PRESTRESSED CONCRETE BEAMS WITH A LONGITUDINAL CAVITY

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A prestressed concrete beam of rectangular cross section with a circular void is described in terms of elastic beam theory of bending and designed in accordance with the guidelines specified in ACI 318-71. A prototype beam was tested to verify the adequacy of the above hypothesis and to determine appropriate application for such beams. The materials used and the experimental methods employed are also described.

Three common types of prestressed concrete pipe beams were described in a previous paper[1] as a solution for crossing streams, rivers, peat bogs, swamps, and valleys with sewage or telephone and electrical cables. Over four beams of this type were built and erected by Northeast Concrete Products in recent years (see Table 1). The analysis of these beams was based on the elastic beam theory and the design procedures were in accordance with the existing AASHO Code. Since 1970, the design procedures were modified to follow those given by ACI 318-71[2] and its Commentary[3] with the exception, that no tensile stresses are permitted in the member.

This paper pertains primarily to pretensioned, prestressed concrete beams of rectangular cross section with any number of discontinuities. A full-sized beam was tested to compare the adequacy of the above modified design method.

Design approach

The flexural stresses of a prestressed member at any fiber may be computed using the elastic beam theory. The usual Navier-Bernoulli's hypothesis of a plane cross section before bending remaining plane and normal to the longitudinal axis after bending will be assumed.

Table 1. Pretensioned pipe beams

W.O. Number	Project	Dimensions	Engineer	General Contractor
6010	South End Road and Milldale, Interceptor Sewers, Southington, Connecticut	15 x 30 x 24 in. ID	Metcalf and Eddy	Greer Construction Co.
6377	Onota Brook Crossing, Pittsfield, Massachusetts	10 x 24 x 20 in. ID	Camp, Dresser and McKee	Western Massachusetts Contracting Engineers
6664	Sewers and Appurt Work, Enfield, Connecticut	12 x 30 x 24 in. ID	Metcalf and Eddy	A & M Construction Co.
6825	Northeast Metropolitan Regional Vocational School, Wakefield, Massachusetts	8 x 20 x 20 in. ID	Korslund, LeNormand and Quann, Inc.	Frasca Construction Co.
68100	Sewers and Appurt Work (Contract No. 1965-3) Enfield, Massachusetts	21 x 30 x 30 in. ID	Metcalf and Eddy	Seminole Construction Co.
7039	Contract No. 6622, Southington, Connecticut	30½ x 32 x 21 in. ID	Metcalf and Eddy	Eire Construction Co.
7102	Waste Water Disposal Facilities (Contract No. 5) Litchfield, Connecticut	18 x 24 x 8 in. ID	C. A. Maguire Associates	Giordano Construction Co.
7103	Weaver Street Sewers, Greenwich, Connecticut	24 x 24 x 8 in. ID	Metcalf and Eddy	M. Rondano Inc.
7136	Sewerage Project WS-07-01, East Berlin, Connecticut	22 x 34 x 10 in. ID	Cahn Engineering	Town of Berlin, Connecticut
7139	Interceptor Sewers (Contract No. 3) Merrimack, New Hampshire	26 x 26 x 18 in. ID	Anderson-Nichols	Griffin Construction Co. Inc.
7211	Telephone Cables (Project No. 112373) Lexington, Massachusetts	30 x 30 x 16 in. at 4 in. ID	New England Telephone Co.	New England Telephone Co.

The pipe beam is generally designed to resist stresses caused by:

1. Live load
2. Wind load
3. Gravity weight of beam and gravity load of contained substance
4. Buoyancy
5. Horizontal external liquid pressure

The following two possible loading combinations may be considered for the design of pipe beams:

Case I. Dead load plus live load plus wind load

Case II. Dead load plus buoyancy plus horizontal external liquid pressure

Case I is where the pipe beam is exposed while Case II is where the beam is submerged.

The critical stress condition may be selected from the above to establish the

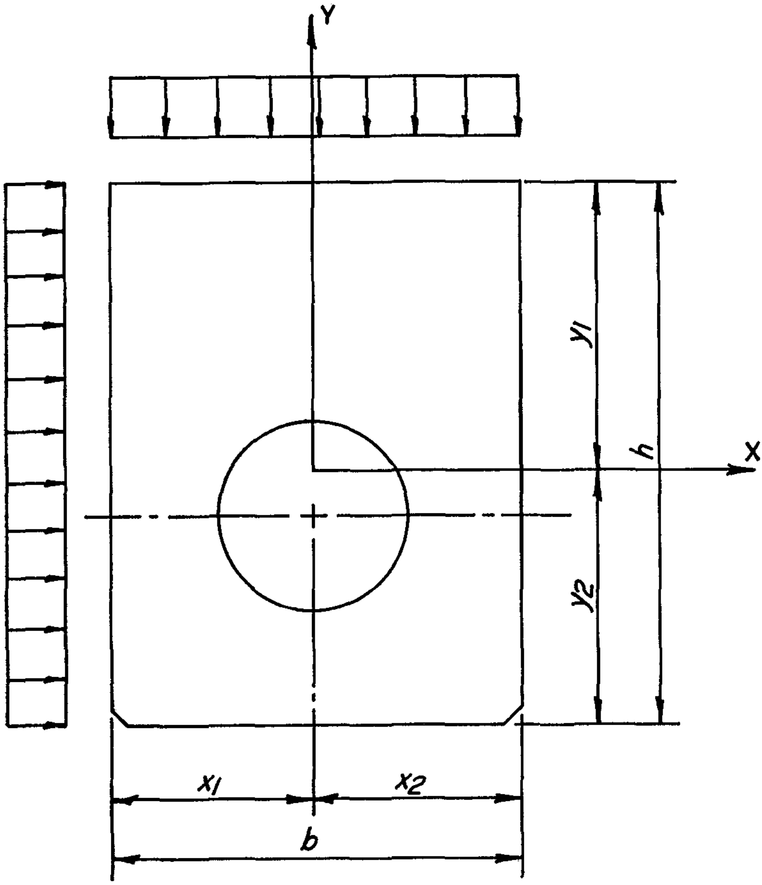

Fig. 1. Cross-sectional symbols and loading of pipe beam

required prestress. For a simply supported beam (see Fig. 1), the equations for the biaxial stresses are:

$$f_i^t = \frac{P_i}{A} - \frac{P_i e y_1}{I_x} \tag{1}$$

$$f_i^b = \frac{P_i}{A} + \frac{P_i e y_2}{I_x} \tag{2}$$

$$f_f^t = \frac{P}{A} - \frac{P e y_1}{I_x} + \frac{M_x y_1}{I_x} + \frac{M_y x_1}{I_y} \tag{3}$$

$$f_f^b = \frac{P}{A} + \frac{P e y_2}{I_x} - \frac{M_x y_2}{I_x} - \frac{M_y x_2}{I_y} \tag{4}$$

The design should result in stresses below those allowed in ACI 318-71. However, no tensile stresses are permitted in any part of the cross section.

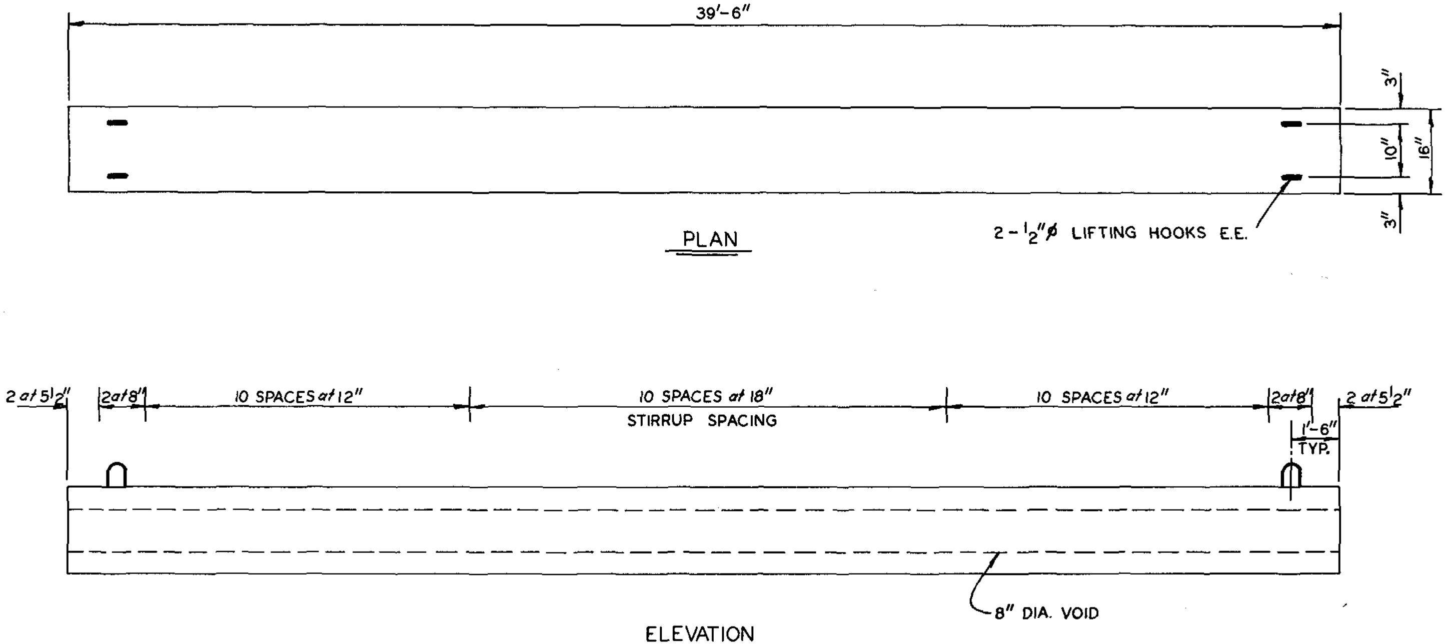

Fig. 2a. Plan and elevation details of pipe beam

The computation of ultimate design strength may be carried out using the equations provided in ACI 318-71.[3] The value of this moment must be at least equal to the following combinations of load effects as given below:

$$0.75\,(1.4\,D + 1.7\,L + 1.7\,W) \qquad (5)$$

or

$$0.9\,D + 1.4\,F \qquad (6)$$

Experimental data

A pretensioned, prestressed concrete beam of 39 ft 6 in. long was tested in this investigation. The beam cross section was 16 x 16 in. with an 8 in. diameter circular void. The beam was fabricated in accordance with the shop drawing shown in Fig. 2a and 2b.

The concrete used was normal

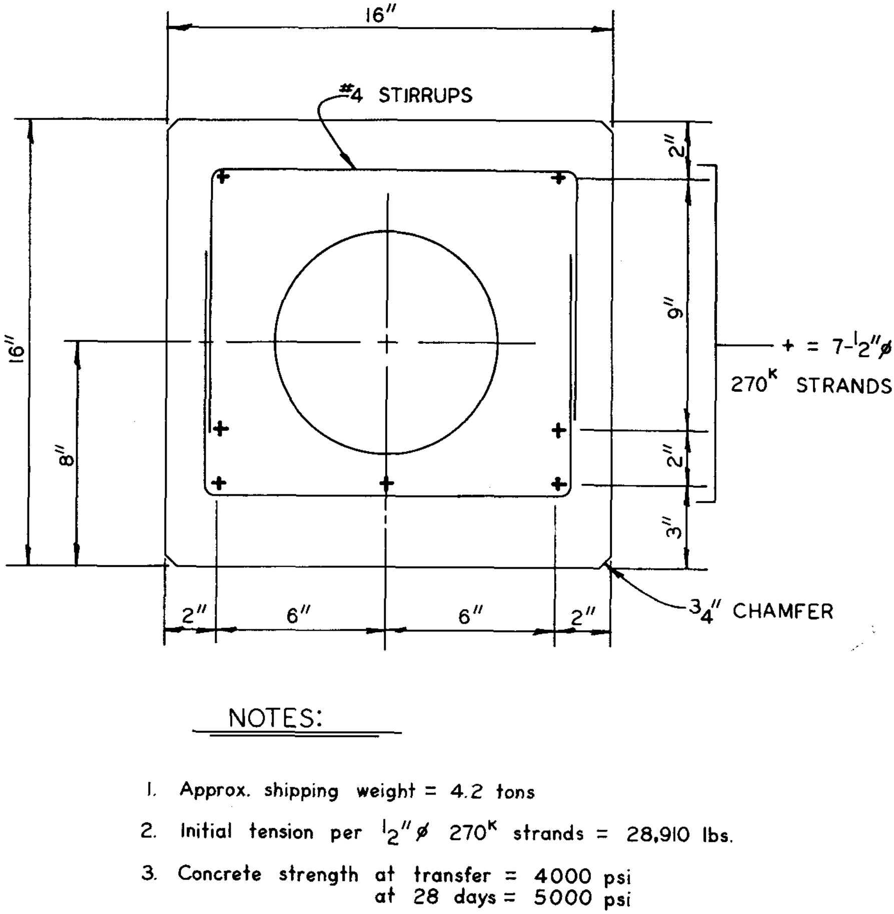

Fig. 2b. Cross-sectional details of pipe beam

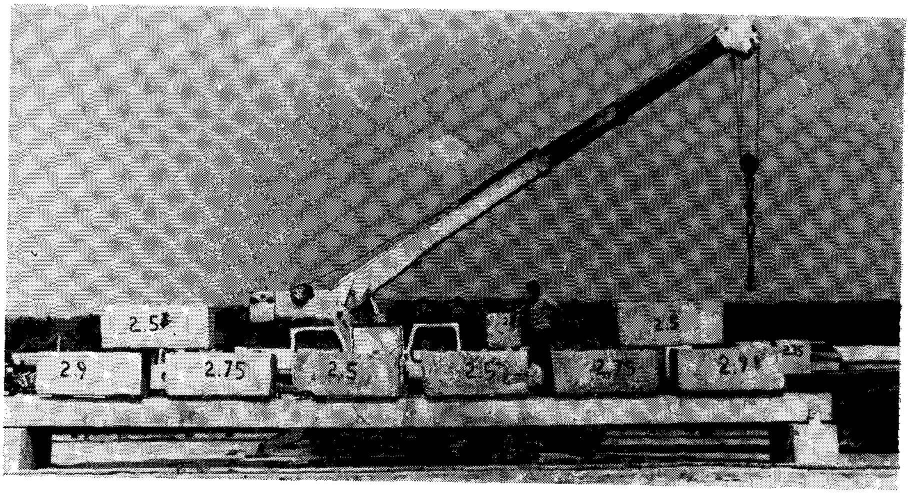

Fig. 3. Loading of pipe beam for flexural test

weight mix with ½ in. maximum size of aggregate (gravel); a minimum ultimate compressive strength f'_c at 28 days equal to 5000 psi and 4000 psi at release. Prestressing strands were uncoated seven-wire stress-relieved, ½ in. diameter conforming to ASTM A416 for 270,000 psi ultimate tensile strength. The No. 4 stirrups conformed to ASTM A15 for 40,000 psi yield strength. The test beam was cast in a metal form. From the concrete batch four 6 x 12 in. and four 4 x 8 in. concrete control cylinders were made for compressive strength tests and its stress-strain relation. The control cylinders were cured with the test beam. Later, after releasing the prestress, the control cylinders were transferred to the plant wet room until tested. The wet room was conditioned to 100 percent relative humidity at 70 F.

The initial jacking force applied was 28,910 lb per cable corresponding to a stress of 189,000 psi. The effective prestress was estimated at the time of testing to be 166,500 psi or 21 percent loss. The percent loss assumed was based on the prior design experience and was to be very reliable.

The test beam was supported on two concrete piers to span 37 ft 6 in. At the reaction points two neoprene pads were placed to assure uniform bearing for the test beam. A standard scale mirror was placed at midspan for deflection measurements. Electrical resistance, foil strain gages were used to measure the strains on the boundary surface of the beam at midspan. Vertical test loads were applied to the test beam in five increments using concrete blocks. The concrete blocks ranged in weight from 2.5 to 2.9 kips as shown in Fig. 3. At each load increment, the strain readings and the midspan vertical deflection were recorded. The reading under the beam gravity weight is considered as a reference point.

Discussion of test results

From the strain measurements, the stresses were computed using Hooke's

Law. The flexural stresses and strains are plotted in Fig. 4. The average value of Poisson's ratio for the uncracked beam was found to be 0.16. From the strains measured on the control cylinders, the stress-strain relation was plotted in Fig. 5, and the Young's modulus for the concrete was approximated to be equal to 3,000,000 psi.

The load-deflection history during the test is shown in Fig. 6. The test beam behaved in a ductile manner beyond its usefulness. The mechanism of failure was a flexural compression in the

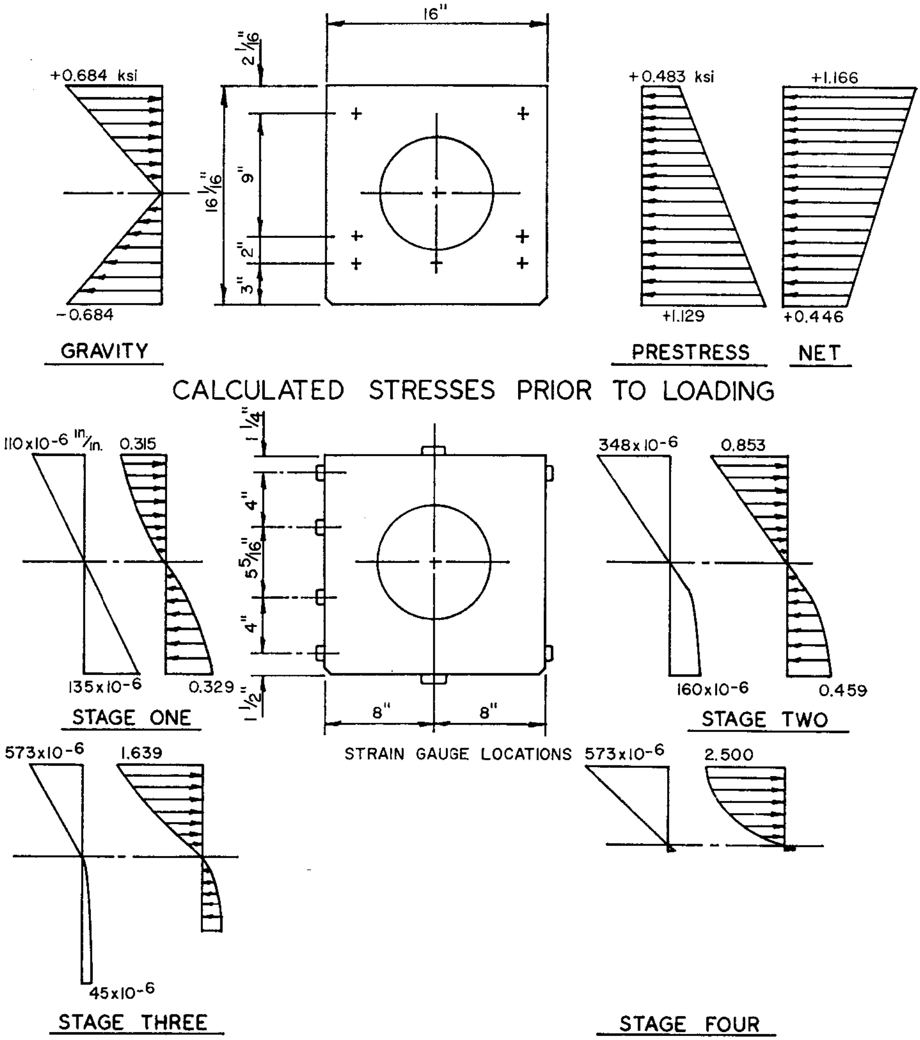

Fig. 4. Stresses and strains due to loads

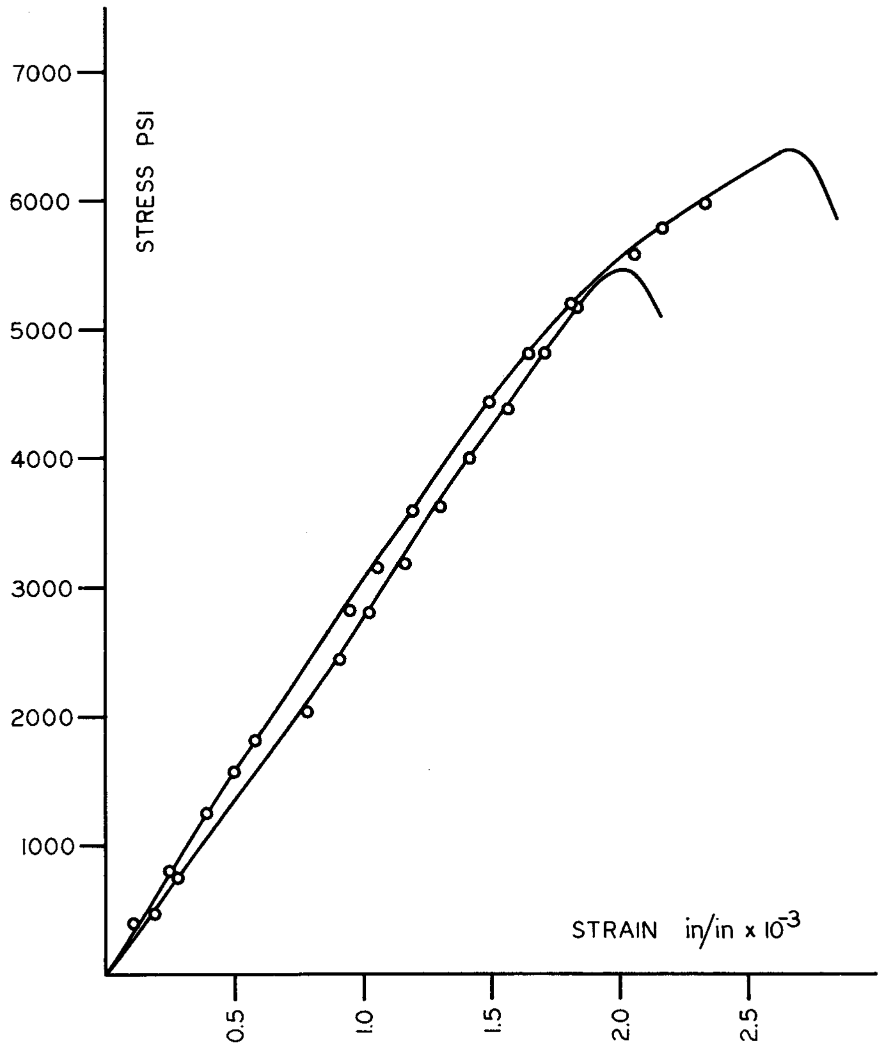

Fig. 5. Stress-strain relation for concrete of pipe beam

top region at midspan. Further investigation of the failure revealed that steel had yielded, while concrete crushed in the compression zone. The stresses predicted by the elastic beam theory were slightly lower than those obtained from the experimental analysis.

On application of Load Increment 3, visible cracks appeared at near midspan. The corresponding total moment for this stage was 114.58 ft–kips and the maximum principal stress was 861 psi. The length of the cracks was about 2¼ in. from the bottom surface of the test beam. The cracks propagated and their number increased with increasing

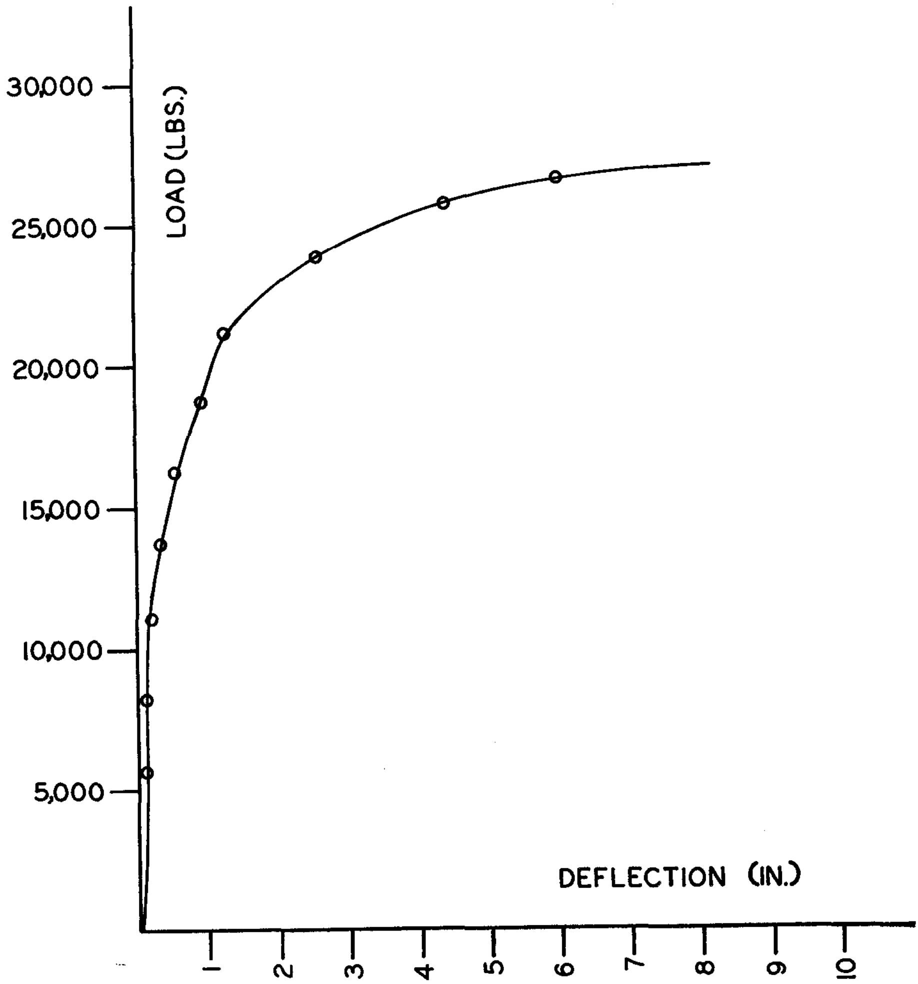

Fig. 6. Load-deflection curve of pipe beam

test loads. Fig. 7 shows the crack pattern at near ultimate load. The ultimate capacity of the test specimen was computed from ACI 318-71[2] and was to be 147.0 ft–kips in comparison with the test value of 155.26 ft–kips. The maximum moment carried by the beam prior to failure was 173.66 ft–kips. Hence, the ultimate moment computed from the ACI Code was found to be a conservative value.

Conclusions

1. Pretensioned, prestressed concrete beams of a rectangular cross section with a circular void can efficiently be

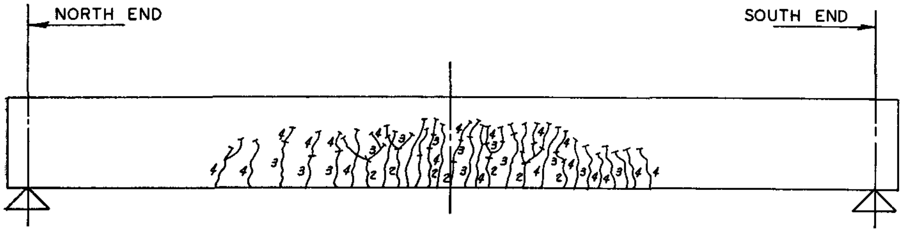

Fig. 7. Flexural crack pattern of pipe beam

used for various structural purposes. One such application is to cross streams carrying water, sewage, telephone and electrical cables, under or above the stream. Their use has shown appreciable saving in construction cost and maintenance cost as well.

2. The stresses predicted by the elastic beam Eq. (1) through (4) agree satisfactorily with experimental results. Thus, a rigorous elasticity solution is of little value in this case as long as the span-to-depth ratio of the beam is fairly large.

3. The ultimate capacity for the beam may be predicted by the governing guidelines given in ACI 318-71 with a satisfactory safety margin.

Recommendations

The following points are recommended for the design of a prestressed concrete beam containing a longitudinal cavity:

1. The stresses due to service loads and weight of beam may be obtained from the elastic beam theory for a combined state of stress. The values of the service loads normally applied are:

   1. Live load = 40 psf
   2. Wind load = 50 psf
   3. Horizontal external liquid pressure = 150 psf

2. To minimize the lateral and vertical displacements, the ratio of span length to depth of cross section should not be greater than 25 for sections containing a maximum inside void of 12 in. in diameter and 20 for cross sections with a void greater than 12 in. in diameter.

3. ACI 318-71[2] and the ACI Commentary[3] may be followed for the design of pipe beams with the exception that no tensile stresses be permitted at a distance of $b/4$ from the vertical centroid axis of the cross section, where b is the width of the beam.

4. The vertical displacement should be a minimum to allow gravity flow of contained substance (i.e., water or sewage).

5. Elementary trial sections may be obtained from prepared load tables. (This information will be furnished upon request to Northeast Concrete Products, 99 Needham Street, Newton Upper Falls, Massachusetts 02164.

Acknowledgments

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References

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Appendix—Notation

f_i^t, f_i^b = top and bottom fiber stress at time of initial prestress
f_f^t, f_f^b = top and bottom fiber stress under working load
P = effective prestressing force after losses.
P_i = initial prestressing force
A = transformed area of concrete
e = eccentricity of prestress
I_x, I_y = moments of inertia about principal axis of cross section
x_1, x_2 = distance from centroidal axis of section to extreme side fibers (see Fig. 1)
y_1, y_2 = distance from centroidal axis of section to top and bottom fibers (see Fig. 1)
M_x = moment due to vertical loads
M_y = moment due to horizontally applied loads
D = dead load
L = live load
W = wind load
F = lateral liquid pressure

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