Review of Research on Prestressed Concrete Loaded with Torsion

JIM D. HAHS and H. ALDRIDGE GILLESPIE,
University of Oklahoma, Norman

Introduction—Prestressed concrete is a relatively new construction material when compared to plain and reinforced concrete. Thus, it is reasonable to assume that the quantity of analytical and experimental work in prestressed concrete to date is less than that on either plain or reinforced concrete.

The available research on prestressed concrete under torsion is limited and is of recent origin. One of the primary reasons for this recent desire for an understanding of the effects of torsion is that modern structures tend to be of higher degrees of statical indeterminacy and continuity, thereby incurring combined stress states which regularly include torsion. The second reason is found in those instances in which torsion cannot be eliminated, not even on paper. In the past this was either ignored or taken care of by reducing the permissible stresses.

Early research on concrete in torsion was conducted using plain concrete, which has formed a basis of comparison for more recent programs involving tests on reinforced and prestressed concrete.

Pure Torsion—The results of pure torsional tests on plain concrete sections can be separated into two distinct types. The first type is that of convex cross sections which fail as soon as the first crack forms. This failure is sudden, destructive and without warning (Anderson, 1937; Miyamote, 1927; Turner and Davies, 1934).

The torque-twist curves for convex cross sections show an almost linear relationship between torque and angle of twist up to approximately 80% of the torsional capacity of the specimen (Andersen, 1937; Ernst, 1957). Just prior to failure, the torque-twist curve bends over slightly, indicating that there exists an inelastic stress redistribution in the concrete and a decrease in stiffness of the member.

The specimens fail along an angle of 45° with respect to the center line of twist where the principal tensile stress is the largest. This type of failure is a justification of the theory that the concrete fails in tension.

Concave cross sections, particularly I-beams, behave in a manner similar to that of convex cross sections up to the initial cracking load. The first cracking occurs in the web where the maximum principal tension stress occurs. The initial cracking reduces the stiffness of the specimen but failure does not occur until the 45° cracks propagate through the flanges.

Pure torsion on prestressed concrete without web reinforcement produces effects similar to an equivalent plain concrete specimen. The effect of axial compression is to increase the torsional capacity of the specimens, in certain cases as much as three times. This increase can be explained by the reduction in the magnitude and change in the direction of the principal tensile stresses due to the axial compressive stress (Humphreys, 1957; Zia, 1961). The maximum compressive stress is reported to be approximately 80% of the standard 6-× 12-inch cylinder strength.

Prestressed specimens typically form cracks of less slope than those formed in plain concrete sections with the minimum of approximately 20° (Zia, 1961: Gardner, 1960). Convex cross sections fail with the formation of the first crack while members with concave cross sections crack initially at mid-height and fail abruptly when the stresses in the flanges reach the tensile strength of the concrete (Humphreys, 1957; Gardner, 1960; Cowan and Armstrong, 1955).

The primary difference between the torque-twist curves of prestressed specimens without web reinforcement and those of plain concrete specimens appears to be the point at which the curves start to bend. The amount of prestress has little effect upon the intiial stiffness of the member, but increase in prestress does cause the curve to have a longer linear range (Andersen, 1937; Zia, 1961; Cowan and Armstrong, 1955).

It should be noted that although concave sections show ductility before failure, this ductility is of little practical use since the magnitude of the permanent cracks in the web is not acceptable under general public scrutiny.

Torsion Combined With Moment—The available information on torsion combined with moment is even more limited than that of torsion alone. It might appear logical that the available test data on moment could be superimposed on that available on torsion to predict the situation when they act simultaneously. This simple superposition does not offer a suitable prediction of the failure mode.

When pure torque is applied to a plain concrete specimen, the cracking occurs at an angle of 45° to the axis of twist. Flexure on the other hand causes vertical cracks to propagate toward the neutral axis. Applying the two conditions simultaneously will cause the cracking to occur between 45° and 90°. When axial compression is applied, the trend is to cause the slopes of the cracks to be more nearly parallel to the axis of the specimens (Kemp et al., 1961).

Presentation of combined-moment data is often made using an interaction diagram. This diagram plots the dimensionless variables of T_u/T_{uo} versus M_u/M_{uo}, where

M_u = ultimate moment in combined bending and torsion

M_{uo} = ultimate moment for pure bending

T_u = ultimate torque in combined bending and torsion

T_{uo} = ultimate torque for pure torsion

The general shape of the interaction curves for reinforced concrete members under torsion-moment resembles a deformed upper right quarter of a circle (Kemp et al, 1961). The lower end of the curve shows that if a small amount, i.e. less than 50% of the ultimate torsional capacity of a member, is added to a flexural specimen it will increase the flexural capacity slightly. The upper end indicates a similar effect on the torsional capacity when a small moment is applied to the specimen (Cowan and Armstrong, 1955). Experimental verification is especially limited in the region of the lower end of the interaction diagram.

Cowan and Armstrong (1955) presented a torsion - moment interaction diagram for plain and prestressed concrete specimens by a plot of Torque (T) verses Moment (M). This plot resembles an upper right quarter of an ellipse. The interaction diagram for plain concrete at the formation of first crack is also the interaction diagram for failure since failure occurs with the formation of the first crack (Gardner, 1960; Cowan and Armstrong, 1955).

The interaction for prestressed concrete without web reinforcement of convex cross sections at first cracking is also the failure diagram for small moments, but for large moments the failure becomes gradual and the failure load becomes larger than that causing initial cracking. The ellipse for the prestressed concrete has larger major and minor axes since prestressing increases the capacity of the section. The limited data available indicates that the ellipse for either of the above cases is not as badly deformed as the circle for reinforced concrete sections.

A recent series of tests (Gardner, 1960; Reeves, 1962) on prestressed concrete T-beams indicates that the interaction for concave cross sections behaves differently than those of convex cross sections. The results of this research show that an increase in the torsional capacity of the member is obtained with the application up to 80% of the moment capacity. The maximum increase in torsional capacity occurs at approximately 50 to 60% of the moment capacity with the maximum ratio of actual torsion to pure torsion being in the order of 1.6.

When web reinforcement is added to prestressed concrete specimens, they behave almost as unreinforced members until cracking starts. After cracking has initiated, the reinforced prestressed member shows increased ductility, but due to the limited research and the number of variables involved no definite conclusions can be made.

Torsion Combined With Shear—The foregoing discussion on combined torsion and moment indicates that the capacity of a given section is not adversely affected and, in fact, may even be fortified by the combined loading. However, this is not the case when shear and torsion act in combination (Kemp et al., 1961).

Flexural shear causes the principal tensile stresses to be oriented in the same inclined direction on both vertical faces while the torsional effect is to cause a helical pattern around the longitudinal axis. When a specimen is loaded with both flexural shear and torsional shear, the stresses tend to cancel on one face but they add to each other on the opposite face.

The interaction diagram for shear and torsion combined is usually approximated by a straight line $[(V_u/V_{uo}) + T_u/T_{uo}) = 1]$. It should be noted that this interaction diagram is not distorted at the ends, indicating no stress build-up.

Torsion Combined With Shear and Moment—Although torsion, shear and moment combined is the most practical loading condition, this problem has been almost completely ignored by researchers. The primary reason for its avoidance is likely due to the many variables and unknowns encountered with simpler loads.

It apears that a surface interaction diagram should be obtained with the axes of the surface being shear, torsion and bending moment. At the present stage of the research, it is difficult to justify such a complicated graphical summary.

SUMMARY

From the presented review of the limited information concerned with torsion on prestressed concrete, it is apparent that more research is required. This can be further emphasized by reference to the ACI Building Code and its recommendations for prestressed members, which totally lacks aids for torsion even as a secondary condition.

Research on torsion as the primary loading condition is required to further our understanding of its effects. This basic investigation should include eccentrically prestressed specimens with varying amounts of prestress and web reinforcement, as well as, concentrically prestressed members. It should also include the study of pretensioned and posttensioned specimens of practical cross sectional sizes and shapes.

Although not as basic, but more practical, a study of prestressed concrete under combined loading is also required. This combined loading investigation should include torsion with shear, torsion with moment, and torsion with shear and moment. Different sequences and ratios of these combinations will be required to determine the critical combinations. This investigation should also be oriented toward the more often used eccentrically prestressed members, with variable amounts of prestress, changes in cross section, and amount of web reinforcement being considered.

LITERATURE CITED

Andersen, Paul. 1937. Rectangular concrete sections under torsion. Proc. Amer. Concrete J. 34:1-11.

Cowan, H. J. and S. Armstrong. 1955. Experiments on the strength of reinforced and prestressed concrete beams and of concrete-encased steel joists in combined bending and torsion. Mag. Concrete Res. 7 (19):1-18.

Ernst, G. C. 1957. Ultimate torsional properties of rectangular reinforced concrete beams. J. Amer. Concrete Inst. 29(4):34-356.

Gardner, R. P. M. 1960. The behavior of prestressed concrete I-beams under combined bending and torsion. Tech. Rep. TRA/329. Cement and Concrete Assoc. G. Brit.

Humphreys, R. 1957. Torsional properties of prestressed concrete. Structural Eng. 35(6):213-224.

Kemp, E. L., M. A. Sozen and C. P. Siess. 1961. Torsion in reinforced concrete. A report on a research project sponsored by the University of Illinois Research Board. Univ. Ill., Urbana.

Miyamote, T. 1927. Torsional strength of reinforced concrete. Concrete Constr. Eng. 22(11):637-647.

Reeves, J. S. 1962. Prestressed concrete tee beams under combined bending and torsion. Tech. Rep. TRA/364. Cement and Concrete Assoc. G. Brit.

Turner, L. and V. C. Davies. 1934. Plain and reinforced concrete in torsion, with particular reference to reinforced concrete beams. The Institution of Civil Engineers, Selected Engineering Paper No. 165, p. 31.

Zia, Paul. 1961. Torsional strength of prestressed concrete members. J. Amer. Concrete Inst. 57(10):1337-1359.