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Detailing for Torsion

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This paper discusses the detailing of torsional reinforcement. First, the functions of the longitudinal and transverse torsional steel are explained in terms of a simple, easy to visualize model.

After introducing the concept of spalling of the concrete cover, the detailing requirements which are necessary if the reinforcement is to fulfill its functions are presented. The consequences of incorrect detailing are discussed.

Keywords: anchorage (structural); beams (supports); cover; **cracking (fracturing);** crack width and spacing; **detailing;** reinforced concrete; **reinforcing steels; spalling;** stirrups; structural design; **torsion.**

■ IN ORDER THAT MEMBERS SUBJECTED to torsion perform satisfactorily. not only must an adequate amount of torsional reinforcement be provided, but more importantly, this steel must be correctly detailed. The consequences of incorrect torsional detailing can be excessive cracking and premature, brittle failures.

In this paper the manner in which a reinforced concrete beam resists torsion is illustrated by means of the diagonal compression field model.[1] This rational model enables the designer to visualize the functions of the concrete, the longitudinal steel, and the stirrups and hence aids him in correctly detailing the steel.

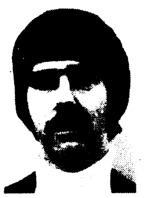
The paper will also illustrate some of the more common torsional detailing errors and their consequences.

FUNCTION OF THE REINFORCEMENT

Shown in Fig. 1 is the manner in which a cracked reinforced or prestressed concrete beam resists pure torsion. After the beam cracks the torsion is resisted by a field of diagonal compression which spirals around the beam. It is the tangential component of this diagonal compression in the concrete that provides the shear flow q required to resist the applied torsion T (see Fig. 1a).

Equilibrium along the longitudinal axis of the beam requires the longitudinal component of the diagonal compression in the concrete to be balanced by tension in the longitudinal steel.

Fig. 1b illustrates the equilibrium of a corner element of the member. It can be seen that the diagonal compression in the concrete has an outward thrusting component, tending to push off the corner of the beam. Equilibrium of the corner elements indicates that in order to balance this outward thrust the stirrups must be in tension on all sides of the member. Without closed stirrups the corners would be pushed off by this outward thrust.



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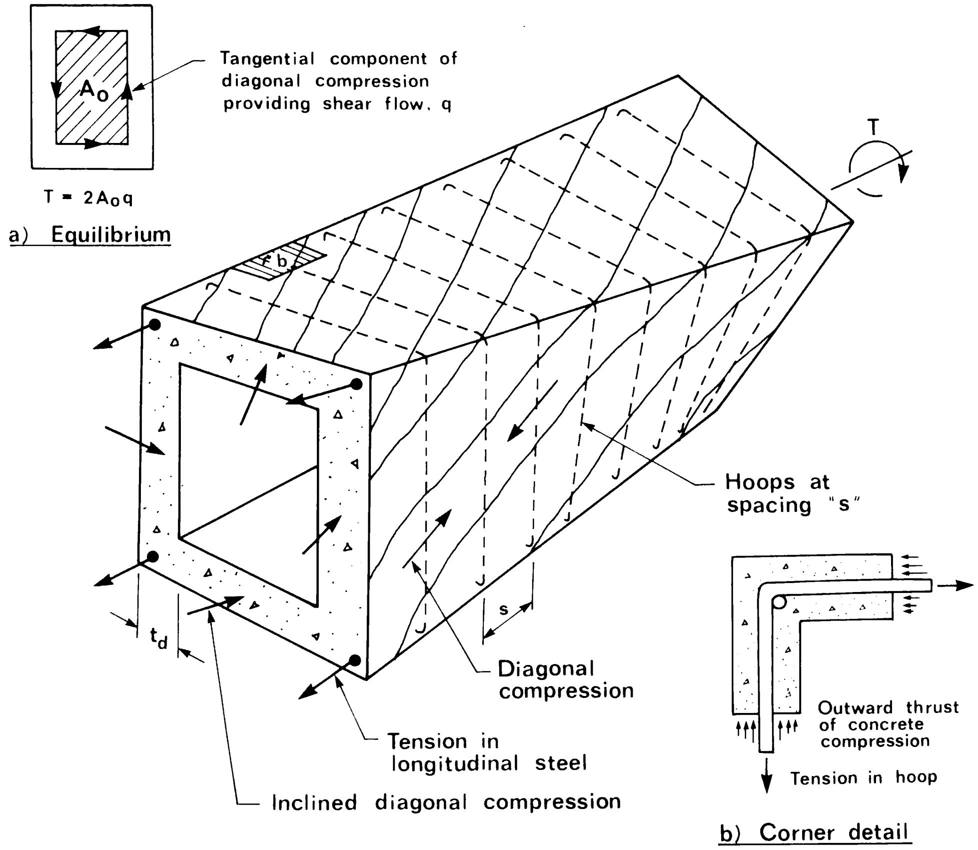


Fig. 1—The diagonal compression field model

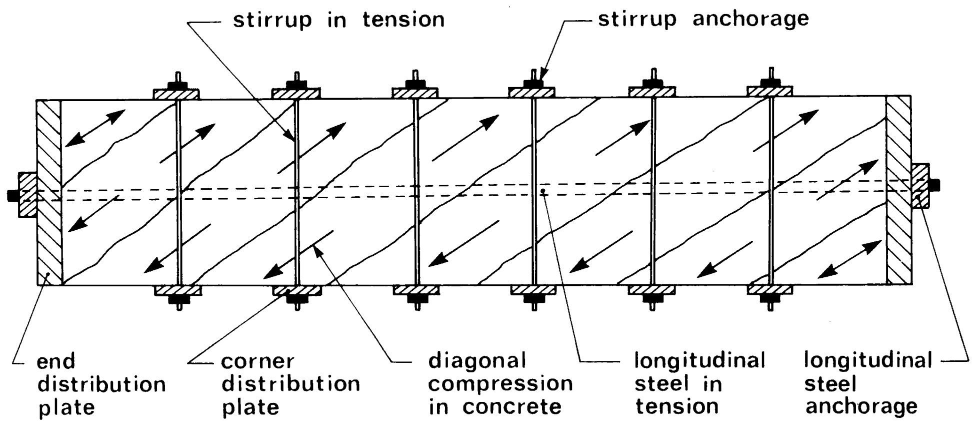


Fig. 2—Idealized functions of the concrete and the reinforcement

A cracked beam in torsion is idealized in Fig. 2 where the functions of the concrete and reinforcement can be visualized more clearly. The function of the concrete is to provide the diagonal compression necessary to resist the torsion; the function of the longitudinal steel is to hold the beam together in the longitudinal direction; and the function of the stirrups is to hold the beam together in the lateral direction.

SPALLING OF THE CONCRETE COVER

Further examination of the corner element in Fig. 3 indicates that since concrete is weak in tension, at higher torsions the cover spalls off. Also shown in Fig. 3 is a 17 in. (432 mm) square beam tested at the University of Toronto[2] that originally had a concrete cover of 1⁹⁄₁₆ in. (40 mm) over the stirrups. Of interest is the loss of concrete cover that has taken place due to spalling.

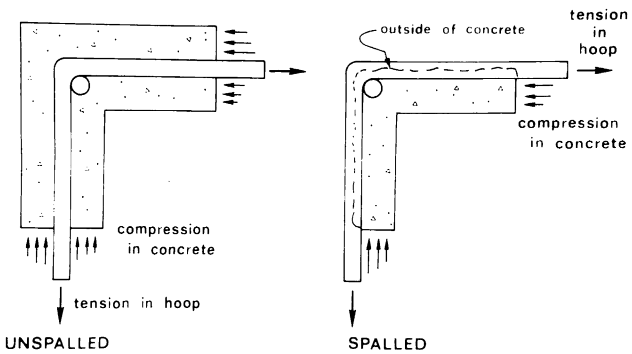


Fig. 3—Spalling of the concrete cover

The spalling of the concrete cover is of considerable significance in the detailing of the stirrups.

DETAILING CONSEQUENCES

Once the functions of the concrete and the reinforcement are understood and it is recognized that the concrete cover will, for higher torsions, spall off, the manner in which the reinforcement must be detailed becomes evident. These detailing consequences for regions where torsion is significant are discussed below.

Holding the beam together longitudinally

The primary function of the longitudinal steel is to hold the beam together along its axis. As can be seen from Fig. 2 it acts as a "tension tie" between the ends of the beam. It follows from this that care must be taken if it becomes necessary to splice the longitudinal steel in regions of high torsion.

As the longitudinal steel is in tension it is essential to provide adequate end anchorage (see Fig. 2). A common error in detailing spandrel beams is to provide inadequate end anchorage for the bottom longitudinal steel;[3] often only a 6 in. (152 mm) extension into the column is used (see Fig. 4).

The end distribution plates in Fig. 2 enable the concentrated tensile force in the steel to be distributed over the ends of the beam balancing the thrusts in the concrete which are attempting to push off the ends of the beam. Usually members subjected to torsion frame into other members which will act as the end distribution plates. If this is not the case then care must be taken to provide proper end anchorage details[4] (see Fig. 5).

Holding the beam together laterally

The primary function of the stirrups is to hold the beam together in the lateral directions. As can be seen in Fig. 2 the stirrups act as ties between the corners of the beam and must be provided on all sides of the beam. Because at higher torsions the concrete cover spalls off, lapped-spliced stirrups will be rendered ineffective leading to a brittle torsional failure. This is illustrated in Fig. 6.

Spalling of the concrete cover also means that considerable care must be taken to achieve proper end anchorage of the stirrups. For example, the 90 deg bend stirrup anchorage shown in Fig. 7

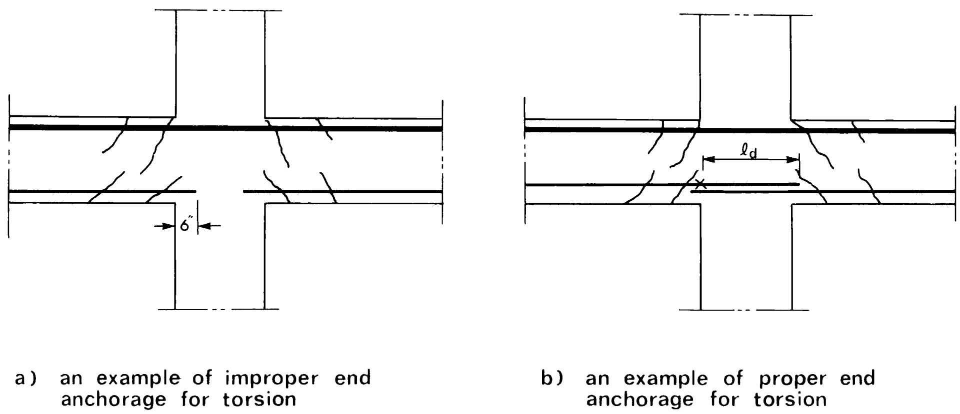


Fig. 4—End anchorage for torsional longitudinal steel in spandrel beam. (1 in. = 2.54 cm)

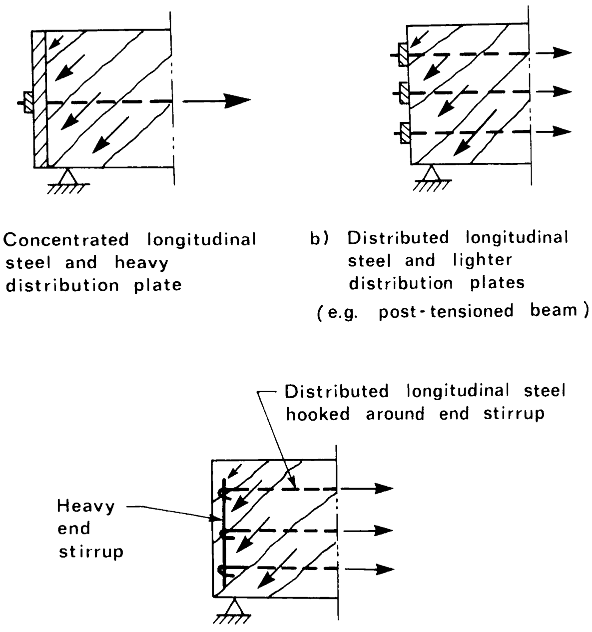
failed in an extremely brittle manner upon spalling of the concrete cover.

In order for a stirrup to be properly anchored the free ends must be bent into the concrete contained within the stirrups. While the standard 135 deg bend with the six-bar-diameter extension[6] would achieve satisfactory anchorage, it may not be possible to provide this degree of bend in some instances (e.g., thin-walled hollow sections). Shown in Fig. 8 is the stirrup anchorage detail used for a hollow beam tested at the University of Toronto.[2] This detail was fully effective in anchoring the stirrups even after spalling of the concrete cover had occurred.

The corner distribution plates of the model shown in Fig. 2 enable the concentrated stirrup tensions to be distributed along the length of the beam, balancing the outward thrusts in the concrete which are attempting to push off the corners of the beam. In an actual beam the longitudinal corner bars will act as the corner distribution plates. The result of having a large stirrup spacing and a small corner bar is illustrated in Fig. 9. It can be seen that for this case the diagonal compression will push off a corner of the beam leading to a brittle failure. It has been found[5] that this type of failure will not occur if the stirrup spacing is less than one-eighth of the perimeter of the closed stirrups (i.e., for a rectangular beam

$$s < \frac{x_1 + y_1}{4}$$

where s is the stirrup spacing and x_1 and y_1 are the stirrup centerline dimensions)[6] and if the corner bar diameter is greater than one-sixteenth of the stirrup spacing.



a) Concentrated longitudinal steel and heavy distribution plate

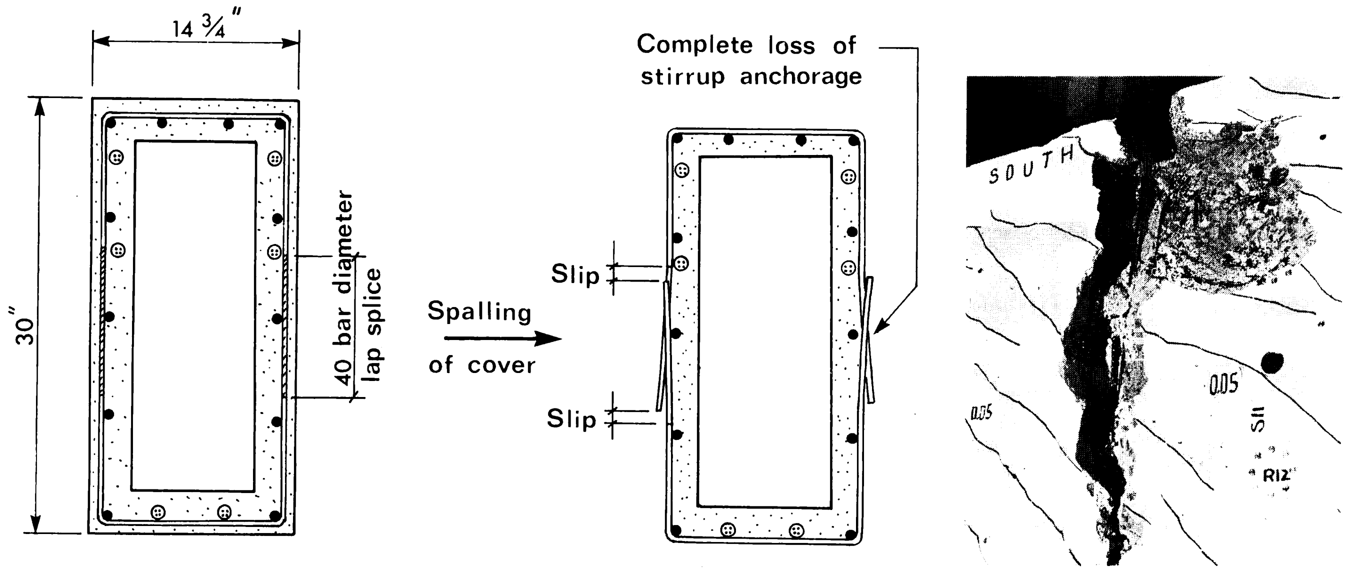
b) Distributed longitudinal steel and lighter distribution plates (e.g. post-tensioned beam)

c) End detail for reinforced concrete beam

Fig. 5—End anchorage details

CRACK CONTROL

Apart from providing the basic functions already discussed, the reinforcement if correctly detailed will control the crack widths. In general as the stirrup spacing and longitudinal bar spacing are increased the cracks become more widely spaced and the crack widths increase.



Lap splice at failure

Fig. 6—Lap splice failure of a beam tested in torsion at the University of Toronto. (1 in. = 2.54 cm)

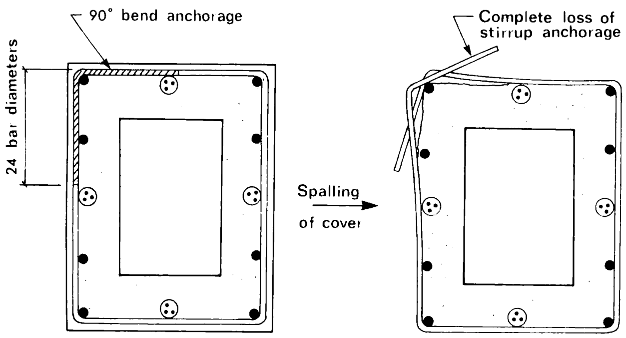


Fig. 7—Failure of 90 deg bend anchorage of a beam tested at the University of Toronto

Shown in Fig. 10 are two beams which contain the same amount of torsional reinforcement. In one beam the torsional reinforcement is closely spaced while for the other beam the reinforcement is widely spaced. The difference in the crack control characteristics for these two arrangements of reinforcement is evident in Fig. 10.

The previously mentioned stirrup spacing limit i.e.,

$$s < \frac{x_1 + y_1}{4}$$

provides reasonable crack control for small and medium sized members. For crack control in larger members the ACI Building Code[6] further limits the spacing of the longitudinal steel and stirrups to 12 in. (305 mm).

CONCLUSIONS

In this paper an attempt was made to show that if the functions of the concrete and the reinforcement are understood and if the spalling phenomenon of the concrete cover is recognized, then it is possible to correctly detail beams in torsion.

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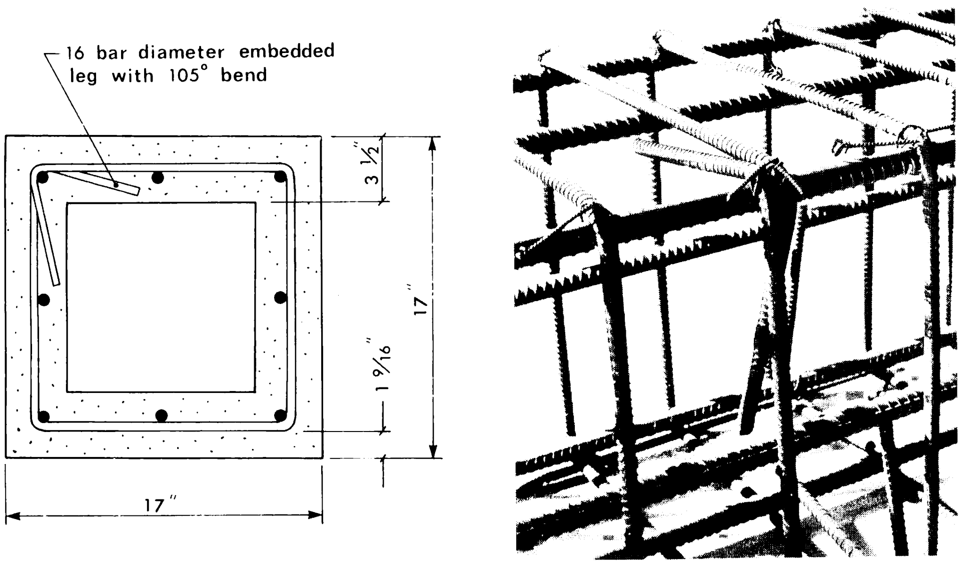
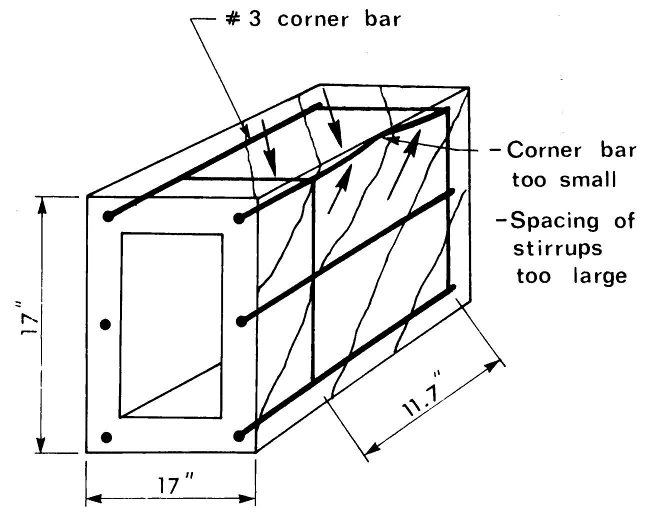


Cross section of beam

Reinforcing cage for beam

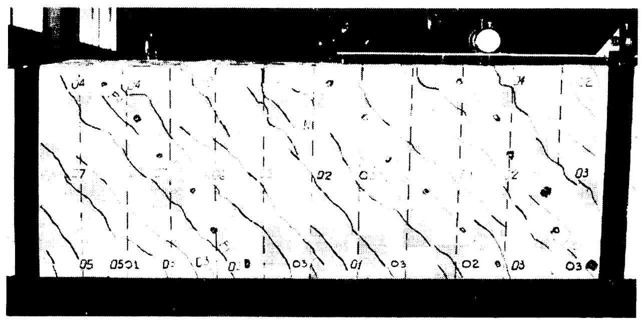
Fig. 8—Satisfactory stirrup anchorage details. Photograph of beam at failure is shown in Fig. 3. (1 in. = 2.54 cm)



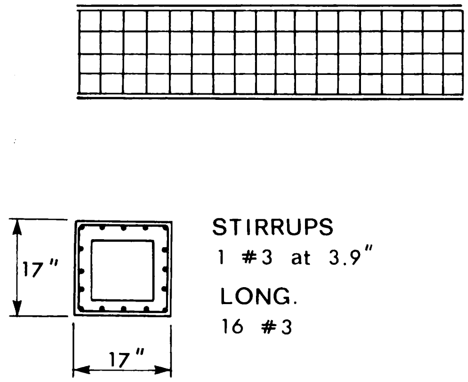
Corner push out

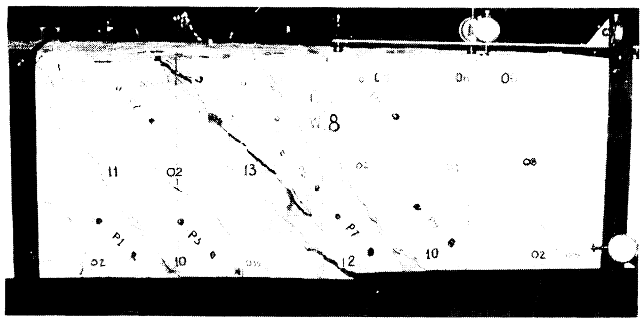
Premature corner pushout failure in Beam CO

Fig. 9—Corner pushout failure. (1 in. = 2.54 cm)



Beam C2 (ductile yielding). $s = 3.9$ in. $\frac{x_1 + y_1}{4} = 7.8$ in.





Beam C6 (excessive spacing failure). $s = 11.7$ in. $\frac{x_1 + y_1}{4} = 7.8$ in.

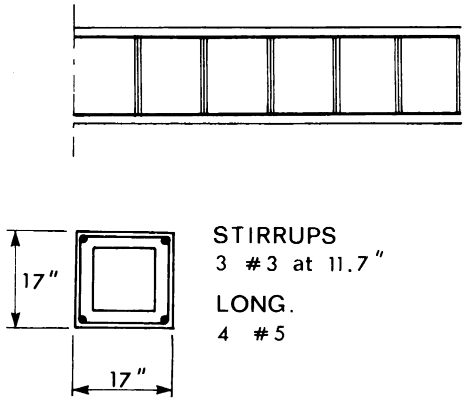


Fig. 10—The effects of reinforcement spacing in the crack behavior. (1 in. = 2.54 cm)

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