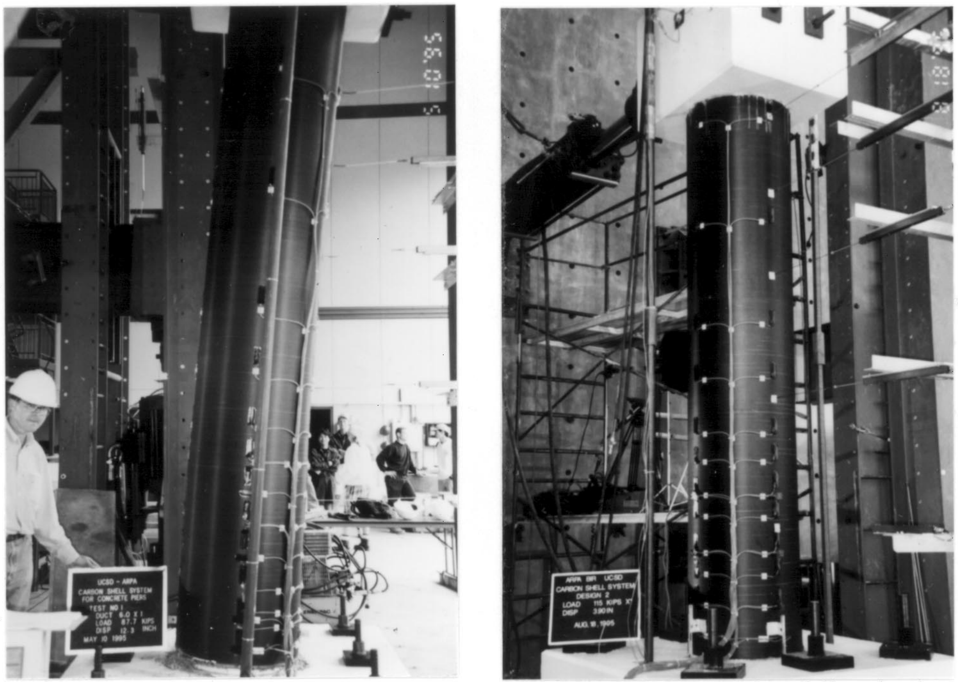


Fig. 4. Experimental Test Setup for Pilot Test Units

The test set-up, shown in Fig. 4, was designed to subject the columns to a constant axial load and cyclic lateral displacements. The unidirectional seismic attack was simulated by fully reversed cyclic loading to the top of the column load stub by a single hydraulic actuator.

Observed Response and Test Results

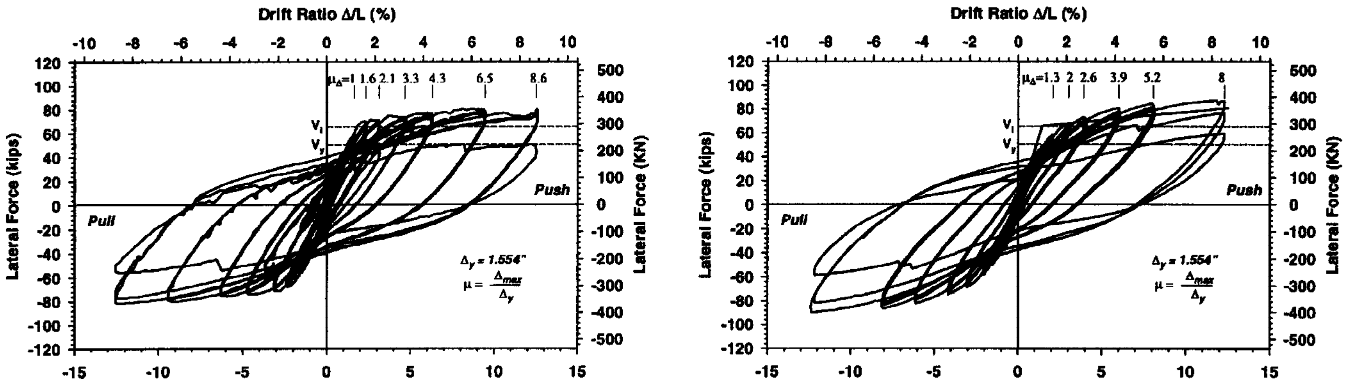
CSS-1 achieved its maximum response at a displacement ductility of 8 with a displacement of 12.4 in. (315mm), corresponding to a drift ratio of ($\Delta L/L$) of 8.6%, at a load of 87.7 kips (390KN), see Fig. 5a. The system displayed a stable hysteretic behavior up to the before mentioned ductility levels, see Fig. 6a. Failure was caused by concentration of inelastic flexural actions in the gap between the carbon shell jacket and the top of the footing leading to the fracture of the longitudinal starter bars. As judged from the excellent response of the system, the force transfer mechanism between the carbon shell and the anchorage bars with the aid of the internal shell ribs was successful. Post evaluation of the concrete core by removal of the carbon shell jacket up to 48 in. (1.2m) from the top of the footing showed that the concrete core, with the exception of the plastic hinge zone was almost intact.



a) CSS-1 Test Unit at $\mu_\Delta = 8$

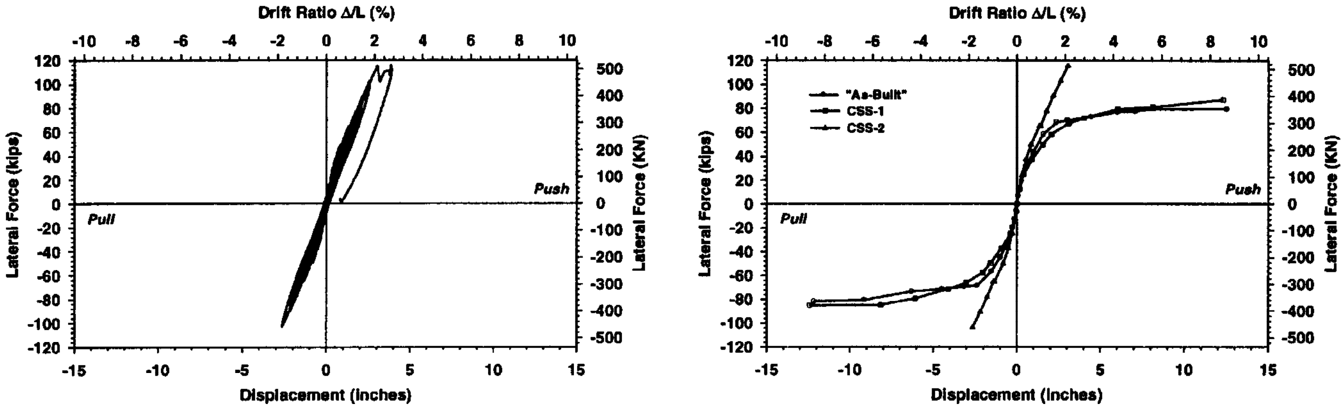
b) CSS-2 Test Unit at failure load of 115 kips (512KN)

Fig. 5. Photo Documentation of Testing Behavior



a) "As-Built" Force-Displacement Hysterisis

b) CSS-1 Force-Displacement Hysterisis



c) CSS-2 Force-Displacement Hysterisis

d) Force-Displacement Envelope Comparison

Fig. 6. Force-Displacement Hysteretic Behavior and Comparative Envelopes of Test Units

The response of CSS-2 was essentially linear elastic and failure was observed at a load of 115 kips (512KN) with a top displacement of 3.05 in. (77.5mm), or a 2.12% drift ratio, during the first cycle in the push direction, see Fig. 5b and Fig. 6c. The premature failure mode appears to be attributable to a combined stress state of in-plane compressive stresses at the toe of the column and high interlaminar shear stresses due to boundary effects that led to the failure of the carbon shell. This stress state is generated at the compression toe of the column due to a Poisson's effect at the connection singularity and high demands for localized transverse shear deformations at the critical section. The transition zone material proved to be effective as far as avoiding a crushing failure of the carbon shell, but it possessed a higher modulus than that required to minimize both the in-plane compressive and interlaminar shear stresses.

Carbon Shell System 1 performed excellently in matching the response of the "as-built" column, whose force-displacement hysteretic response can be seen in Fig. 6a, and verifying the ductile nature of the design concept. The comparative force-displacement response envelopes shown in Fig. 5d indicate how CSS-1 is almost a mirror image of the"as-built" column. The slightly thinner hysterisis loops of CSS-1 compared with the "as built" column can be attributed to debonding of the cross section, and the reduced plastic hinge length of CSS-1. The strength design concept, or Carbon Shell System 2, displayed a slight non-linear force-displacement response believed to be attributed to debonding between the concrete core and the carbon shell and slip of the carbon shell out of the footing anchorage on the tension side. The early failure of the carbon shell jacket represents the only concern with the overall performance of this system. As it can be seen in the force-displacement envelopes in Fig. 6d, the system failed at approximately 42% of the required load needed to obtain equal energy absorption based on the previously mentioned design approach. The observed failure behavior can be improved by a more flexible transition zone at the footing top and by increased hoop fibers in the critical transition region. Further details on the design, construction, instrumentation, and data analysis aspects of the experimental research can be found separately (Burgueño, et al. 1995b).

CONCLUSIONS

Advanced composites or polymer matrix composite materials can only find broad based applications in civil and earthquake engineering when, in addition to the proof of structural and cost effectiveness, appropriate design guidelines and criteria can be developed which allow these materials to be used in full compliance with safety and serviceability requirements.

A rational and comprehensive design approach for bridge columns in seismic zones with a new system based on concrete filled carbon shells was presented. The Carbon Shell System represents an innovative approach to bridge column design by taking advantage of the excellent mechanical properties of composite carbon shells to provide tensile reinforcement to the concrete core. The preliminary research focused on two different connection design concepts. The ductile design concept was successful in developing a stable hysteretic response, while it is believed that the desired response for the strength design concept can be achieved by the strengthening of the shell at the critical section with hoop reinforcement and the provision of a more flexible transition region.

The described research development shows that strength and ductility design approaches for seismic zones are feasible with the concrete filled Carbon Shell System, and that basic design models for the new system can be established and experimentally validated. With the development of these basic tools and design details, the concrete filled Carbon Shell System can provide a viable alternative to conventional steel or concrete columns in seismic zones.

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