DESIGNING THIN-WALLED, REINFORCED CONCRETE PANELS FOR REVERSE BENDING

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ABSTRACT

This paper discusses the design considerations used to produce a new generation of structurally efficient, reinforced concrete composite panels capable of resisting the dangerous stresses produced by reverse bending. The panels rely on a lightweight, polymer modified concrete mix designed to be structurally compatible with a multilayered reinforcement scheme. The design is based on both material compliance and strength, making the strategy different from that taken by conventional reinforced concrete designers.

INTRODUCTION

Several different theories have been developed for strategically reinforcing plates and shells [1], and simplified models have been developed to predict the shear response of reinforced concrete membranes [2,3]. New designs have been introduced ranging from thin-walled prestressed concrete structures for roof construction [4] to stressed-skin panels of mixed construction [5]. The applied loads in these structures are carried predominately through the action of in-plane stress.

Experimental and analytical studies have also been undertaken to investigate the performance of a number of other different geometrical configurations ranging from concrete plates [6] to thin-walled concrete box bridge piers and pylons [7]. Studies have been conducted to quantify the buckling of reinforced concrete plates subjected to compressive loads [8], and plates have been studied under combined loadings [9]. The failure mechanisms associated with such loadings have been investigated [10], and the flexural stiffness has been studied in detail [11].

Despite these considerable efforts, there has been little attention paid to the design and development of thin-walled, reinforced concrete composite panels capable of withstanding reverse bending. However, the potential applications for lightweight, thin-walled panels are enormous, ranging from the construction of low-cost housing in developing countries to the fabrication of low-mass shelters in space.

This paper discusses the design considerations used to produce such panels and includes theoretical arguments, concrete mixture design, concrete testing, reinforcement selection, composite section analysis, and plate testing.

TRANSFORMED SECTION ANALYSIS

In many mechanics of materials applications, the cross section of a beam subjected to pure bending is made up of two or more materials each having a different modulus of elasticity, E. The stress distribution is determined by formulating a transformed section. This is accomplished by choosing one of the materials (with E_1) as a standard, and then formulating a nondimensional ratio in sections made from different materials as follows:

$$n = \frac{E_2}{E_1} \quad (1)$$

The transformed section is obtained by stretching each element in a direction parallel to the neutral axis of the section (by multiplying that dimension by the elastic modula ratio, n). Normal stresses along the longitudinal axis are computed based on the elastic flexure formula by considering that the section is made from a homogeneous material. Assuming that the beam is oriented in the x direction and bent by applying a moment around the z axis,

$$\sigma_x = -\frac{nMy}{I} \quad (2)$$

where y is the distance measured upward from the neutral surface, and I is the centroidal moment of inertia of the transformed section parallel to z.

The value of n is unity for the material with E_1; stresses in other portions of the structure are obtained by multiplying the stress obtained from the transformed section by the n value of the material located there.

REINFORCED CONCRETE DESIGN

An important example of structural members made of two or more materials is furnished by reinforced concrete beams. The method of attack differs slightly from the method outlined above in that only the portion of the concrete that is in compression is used in computing stresses in the transformed section. The local moment of inertia of the reinforcement about its centroid is neglected when computing the total moment of inertia of the transformed section, and stresses are computed in the reinforcement by assuming that the material lies at its geometrical center.

In general, most concrete section designers employ a relatively strong material such as steel to reinforce the tension side of the beam, and strive to increase the compressive stress of the concrete, often at the expense of weight. Typical 'lightweight' concretes have densities ranging from 1600-2400 kg/m^3 (equivalent to a specific weights of 100-150 lb/ft^3) with compressive strengths on the order of several thousand kPa (psi). Most of these mixtures have an elastic modulus on the order of a few million kPa (psi); typical values of n for steel are 9 or 10.

Although stresses can be driven from the concrete to the reinforcement by increasing the flexibility (lowering the elastic modulus and/or decreasing the stiffness) of the concrete relative to that of the reinforcement, compliance is rarely considered. The work documented herein, however, shows that this stress transfer can be facilitated such that the concrete on the tension side of the composite section acts as a viable structural component.

REVERSE BENDING

This traditional approach to reinforced concrete design is inadequate when the structure is subjected to reverse bending. In this case, catastrophic stresses may result when the reinforcement is placed on only one side of the composite section. The negative moment results in a significant reduction in the centroidal moment of inertia of the transformed section and stresses are much higher than those created when a positive moment is applied.

Materials must be placed symmetrically about the geometrical center of the composite section for it to efficiently resist reverse bending. Only in this configuration will the structure be "adaptive" and exhibit the same degree of structural integrity when subjected to equal but opposite bending couples.

ADAPTIVE STRUCTURES

The simplest way of constructing adaptive structures is to place the reinforcement at the geometrical center of the composite section. However, this approach is inefficient, since the stresses in the materials remain relatively high. A better alternative is to place the reinforcement symmetrically in the section, in layers, separated as far away from one another as possible. When the modula of the constituents are the same in tension and compression, the transformed section is equivalent to a wide flange "I" beam, one of the most efficient geometries used in construction to resist bending loads.

PRELIMINARY INVESTIGATION

The method of photoelasticity can be used to illustrate the importance of stiffness and geometry. Figure 1, for example, shows the isochromatic fringe patterns in four beams made from a plastic called PSM-1. All of the beams shown in the figure have a constant thickness, and each beam is subjected to the same moment. The distribution and number of fringes are directly proportional to the stress. The heavy black fringe in each beam represents the neutral axis which passes through the centroid of the section. The stress varies linearly with depth; compression on one side, tension on the other.

The beam situated second from the top is a 2.54 cm (1 in.) deep control standard and represents an unreinforced, homogeneous beam made of concrete having an elastic modulus equal to that of PSM-1. The maximum stress is 1.50 MPa (218 psi). The top beam is only 1.91 cm (0.75 in.) deep and illustrates that the maximum stress [2.76 MPa (400 psi)] becomes much higher when the depth is smaller.

A 0.64 mm (0.025 in.) thick, 9.5 mm (0.375 in.) wide, steel strip is bonded to the lower surface of the beam situated third from the top. The maximum stress in the plastic is 751 kPa (109 psi); half that found in the control standard. Finally, the bottom beam has steel strips bonded on both the top and bottom faces. The isochromatic fringe pattern in the plastic is barely visible and corresponds to a maximum stress of only 103 kPa (15 psi). This value is over fourteen times less than that in the control standard, clearly indicating that the stress has been driven from the plastic (concrete) to the steel (reinforcement).

PARAMETRIC STUDY

An analytical study was conducted on 5 mm (0.2") thick panels subjected to reverse bending. It was assumed that the panels were reinforced using two layers of 3.18 mm (1/8") square welded wire steel mesh, constructed using 0.43 mm (0.017") diameter wires. Figure 2 shows the layers separated by a relatively weak and coarse plastic grid. For comparison purposes, a moment of 1.66 Nm (14.7 in-lb) was applied to a plate of unit [2.54 cm (1")] width.

Figures 3 and 4 show the maximum stresses in the steel and concrete for different values of the elastic modula ratio, n, as the two steel layers are moved progressively further apart in the composite section. The analysis was based on the standard transformed section method, implying that a concrete mixture could be developed to withstand the stress on the tensile side of the section. The plastic spacer was neglected in making these calculations.

It is apparent from the figures that the stresses in the concrete progressively decrease as the value of n becomes higher and the spacing increases. The stresses in the reinforcement are much higher and show a slightly different trend. For smaller n values, the stress in the steel grows as the spacing between layers increases. However, for larger n values, the stress in the steel initially increases, then, it decreases.

EXPERIMENTAL TESTING

Experimental investigations were conducted on panels, made from different polymer modified concretes, having the geometrical configuration illustrated in Fig. 3. In all cases, the steel layers were positioned at the edges of the specimen using the plastic grid. Compression tests provided a quick means for comparing the compressive strength and the elastic modulus of the different concrete mixes. The mix proportions for one of these in kg/m^3 (lbs/yd^3) are: Portland cement, 220 (372); Liv-lite, 10 (17); Perlite, 198 (335); Micro-balloons 25 (43); Latex, 65 (110); and, water 285 (481). The mix has a water to cement ratio of 1.29, a density of 561 kg/m^3 (35 lb/ft^3), and an average 28-day strength of 3.52 MPa (510 psi). The elastic modulus is 0.76 MPa (110 ksi), making n = 273 for the steel.

Third point bending tests were performed to make qualitative comparisons between different designs. For higher n values, the section was under reinforced and failure occurred in the steel strands located directly beneath the applied loads closest to the middle of the beam where both the moment and shear were maximum. Despite extremely large deflections [as high as 4.3 mm (1.7") over a 38.1 mm (15") span], the concrete did not delaminate or spall.

An end-loaded cantilever beam test was used to verify the theory. During the test, the maximum deflection of the beam occurs at its free end (x = L) where,

$$y_{max} \equiv \delta = - \frac{P L^3}{3 E I} . \qquad (3)$$

Tests were initially conducted to determine the elastic modulus of the wire mesh and the plastic grid used to reinforce the concrete composite panels. The procedure was to cut a section of each material, fix one end, load the free end, and measure the maximum deflection there. The elastic modulus was computed based on Eq. (3) as,

$$E = - \frac{P L^3}{3 I \delta} . \qquad (4)$$

The elastic modulus of the steel mesh was found to be 203.4 Gpa (29.5 Msi) while the elastic modulus of the plastic grid was 1.38 Gpa (200 ksi). These values were used in conjunction with the mechanics of materials method to compute the flexural stiffness of each composite panel.

An experimental value for the flexural stiffness was obtained by testing 2.54 cm (1 in.) wide composite samples in the cantilevered configuration. The length of the span was 8.9 cm (3.5 in.).

Digital images were recorded of each sample prior to testing and measurements were made to determine the average thickness and spacing between the steel layers. Then, one end of the sample was fixed and loads were applied to the free end. The deflection at this position was measured with a dial gage as the load was increased to failure. Figure 5 shows a photograph taken while testing one of the samples.

The flexural stiffness of each sample was computed using,

$$E_C I_T = - \frac{P L^3}{3 \delta} = - \frac{m L^3}{3} \qquad (5)$$

where E_C is the elastic modulus of the concrete, I_T is the moment of inertia of the transformed section, and m is the slope of the load versus deflection curve.

Figure 6 shows the load versus deflection plot for the sample shown in Fig. 5 that was prepared using the concrete mixture described earlier. A flexural stiffness of 0.84 Nm^2 (293 lb-in^2) was computed based on Eq. (5); and, a theoretical value of 0.87 Nm^2 (304 lb-in^2) was obtained by applying the transformed section method. The percentage error of four percent was typical for all plates tested in which the n value for steel ranged from 30 to 1000.

DISCUSSION

Structural performance can be improved by using a graphite mesh instead of steel. In comparison to steel, the primary attributes of graphite are its lower mass, higher tensile strength, greater corrosion resistance, lower relaxation, higher strength-to-weight ratio, greater insensitivity to electromagnetic fields and nuclear bombardment, and easier cutting and handling. However, a designer must take into account that, unlike the ductile elasto-plastic behavior of steel reinforcement, carbon fibers are characterized by linearly elastic behavior and undergo abrupt brittle failure. One approach that may be taken to ensure safety and reliability is to monitor deflection as a precursor to failure.

Since an unimpregnated mesh does not take compression outside of the composite section, a compressive embedded modulus must be obtained. This can be accomplished by measuring the deflection of composite samples.

CONCLUSIONS

This paper shows how extremely efficient and lightweight reinforced concrete composite panels can be designed and constructed to resist reverse bending. The design is based on a combination of compliance and strength, and the panels rely on a flexible concrete mixture placed over multiple layers of relatively stiff reinforcement positioned symmetrically in the composite section.

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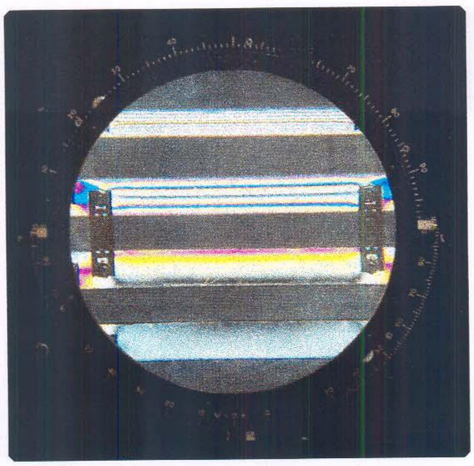

Fig. 1. Photoelastic fringes on beams.

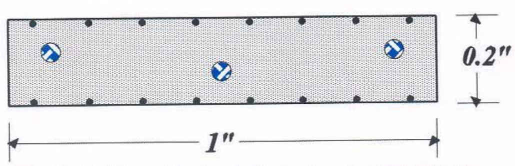

Fig 2. A thin-walled, reinforced concrete panel.

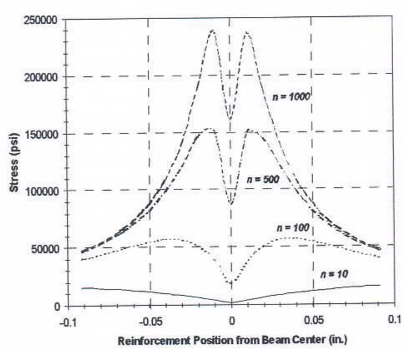

Fig 3. Maximum stresses in steel reinforcing layers for different spacing and n values.

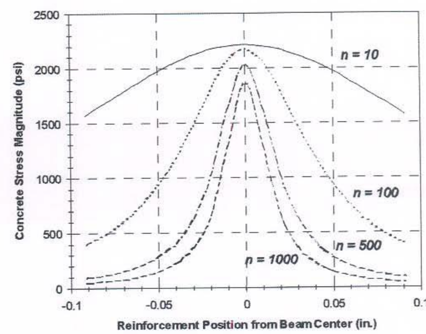

Fig 4. Maximum stresses in concrete for different spacing and n values.

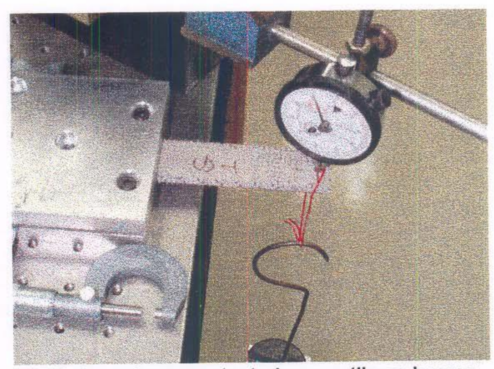

Fig 5. Samples were tested as cantilever beams.

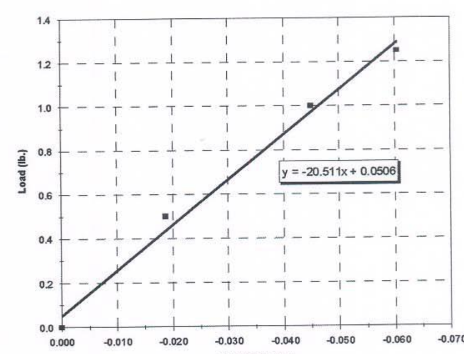

Fig. 6 Cantilever beam test results.