Engineering Structures 82 (2015) 82–92

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Experimental investigation on the shear capacity of prestressed concrete beams using digital image correlation

K. De Wilder [a,*], P. Lava [b], D. Debruyne [b], Y. Wang [b], G. De Roeck [a], L. Vandewalle [a]

[a] KU Leuven, Department of Civil Engineering, Kasteelpark Arenberg 40, 3001 Leuven, Belgium
[b] KU Leuven, Department of Metallurgy and Materials Engineering, Kasteelpark Arenberg 44, 3001 Leuven, Belgium

ARTICLE INFO

Article history:
Received 28 October 2013
Revised 16 October 2014
Accepted 17 October 2014

Keywords:
Mechanical behavior
Prestressed concrete
Shear
Digital image correlation

ABSTRACT

Despite more than a century of continuous effort, shear still remains one of the few areas of research into fundamentals of the behavior of concrete structures where dispute remains amongst researchers about the mechanisms that enable the force flow through a concrete member and across cracks. Due to our incomplete understanding and the brittle failure modes associated with shear, current codes of practice tend to propose highly conservative shear design provisions. This paper investigates the shear capacity and mechanical behavior of prestressed concrete beams. The results of 9 full-scale I-shaped prestressed concrete beams subjected to a four-point bending test until failure are presented. Two stereo-vision digital image correlation (DIC) systems were used to discretely measure three-dimensional displacements and in-plane deformations in both zones where a shear force exists. A numerical technique has been adopted to generate optimized patterns for DIC and the resulting speckle pattern was applied onto each specimen using a stencil printing technique. Using the sectional shear design procedure found in Eurocode 2, a severe underestimation of the experimentally observed shear capacity was found. Direct strut action was the main bearing mechanism of the reported prestressed concrete members with shear reinforcement whereas the presented specimens without shear reinforcement failed when the principal tensile stress reached the tensile strength limit.

1. Introduction

Despite more than a century of continuous research effort [1], shear is one of a few areas into fundamentals of the behavior of concrete structures where dispute remains amongst researchers about the mechanisms that enable the force flow through a concrete member and across cracks. The main reason for this contention can be attributed to the complexity of the shear phenomenon in structural concrete members. Firstly, various interrelated shear transfer mechanisms contribute to the overall shear capacity of a structural concrete member. The 1973 ASCE-ACI Committee 426 report [8] identified four different mechanisms of shear transfer apart from the shear reinforcement contribution: (a) shear stresses in uncracked concrete, i.e. compressive zone; (b) interface shear transfer (also referred to as aggregate interlock or crack friction); (c) dowel action of the longitudinal reinforcement; and (d) arch action. Since that report was issued, a new mechanism was identified, namely (e) residual tensile stresses transmitted directly across cracks. Secondly, many parameters influence each shear transfer mechanism separately. Due to the complexity of the shear phenomenon, a generally accepted theoretical basis to model shear in structural concrete members is still absent within the research community.

Therefore, a multitude of analytical models dealing with shear in structural concrete members can be found in literature. Based on the crack pattern typically observed during beam tests, Ritter [17] idealized the flow of forces in a cracked structural concrete member by means of a parallel chord truss consisting of compressive diagonals inclined at 45° and vertical tension ties, as illustrated in Fig. 1. This approach has ever since been referred to as the truss model approach and was later extended to the case of torsion in concrete members by Mörsch [11]. The necessary amount of shear reinforcement per unit length follows from the calculation of the axial force in the vertical tension ties.

The truss analogy is on one hand easy to understand and highly didactic but on the other hand a very simple representation of the actual structural behavior. It is thus clear that more refined models are needed in order to optimize and economize the overall structural design of reinforced and prestressed concrete beams. An excellent overview of different theoretical approaches to shear in concrete members is given in the review paper by the Joint

* Corresponding author. Tel.: +32 16321987.
E-mail address: Kristof.DeWilder@bwk.kuleuven.be (K. De Wilder).

http://dx.doi.org/10.1016/j.engstruct.2014.10.034
0141-0296/

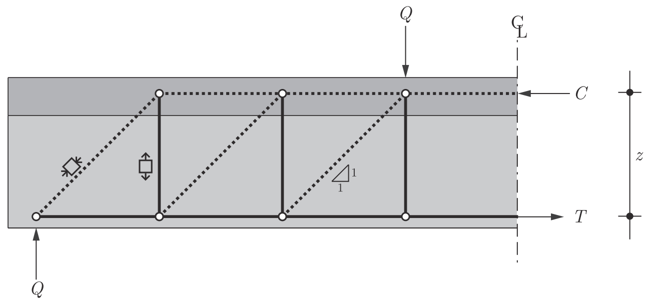

Fig. 1. Truss analogy as proposed by Ritter [17].

ACI-ASCE Committee 445 [16]. However, up to date, none of the existing theoretical approaches for shear in structural concrete elements has been able to fully explain the mechanics behind the problem of shear failure.

The on-going debate in the literature on how to deal with shear in concrete members is also reflected by the code provisions. Current codes of practice all recommend very different approaches that result in different design shear capacities and take parameters affecting the shear capacity into account in a different way. Due to our incomplete understanding and the brittle modes of failure associated with shear, current international codes of practice tend to propose highly conservative shear design provisions. The model found in Eurocode 2 [3,13] is derived from the aforementioned truss analogy and is often referred to as the variable angle truss model (VATM). This model relates the entire shear capacity of a structural concrete member with shear reinforcement to the amount of provided shear reinforcement per unit length. Hence, for members with shear reinforcement, the inherent capacity to resist shear is ignored. This is particularly disadvantageous for prestressed concrete elements.

This paper therefore presents the results of an extensive experimental campaign consisting of 9 full-scale shear-critical prestressed concrete beams. In the first section, the experimental program is elaborated. The specimen properties and the experimental setup are reported. Specific attention is paid to the use of the stereo-vision digital image correlation (DIC) technique as an optical-numerical full-field measurement technique for full-scale tests. In the second part of this paper, the experimental results are presented and compared to analytical predictions of the shear capacity obtained using the current shear design provisions found in Eurocode 2. Based on the DIC measurements, an investigation is performed of the shear carrying mechanisms of the reported test beams.

2. Experimental research

2.1. Specimen design

This paper presents the results of 9 factory-made prestressed concrete I-shaped beams. The beams were labeled with the descriptive letter *B* followed by a number ranging from 101 to 109. Each specimen was 7000 mm long and 630 mm high with a flange width equal to 240 mm. The web of each specimen was 70 mm wide. Specimens B101–B106 were provided with eight 7-wire strands at the bottom whereas specimens B107–B109 were prestressed at the bottom using four 7-wire strands. The nominal strand diameter was equal to 12.5 mm. To counteract the induced bending moment due to the eccentric prestressing force and thus avoid cracking at the top of the beam, each specimen was also prestressed with two 7-wire strands at the top with a nominal strand diameter of 9.3 mm. Shear reinforcement was placed in each specimen except for beams B103, B106 and B109. Shear reinforcement consisted of single legged stirrups with a nominal diameter of 6 mm and a center-to-center distance equal to 150 mm, leading to a shear reinforcement ratio ρ_w equal to 0.0027 which is approximately 2.5 times the required minimum shear reinforcement ratio according to EC 2 [3]. The chosen shear reinforcement ratio allowed for a safe margin to avoid failure immediately after the onset of diagonal cracking and failure due to bending. Splitting reinforcement was provided at both ends of each specimen with a nominal diameter of 8 mm and a center-to-center distance equal to 50 mm. The geometry and reinforcement layout of all specimens are shown in Fig. 2(a–f).

2.2. Materials

The concrete mixture was designed to have a characteristic cylindrical compressive strength equal to 50 MPa. Cement was specified as CEM I 52.5R, whereas the coarse aggregate consisted of 12 mm maximum size limestone gravel. Limestone filler and a high-range water reducer were also used. The concrete mixture composition is listed in Table 1.

Tensile tests were performed on both shear and splitting reinforcement bars to determine the modulus of elasticity E_s, the yield and ultimate stress, f_{ym} respectively f_{tm}, and the strain at failure ϵ_{su}. The same characteristics of the prestressing strands were taken from the manufacturer. The results are summarized in Table 2.

2.3. Specimen construction

Concrete mixtures were made in volumes of 2 m^3 enabling the construction of three specimens with one mixture. Together with each beam, cubes (sides: 150 mm), cylinders (height/diameter: 300 mm/150 mm) and prisms ($150 \times 150 \times 600$ mm^3) were cast to determine the mean compressive strength on cubes and cylinders, $f_{cm,cube}$ respectively f_{cm}, the mean secant modulus of elasticity E_{cm} and the mean flexural tensile strength $f_{ctm,fl}$ at the day of testing. A summary of the results per specimen group is given in Table 3. The mean mixture density ρ_m and the age of each specimen at the day of testing is also indicated in the aforementioned Table 3. From the results presented in Table 3, it can firstly be seen that a relatively large scatter was found on both the experimentally measured cube and cylinder compressive strengths. Moreover, it can be seen that the cylinder compressive strength is lower than the cube compressive strength for specimen set B101–B103 whereas the opposite is true for the remaining sets B104–B106 and B107–B109. In general, the cube compressive strength is higher than the cylinder compressive strength due to the confinement originating from friction stresses between the specimen and the testing device. For standard size concrete specimens, this effect tends to be larger for cubes than for cylinders, hence resulting in higher cube compressive strengths. However, for high strength concrete, which is the case in the reported study, the effect of confinement becomes less effective [12].

The day after casting, demountable mechanical strain gauges (DEMEC) were glued onto the concrete side surface to determine the immediate and time-dependent stress losses in the prestressing reinforcement. The location of the aforementioned DEMEC-points was already presented in Fig. 2(a–b). Each strand of specimens B101–B103 and B107–B109 was given an initial prestrain equal to 0.0075 mm/mm ($\sigma_{pm,0} = 1488$ MPa) whereas each strand of specimens B104–B106 was given an initial prestrain equal to 0.0038 mm/mm ($\sigma_{pm,0} = 750$ MPa). While it is uncommon in the industry to reduce stress levels below the allowable, the stresses were varied to isolate the effect of varying the prestressing force while keeping the longitudinal reinforcement ratio ρ_l constant. At the day of testing, it was found that the stress losses in