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Twist behavior of high-strength concrete hollow beams – Formation of plastic hinges along the length

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ABSTRACT

Torsion tests on high strength concrete hollow beams have revealed some ductile behavior. However, this ductile behavior only occurs for a narrow interval of the torsional reinforcement ratio. Tests have shown that a torsion plastic hinge can be formed. Furthermore, this torsion plastic hinge is concentrated in a small length of the longitudinal axis of the beams. In this paper, the authors show that plastic models are possible for beams under torsion. A torsion plastic hinge at the failure cross section can be assumed. This paper also shows that torsional ductility becomes more difficult as the concrete strength increases.

1. Introduction

High Strength Concrete (HSC) is being increasingly used in new structures. When compared to Normal Strength Concrete (NSC), HSC has advantages that compensate for its higher production costs, due to selection of aggregates, mix proportioning, curing and quality control. Current building structures, and especially bridge structures, can benefit from the economical advantages of HSC. However, the mechanical behavior of HSC structures is somehow different from those of NSC. For instance, the ductility performance is certainly different when comparing HSC with NSC structures.

The study presented in this paper is based on pure torsion tests on HSC hollow beams. Pure torsion is surely not frequent in real structures. When it takes place, torsion is normally combined with shear and flexure. However, in some cases, such as in curved bridges, torsion can be very important. In any cases where torsion takes place, design of the structure using interaction graphs requires a knowledge of the structural behavior of the member under pure torsion.

In long span bridges, hollow beams are a normal solution for the cross section. Therefore, a study on the behavior of HSC hollow beams under pure torsion is very important.

The theory of plasticity can be easily used as a structural designing tool. Codes of practice refer to this theory. However, its application is only possible if the structure has a ductile behavior to accommodate internal redistributions of forces, to prevent brittle failure. It is well known that concrete structures that are correctly reinforced normally have a capacity to withstand inelastic flexural deformations that are sufficient to permit the use of plastic theory.

Although ductile behavior is well accepted for bending moments [1–3], shear and torsion failures are normally associated with brittle behavior. However, shear and torsion may not necessarily lead to brittle failure. As far as shear is concerned, a good choice of longitudinal and transversal reinforcement will induce some ductility. Cladera and Marí have recently studied shear failure in beams with and without stirrups. In a first pair of papers, they proposed a new simplified shear design method to be used in design codes [4,5]. In a following article they [6] presented a shear force versus shear deformation graph and some curves clearly show a great increase of deformation without great variations in the shear force. At the ultimate load, the softening effect (influence of the diagonal cracking on the behavior of the compressed strut) takes place. This phenomenon permits a better dissipation of the internal energy through a reasonable amount of inelastic deformation. In this case, the theory of plasticity can

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be also valid for shear. Due to the similarities of internal stress mechanisms between members under torsion and those under shear forces, beams under torsion can also be sufficiently ductile to permit plastic analyses. For the case of torsion, sufficient ductility can be obtained through the control of various factors: use of steel bars with special ductility requirements, detailing of bars using small spacing values, and use of reinforcement ratios limited by an upper and a lower values (as in flexure).

Many codes do not have specific requirements of minimum reinforcement amount to ensure a ductile behavior of beams under torsion. ACI 318R-05 [7] does present a specific minimum value, but the calculation procedure is based on empirical considerations, which could lead to some incongruent results, as explained by Ali and White [8]. Other codes, such as MC 90 [9], EC 2 [10] and CSA A23.3-04 [11], adopt the minimum values intended for shear. This aspect is very important for high strength concrete beams [12]. As far as the maximum reinforcement is concerned, the codes normally indicate a procedure that indirectly lead to it. The maximum reinforcement ratio is conditioned by enforcing a maximum compressive stress in the concrete struts.

Although the codes show some concern in ensuring a ductile behavior of members under torsion forces, it is not sufficient because the specific studies on this subject are rare, and non-existent for the particular case of high strength concrete beams.

This paper covers the overall behavior of hollow beams under pure torsion, especially plastic behavior. The study is based on experimental results from sixteen beams.

2. Research significance

Experimental studies on high strength concrete beams under pure torsion are very rare. A study was published by Rasmussen & Baker in 1995 and reports tests on nine small rectangular plain beams [13,14]. These beams were over reinforced, and the concrete strength was the only variable parameter. Another study was published by Wafa et al. in the same year [15]. This study reported tests on 14 small rectangular plain beams. The variables were the concrete strength (with large variation), the aspect ratio of the cross section, the level of uniform prestress, and the amount of torsion reinforcement. The general analysis of the results gave some indications on the advantages in using HSC on the maximum torsional strength of such beams.

The studies cited above do not approach the topic of ductility in torsion. As explained later in this paper, this topic is very important, especially in continuous structures in which torsion plays an important role. The concept of a torsion plastic hinge in zones where the reinforcement bars yield can be an important design tool. In hollow beams under pure torsion the ductile behavior is more difficult to achieve than in plain beams. Since the beams are hollow, when the outer fibers of the section reach their maximum strength, there is no concrete in the interior of the cross section to take stresses when the flow of stresses can no longer run in the maximum size ring that can be accommodated in the cross section. As the outer fibers fail, the side or diameter of the ring gets smaller, and the performance of the beam starts to be very dependent on the existence of a concrete nucleon. Therefore, the specific study of the plastic rotation capacity under torsion is of great importance.

3. Importance of the torsional ductility

It is widely accepted that flexural ductility is very important if moment redistributions are expected to take place in hyperstatic structures. Would the ductility be also important and is the torsion redistribution relevant? This is the key question the authors will try to answer in this Section.

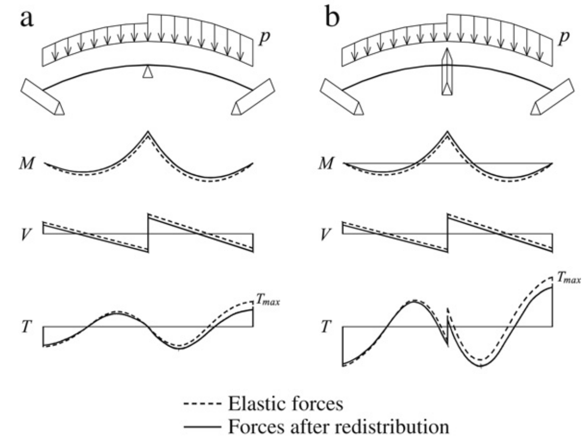

Fig. 1. Redistribution of forces in continuous curved beams.

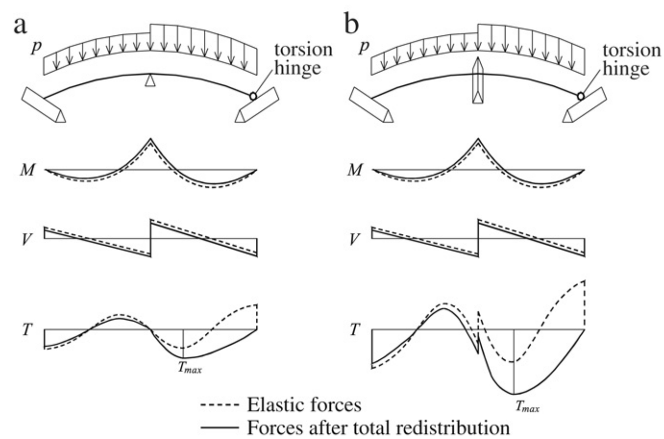

Fig. 2. Total redistribution of torsional moments.

A continuous curved beam (frequent situation in bridges) is a good example for showing the importance of ductility. In this type of beam, torsion forces are very important, and when a redistribution of internal forces takes place it would involve torsion forces. Fig. 1 shows the diagrams for the elastic forces (dotted lines) and for the forces after redistribution (solid lines) of two curved beams with non-symmetric loading (for instance, due to a live load). In the beam of Fig. 1b all the three supports have full restriction to twist, whereas the beam of Fig. 1a has the two end supports with no twist possibility; the inner support free to twist. If the torque at the right end support reaches the maximum value, then, the reinforcement bars of this section yield. The beam will suffer great twist deformation at the section and some redistribution might take place, leading to the diagrams represented by the solid lines (Fig. 1). The change of the torque diagram implies a change in the bending moments and shear diagrams. However, the changes on these two types of diagrams are smaller than those of torque.

If the end sections do not have sufficient torsion ductility, then the variation of twist is not gradual and, at the limit, the torque at the section might drop sharply to nil. In this case the diagrams are those shown in Fig. 2. Hinge is confined to a small length, as showed by tests (the authors will address this point later in this article). From Fig. 2(a) and (b), the maximum torque at mid span suffers a great increase, and the new maximum value could create new plastic hinges at these points. This could lead to a mechanism (Fig. 3), which leads to a partial failure of the structure, due to torsion.