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Plastic analysis and twist capacity of high-strength concrete hollow beams under pure torsion

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ABSTRACT

In this article, a study on the plastic behavior and twist capacity of High-Strength Concrete (HSC) hollow beams under pure torsion is presented. The results of 16 tested beams are used to perform the plastic analysis. The plastic twist capacity of the beams was studied by using a Plastic Trend Parameter (PTP). This parameter was defined from the plastic local twist "versus" total twist curves of the test beams. It was shown that PTP is a good parameter to reflect the degree of the experimental twist capacity of the tested beams. The analysis with PTP shows that some plastic behavior of HSC hollow beams under torsion exists but is very narrow. Two study variables were also considered: the concrete compressive strength and the torsional reinforcement ratio. It is shown that PTP seems to decrease slightly as concrete strength increases. It is also shown that a high reduction of PTP exists with the increase of torsional reinforcement ratio and that the top limit to ensure some plastic twist capacity is approximately 1.30%. Some important codes (American, Canadian and European) are analyzed in the light of the plastic twist capacity observed for the tested beams. It is shown that the actual American code is the most appropriate by imposing a maximum and minimum value for the reinforcement ratio.

1. Introduction

The theory of plasticity is a common tool used for the design of concrete structures. The validity of such theory is dependent from a ductile and plastic behavior in the critical sections. Some ductility prevents premature and brittle failures and allows the internal forces to be redistributed. Nowadays, it is accepted that, if properly designed and detailed, Reinforced Concrete (RC) members can exhibit high plastic deformations after yielding of the reinforcement. This allow the theory of plasticity to be used.

For instance, ductility behavior is widely accepted for members under bending, such as beams [1–3]. In such elements, the ultimate bending moment, as obtained from theory of plasticity is accepted to be a good value of the actual flexural strength.

For members under shear, the theory of plasticity still raises some doubts. It is accepted that plain concrete is brittle under shear. However, such behavior cannot be extended to RC members if they have an adequate amount of transversal and longitudinal reinforcement and if this reinforcement is properly detailed in order to minimize the risk of brittle failure. Experimental tests on RC panels under shear [4–7] shows that, for high loading levels, the element gradually develops the so-called softening effect (influence of diagonal cracking on the compressive concrete behavior in the struts), that leads to a relatively high internal energy dissipation through a certain level of deformation. In these cases, the theory of plasticity can also be used.

In beams under torsion the considerations presented above for RC panels under shear are also valid, because the shear stresses are the limiting factor. The risk of failures of continuous beams with high torsion forces can lead to unwanted failure mechanisms [8], and reports of failure of curved bridge decks with high torsional forces can be found in the literature [9], so it is important to ensure sufficient ductility in the critical sections. The use of High-Strength Concrete (HSC) makes this issue even more important because this concrete is more brittle than Normal-Strength Concrete (NSC).

In actual structures, torsion forces are usually combined with other internal forces (bending moments, shear and axial forces). But in some structures, such as bridges, torsion can be a very important action in the design. In structures with combined forces the design procedures are normally based on force interactions and require that the behavior under pure torsion need to be known and quantified. Since HSC and hollow beams are frequently being used in bridges, a study on the plastic behavior of HSC hollow beams under torsion is a very important issue.

2. Research significance and previous study

To guarantee a minimum degree of ductility for beams under torsion it is necessary to impose a maximum and a minimum value

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for both transversal and longitudinal torsional reinforcement ratio. Among the codes of practice analyzed in this study only the ACI codes [10,11] include explicit clauses to ensure a minimum torsional reinforcement. However, the equation for the minimum torsional reinforcement remains empirical when compared with previous versions and sometimes lead to questionable solutions [12]. The lack of specific rules for torsion in other codes (for instance, European [13,14] and Canadian [15] codes) is solved by requiring that the minimum amount of transversal and longitudinal reinforcement for torsion should be considered to be the corresponding ones for shear and for bending moments.

As far as the maximum torsional reinforcement is concerned, the current codes of practice do not generally have explicit clauses to compute this parameter. However, the codes generally indicate a maximum value for the compressive stress in the concrete struts, to prevent the concrete from crushing before the torsion reinforcement yields (before 1995, the ACI code proposed an explicit rule for the maximum transversal reinforcement). This limit can be used to compute the maximum amount of the transversal reinforcement.

For HSC beams under torsion it is known that some aspects of the structural behavior of HSC members are not fully known yet. The current rules of codes, mainly calibrated for NSC members, need firm confirmation and there have not been enough studies on torsion ductility to permit unquestionable conclusions. As referred in a previous publication by the authors [8], so far, only a very limited number of experimental studies on HSC beams under pure torsion have been carried out [16–20]. As far as ductility and plastic behavior under torsion is concerned, HSC beams are more problematic than NSC beams, and hollow beams are more problematic than plain beams [20–22] because such elements have a lower capacity to redistribute stresses in the cross section (no concrete core exists). This shows that a specific study of the plastic behavior of HSC hollow beams under torsion is very important.

In a previous study by the authors [20], HSC hollow beams under torsion were studied with respect to their ductility. The study shown that the torsional ductility is low and that the range of reinforcement ratio where ductility still occurs is very narrow. Different codes of practice were compared in the light of the experimental results. As a consequence, the authors found that ACI code is the most appropriate to ensure some ductile behavior by limiting the amount of torsional reinforcement.

In another previous study by the authors [8], the same HSC hollow beams were used to study the formation of plastic hinges along the length. The study shows that a torsion plastic hinge can be formed in beams with ductile behavior. Furthermore, this torsion plastic hinge is concentrated in a small length of the longitudinal axis of the beams. This shows that plastic models are possible to be used for beams with ductile behavior under torsion.

The authors did not find in literature any study focused on twist capacity of HSC hollow beams under torsion. As previously referred, some torsional ductility was observed by the authors in HSC hollow beams (by using a torsional ductility index) and some important codes were analyzed in the light of the torsional ductility [20]. Since ductility is a very important property, these results should be confirmed by other analyzes. This should be possible because the authors also observed that torsional plastic hinges can be formed in HSC hollow beams with ductile failure [8]. Therefore, such beams show some twist capacity and should allow a plastic analysis to be applied.

3. Test program and experimental twists

The experimental program was already presented by the authors on a previous article [8]. In this section, only a brief summary on the test beams, on the test setup and on some experimental results is presented.

A set of 16 rectangular HSC hollow 5.90 m long beams were tested up to failure. The beams had a constant square cross-section and were symmetrically reinforced. The variable parameters were the concrete's compressive strength, from 46.2 to 96.7 MPa, and the total torsional reinforcement ratio, from 0.30% to 2.68%.

Three sets of beams were considered (Groups A–C) as a function of the range of the concrete compressive strengths.

Hot-rolled steel ribbed bars (S500) were used as reinforcement with $f_y = 686$ MPa and $\varepsilon_y = 3430 \times 10^{-6}$ (average values of yield stresses and strains, respectively).

Fig. 1 shows the dimensions of the beams, two examples of reinforcement detailing and a scheme of the testing equipment.

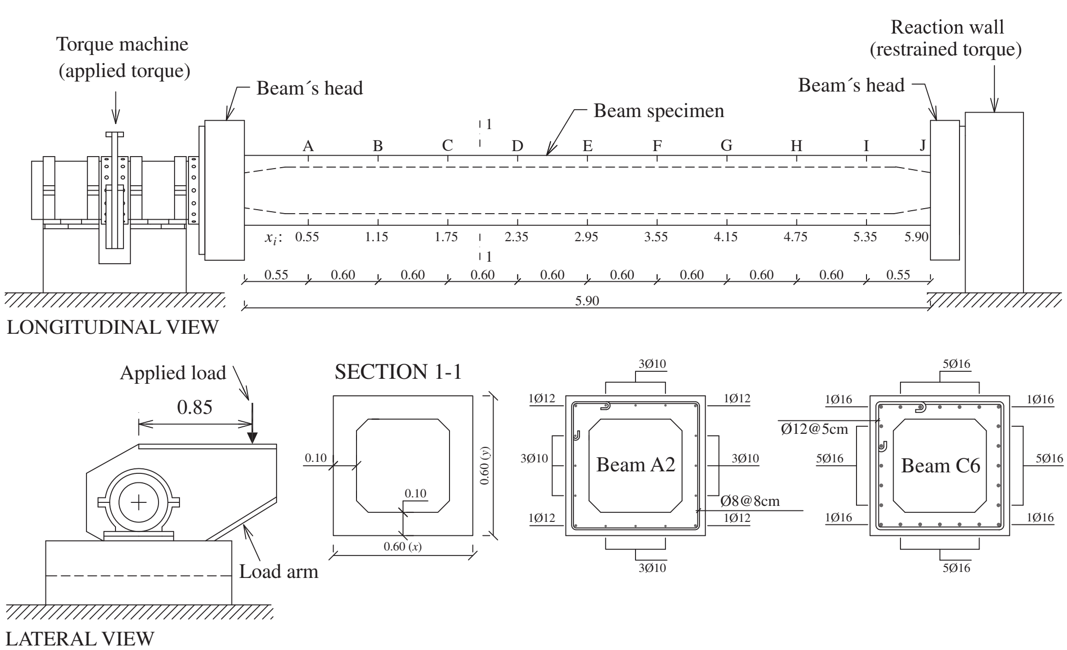

Fig. 1. Scheme of test setup and test beams [8].