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Concrete Composite Construction for Durability and Strength

Construction en béton composite pour améliorer la durabilité et la résistance

Betonverbundbauweise für Dauerhaftigkeit und Festigkeit

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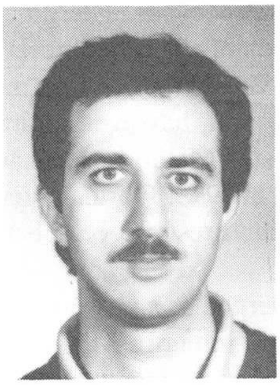

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SUMMARY

Strength, ductility and durability of concrete columns and walls could be significantly enhanced in composite construction with Fiber Reinforced Plastics (FRP). An FRP-concrete column is proposed in which the filament-wound tubular shell is the pour form, protective and confining jacket, and bi-directional reinforcement. Behavior of composite columns is studied analytically and experimentally. Results indicate higher compressive and flexural strength, as well as pseudo-ductile characteristics.

RÉSUMÉ

Il est actuellement possible d'augmenter la résistance, la dureté et la durabilité des piliers et parois en béton, en faisant appel à un mode de construction mixte à base de matières plastiques renforcées par fibres. L'auteur propose un type de pilier en béton composite, dans lequel une enveloppe de fibres tissées sert à la fois de coffrage perdu, de couche protectrice, de frettage et d'armature bidirectionnelle. L'article présente une étude analytique et expérimentale du comportement de ce type de pilier mixte. Les résultats obtenus mettent en évidence des résistances élevées à la compression et à la flexion ainsi que des propriétés de pseudo-ductilité.

ZUSAMMENFASSUNG

Die Festigkeit, Zähigkeit und Dauerhaftigkeit von Betonwänden und -stützen könnten durch eine Verbundbauweise mit faserverstärkten Kunststoffen deutlich verbessert werden. Es wird eine Verbundbetonstütze vorgeschlagen, bei der eine fasergesponnene Hülle als verlorene Schalung, Schutzschicht, Umschnürung und kreuzweise Bewehrung dient. Das Verhalten solcher Verbundstützen wird analytisch und experimentell untersucht. Die Ergebnisse deuten auf eine höhere Druck- und Biegefestigkeit sowie pseudoduktile Eigenschaften.

1. INTRODUCTION

The nation's infrastructure is plagued with two major problems; premature deterioration and structural deficiency. The average remaining life of highway bridges in the U.S. is estimated to be between 9 and 34 years depending on the bridge type [1]. Even in newer bridges, premature decay caused by service conditions has been a growing problem. On the other hand, survey of damaged structures in recent earthquakes indicates that in several cases catastrophic failure of an entire structure was triggered by the failure of columns in a chain action. Hence, it is vital to the national economy that new technologies be developed to extend service life, and to improve performance and strength of highway bridges.

Concrete members exposed to corrosive environments undergo an accelerated decay when chloride ions penetrate concrete cover and cause corrosion of embedded steel. The most important factor in long-term durability of concrete is its permeability. Current protection measures are designed to delay corrosive agents from reaching steel re-bars. They do not, however, entirely solve the corrosion problem, nor do they address the permeability of concrete. Methods such as epoxy coating have failed in severe environments such as the Florida Keys [2]. In 1991, Florida initiated expensive plans for galvanizing the corroded epoxy-coated re-bars for substructures of several bridges along its coastlines [3].

Fiber Reinforced Plastics (FRP) have emerged as a potential solution to the problems associated with the infrastructure. The most effective application of FRPs is in the form of protective jacket as well as load-carrying partner in composite construction with concrete. This provides for optimal use of materials based on mechanical properties and resistance to corrosive agents. Moreover, it results in structural members with pseudo-ductile characteristics. One such application has been demonstrated in fiber jacketing technique [4], which is now considered an effective retrofitting tool for existing columns.

2. FRP-CONCRETE COLUMN

Using the principles of fiber or steel jacketing [4,5], concrete-filled steel columns [6], and pressure vessel technology [7], a novel composite column is proposed that consists of a concrete core confined in an FRP shell (Fig. 1). The tubular shell, while an integral part of the system, is also the pour form for concrete. It may be a multi-layer FRP tube consisting of at least two plies; an inner ply of axial fibers and an outer ply of circumferential fibers (Fig. 1a). This shell type is manufactured by a continuous normal-axial winding process that generates both axial and hoop reinforcement. Axial fibers are inhibited from outward buckling by the outer

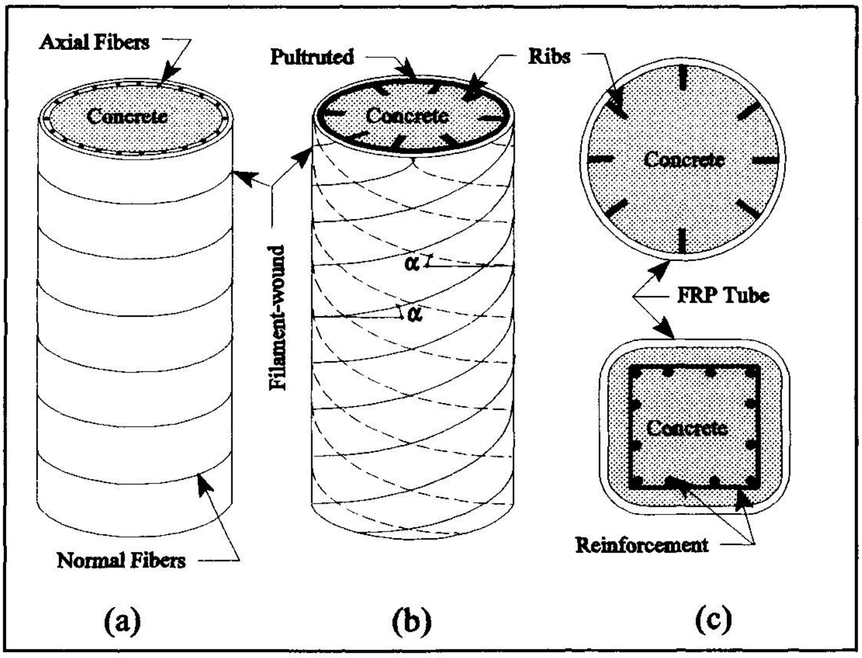

Fig. 1 Composite FRP-concrete column; (a) Normal-axial winding, (b) pultruded shape with stiffening ribs and angle-ply cover, and (c) typical sections with and without reinforcement

normal fibers, and from inward buckling by the concrete core. The author has also proposed a unique cross section that consists of a pultruted tube on which an angle-ply laminate ($\pm\alpha$) is wound. As shown in Fig. 1b, the pultruted tube may have stiffening ribs that act as axial reinforcement for concrete. In either of the proposed configurations, the jacket provides bi-directional reinforcement for concrete core; i.e., hoop and axial reinforcement. The hoop reinforcement confines concrete and prevents buckling of longitudinal fibers and ribs or bars (if any). It also increases the bond strength of reinforcing bars (if any). The longitudinal fibers improve the axial-flexural capacity of the column similar to a concrete-filled steel tube [6]. The jacket further enhances column's shear strength even more effectively than spiral reinforcement [5]. Bi-directional fiber arrangement makes it possible to remove the entire steel reinforcing cage from the column (Fig. 1c). This will significantly reduce construction cost and time, and will further improve durability of the structure in saline environments.

3. DURABILITY

Sealing and covering of a concrete column by non-corrosive FRP material increases its service life tremendously. This will protect concrete from moisture intrusion that could otherwise corrode the steel re-bars (if in existence) and potentially deteriorate the concrete itself. Sheet membrane systems have been used in the past to protect concrete bridge decks. Currently, in an effort to design and construct the first cable-stayed composite bridge in the U.S., researchers at the University of California, San Diego are investigating the use of concrete pylons covered by carbon fiber jackets. Therefore, it is appropriate to envision encasing concrete columns in FRP tubular jackets to protect concrete and the embedded steel. On the other hand, plastics have been used as main structural members as well as protective jackets. In a hot oil pipeline project that ran over the water in the Gulf of Mexico, a glass fiber jacket was chosen over aluminum and stainless steel alternatives [8]. After 11 years, reports indicate that the jacket has withstood a harsh, salty environment with over 140° F internal temperature, direct sunlight, moisture, vapor, and seawater. Another application of plastics was recently introduced as a composite plastic-steel pile in the form of a steel pipe encased in recycled plastic [9]. Army Corps of Engineers has used durable glass-flake isophthalic resin as protective coating for steel pier piling against corrosive effects of saltwater [10]. Other applications include storage tanks, composite seawalls, and liners for concrete chimneys.

4. STRUCTURAL BEHAVIOR

Confinement depends on two factors; tendency of concrete to dilate, and radial stiffness of the jacket to restrain the dilation. This will place concrete in radial compression, and the confining member in circumferential tension (Fig.2). The proposed system creates a passive confinement, since the confining pressure is developed only after hoop elongation is imposed on the shell by expansion of concrete (Poisson's effect). On the other hand, in fiber-wrapping method [4], high-strength synthetic fibers are wrapped around the column while being tensioned, thereby producing an active confinement. While active confinement methods could potentially be used only after concrete is hardened, passive methods of confinement such as the proposed technique are suitable for new construction, since the jacket becomes the pour form for concrete.

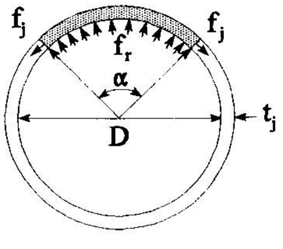

Fig.2 Confining Action

Regardless of the method, the ultimate degree of confinement is a function of the strain energy stored in the confining member. Confinement ratio (C_r) is defined as the ratio of radial pressure f_r to the 28-day compressive strength of unconfined concrete (f'_{co}). The radial pressure is in turn balanced by the hoop tensile stress in the jacket (f_j) such that

$$f_r = \frac{2 f_j t_j}{D} \tag{1}$$

where, D=inside diameter of the jacket, and t_j=jacket thickness. Of the various confinement models for concrete, Mander, et al [11] offer a simple method to predict the compressive strength of confined concrete based on the confinement ratio:

$$C_a = [\ 2.254 \sqrt{1 + 7.94\ C_r} - 2\ C_r - 1.254\ ] \tag{2}$$

where $C_a = f'_{cc}/f'_{co}$ (compressive strength of confined and unconfined concrete), and C_r=confinement ratio (f_r/f'_{co}). For example, for a 1270 mm.-diameter circular column with 27.6 MPa concrete, a mere 3.18 mm. fiberglass tube with 1165 MPa hoop strength will result in a confinement ratio of 20%, which in turn doubles the compressive strength of concrete. It should be noted that the confinement developed by internal hoops or spirals only applies to an effective concrete area within the center core. This area is less than the normal core area bounded by the centerline of the perimeter tie. In fact, in the axial direction, the effective confined area is at the mid-point between the lateral ties. Hence, the confinement effectiveness is a function of core area as well as shape and spacing of transverse reinforcement. It then seems logical to conclude that externally confined columns such as the one proposed here could offer the most effective form of confinement. In this method the concrete area outside longitudinal reinforcement becomes structurally confined and its spalling will be contained. Despite its simple form, since Mander model does not take into account the constitutive model of the confining agent, it only yields upper bound values for fiber composite jackets. The author has developed a new confinement model that is applicable to both steel and fiber jackets, i.e., whether or not the jacket demonstrates a plastic behavior [12].

The proposed model is used to predict the ultimate moment and curvature at failure of beam-columns for a range from pure axial compression to pure flexure. The main assumptions in this analysis are the linear strain distribution through full depth of the cross section, and the strain compatibility of steel-concrete and concrete-FRP. Also, the confinement contribution of the interior hoops or spirals are neglected. Fig.3 shows the interaction diagrams for a typical bridge column. The curves are normalized in both directions with respect to the maximum axial and flexural capacities of the unconfined concrete. Two different confinement ratios of 0.5 and 1.0 are examined. One can easily relate the confinement ratio to the jacket parameters such as thickness and strength of the FRP shell. For example, for the same confinement ratio a thicker fiberglass shell is required as compared to a carbon fiber jacket. Two series of interaction diagrams are developed with and without contribution of the longitudinal fibers of the jacket. When contribution of axial fibers is neglected, confining effect of the jacket is more pronounced in pure compression rather than in pure flexure. For example, for confinement ratios of 0.5 and 1.0, the maximum compressive force in the section is increased by 126% and 182%, respectively, while maximum moment in pure flexure is only increased by 7.9% and 10.2%, respectively. On the other hand, when contribution of axial fibers is taken into account, the maximum compressive force in the section is increased by 161% and 278%, respectively, and the maximum moment in pure flexure is increased by 205% and 454%, respectively. The effect of actual bond strength on the interaction diagrams is reported elsewhere [13].

5. EXPERIMENTAL STUDY

A series of small-scale specimens were tested. The specimens were made of 152.5 mm. x 305 mm. concrete core with three different jacket thickness; 1.6 mm., 3.8 mm., and 6.4 mm. The jacket was made

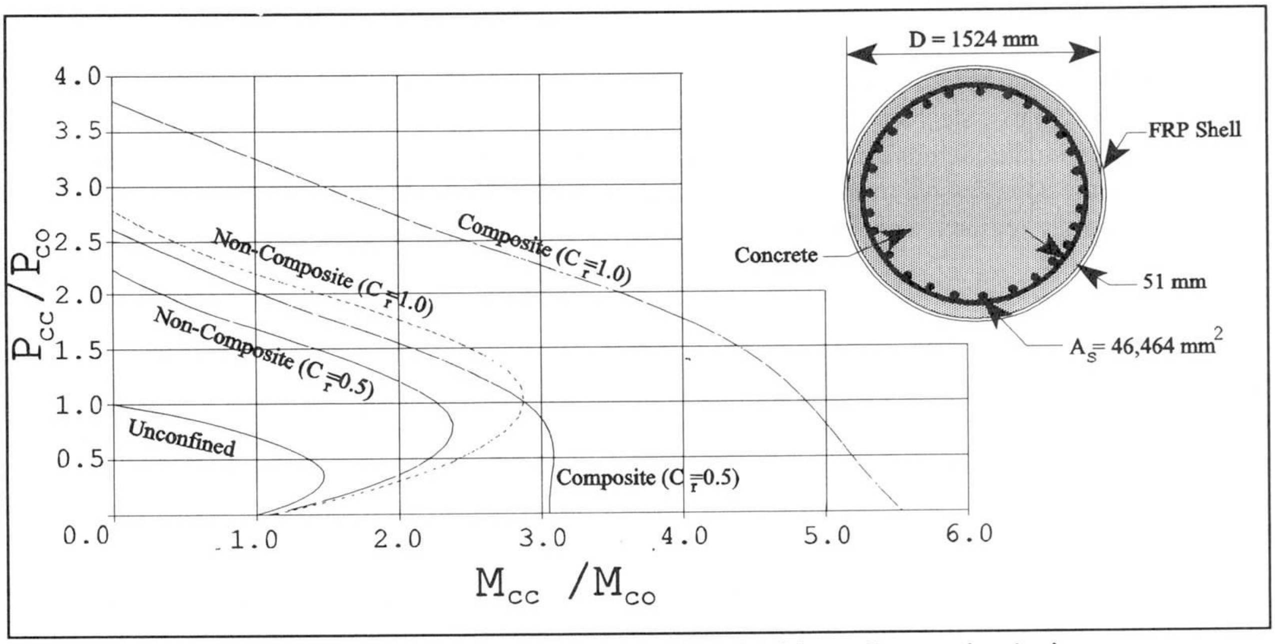

Fig.3 Column Interaction Diagrams with and without Composite Action

of an angle-ply of polyester resin and uni-directional glass fibers with $\pm$ 15° winding angle. Therefore, the jacket was primarily functional in the circumferential direction. Fig.4 shows a control specimen next to a composite specimen with 1.6 mm. jacket thickness, both after failure. The control specimen in this case failed at 378 kN (i.e., f'_{co}=20.7 MPa). The composite specimen, however, failed at 907 kN (i.e., f'_{co}=49.8 MPa), showing a 140% increase in axial strength. As shown in the figure, the control specimen failed by spalling off parts of the concrete cylinder. On the other hand, the composite specimen showed a remarkable ductility and did not fail until the first hoop fracture initiated at some point in the top of the specimen. For brevity, detailed experimental results are not reported here.

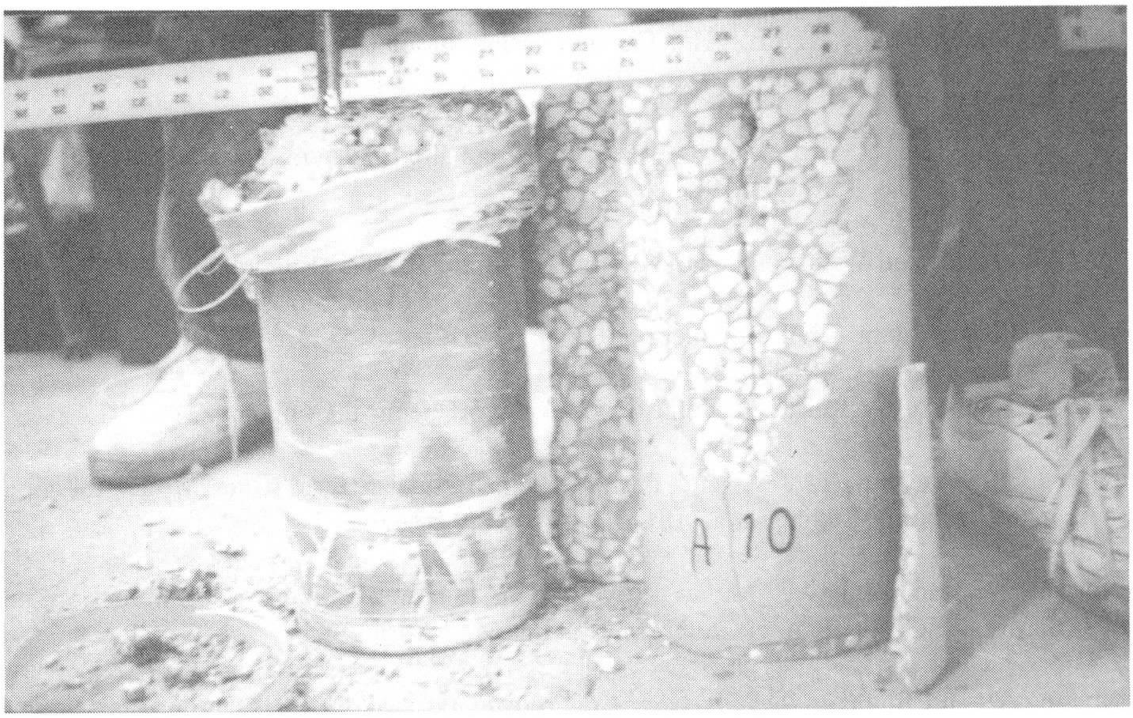

Fig.4 Control and Composite Specimens after Failure

6. CONCLUSIONS

A novel type of composite column is proposed that is similar to the classic steel-concrete composite construction, except that steel has been replaced with Fiber Reinforced Plastic (FRP) shapes. Analytical and experimental studies demonstrate the advantages of the proposed system. A mere 1.6 mm fiberglass tube increased the compressive strength of a standard concrete cylinder by 140%. The jacket is specially suitable for seismic regions, since it increases both strength and ductility of the column.

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