Construction and Building Materials 148 (2017) 49–61

Contents lists available at ScienceDirect

Construction and Building Materials

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

Experimental investigation of cracking and deformations of concrete ties reinforced with multiple bars

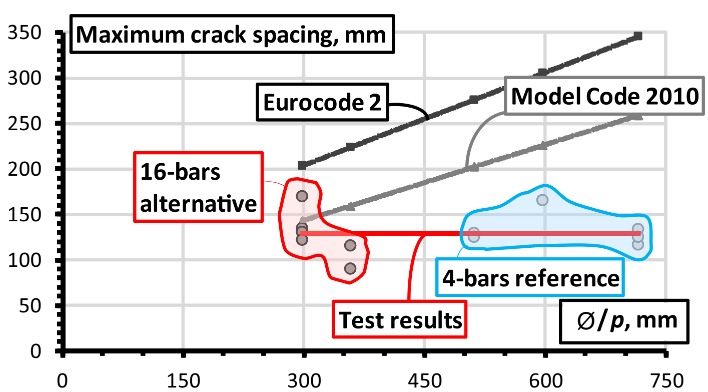
Arvydas Rimkus, Viktor Gribniak *

Research Laboratory of Innovative Building Structures, Vilnius Gediminas Technical University, Vilnius, Lithuania

HIGHLIGHTS

- Cracking and deformations of concrete ties with multiple bars are investigated.
- A specific equipment for producing and testing such ties was developed.
- Two reinforcement schemes are considered: 4-bars reference and 16-bars alternative.
- The alternative schemes secure indistinguishable deformation behaviour of identical ties.
- The experimental crack spacing is practically independent on the $\varnothing/p$ ratio.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 9 January 2017
Received in revised form 21 April 2017
Accepted 5 May 2017
Available online 11 May 2017

Keywords:
Reinforced concrete
Multiple bars
Tensile test
Deformations
Cracking

ABSTRACT

Interpretation of test results may be inadequate even for simple test layouts. On the one hand, conventional tests, that investigate a concrete prism reinforced with a single bar in the centre, do not allow to account for the effect of variation of the diameter-to-reinforcement ratio ($\varnothing/p$). This important limitation should be related to the use of simple specimens in constitutive modelling. On the other hand, a tie-test typically provides measurements of average deformations of the internal reinforcing bar and the concrete surface. The experimental evidence, however, often contradicts the general assumption of the equivalence of the mean strains of reinforcement and concrete. The strain difference is closely related to the width of the concrete cover. This paper investigates the effect of distribution of bar reinforcement on deformation and cracking behaviour of tensile elements. Special testing equipment has been developed to investigate ties reinforced with multiple bars. The test program consists of 23 ties. The number and diameter of the bars vary from 4 to 16 and from 5 mm to 14 mm, respectively. Two different covers (30 mm and 50 mm) are considered as well. The deformation analysis is based on measurements of the average reinforcement and concrete surface strains. The development of cracks was investigated using digital image correlation (DIC). The Model Code 2010 and Eurocode 2 predictions are compared with the experimental data. While the Design Codes predict that the maximum crack spacing is dependent on the $\varnothing/p$ ratio, the test results indicate that the crack distances are actually much less dependent on the reinforcement characteristics.

* Corresponding author at: Head of Research Laboratory of Innovative Building Structures, Vilnius Gediminas Technical University, Sauletiekio av. 11, Vilnius LT-10223, Lithuania.

E-mail address: Viktor.Gribniak@vgtu.lt (V. Gribniak).

http://dx.doi.org/10.1016/j.conbuildmat.2017.05.029
0950-0618/

1. Introduction

Excessive cracking due to the tensile stresses in the concrete can be identified as a key source of deterioration of reinforced concrete structures. Rostásy et al. [1], Hwang and Rizkalla [2], Williams [3], and Purainer [4] have demonstrated experimentally that distributing the same reinforcement area in a higher number of bars (of a smaller diameter) may noticeably increase the stiffness of concrete ties. Such an increase might be a consequence of two effects. On the one hand, an increase in the total bond area also increases the bond capacity to release the extra fracture energy during the crack formation stage. On the other hand, the confinement of the intact concrete between the closely spaced bars constrains the internal cracks. The test data reported by Broms and Lutz [5] supports the latter inference. Otsuka and Ozaka [6] found that the bond stiffness will increase if the distance between the reinforcement bars is reduced. Experimental results obtained by the authors [7–9] and other researchers, e.g., [5,10,11], indicated that the cracking pattern is dependent on the geometry of the specimen and the arrangement of the reinforcement. Using the test results of ties with different reinforcement and testing layouts, Rimkus et al. [12] revealed that differences in the crack spacing are dependent on the concrete cover. The total area of the bonded surface of the reinforcement with different number of bars was identified as another source of the different crack distributions.

Although a standard test setup for reinforced concrete elements under tension does not exist, the direct tensile test of a concrete prism reinforced with a single bar is the most widely used experimental layout for investigation of cracking problems [13]. Despite the apparent simplicity of the setup, the interpretation of the test results might be misleading: the experimental evidence often disagrees with the general assumption of similarity between average strains of the reinforcement and concrete. This discrepancy can be attributed to two well-known, but often neglected issues, namely, the effective area of concrete in tension and the end effect [13–16].

The European normative documents [17,18] imply similar expressions for the maximum crack spacing, $s_{r,\max}$, assuming it to be a linear combination of two components related to the cover, c, and the ratio of the bar diameter to the reinforcement ratio $\varnothing/p$:

$$s_{r,\max} = k_1 \cdot c + k_2 \cdot \frac{\varnothing}{p}, \tag{1}$$

where k_1 and k_2 are coefficients dependent on various factors (concrete strength, bond quality, loading type, etc.). Considering a simple laboratory tie (square prism with a centre bar), the parameters c, $\varnothing$, and p become correlated:

$$c = \tfrac{b-\varnothing}{2} \approx \tfrac{b}{2}; \quad p = \tfrac{A_s}{A_c} = \tfrac{\pi\cdot\varnothing^2/4}{b^2-\pi\cdot\varnothing^2/4} \approx \frac{\pi\cdot\varnothing^2/4}{b^2}, \tag{2}$$

where b is the side length of square section. Thus, Eq. (1) can be rearranged as

$$s_{r,\max} = k_1 \cdot \frac{b-\varnothing}{2} + k_2 \cdot \left(\frac{4b^2}{\pi\cdot\varnothing} - \varnothing\right) \approx k'_1 \cdot b + k'_2 \cdot \frac{b^2}{\varnothing} \tag{3}$$

with coefficients k'_1 and k'_2, which now include constants 1/2 and $4/\pi$. This simplification is acceptable if the ratio $\varnothing/b$ is small enough. The common tests, dealing with 100 × 100 mm cross-section of the prism (i.e. b = 100 mm), allow to account only for the effect of the bar diameter. This important limitation should be related to the use of simple specimens in constitutive modelling. The current design approaches, however, were empirically deducted by neglecting that limitation. A number of previous studies, e.g., [19–23], recognised this problem. Moreover, a tie-test typically does not provide measurements of both, the average deformations of the internal reinforcement bar and the concrete surface. The experimental evidence, however, often contradicts the general assumption of the equivalence of mean strains of the reinforcement and concrete [24].

With an intention to evaluate the effect of reinforcement parameters on cracking and deformations of tensile elements, this paper investigates the behaviour of concrete prisms reinforced with multiple bars. Special equipment has been developed for these tests [25]. The test program consists of 23 ties. The number and diameter of the bars vary from 4 to 16 and from 5 mm to 14 mm, respectively. Two concrete covers are considered as well: the reference 30 mm cover is typical for most structural applications [26], while the alternative 50 mm cover is characteristic of laboratory specimens. The deformation analysis is based on the results obtained by monitoring the average elongations of the reinforcement and the concrete surface. Development of the cracks is investigated using a digital image correlation (DIC) technique. The Model Code 2010 (MC 2010) and Eurocode 2 (EC 2) predictions are compared with the experimental crack distances.

2. Test program

The experimental campaign consists of 23 ties with different arrangement of the reinforcement. Three types of sections (with different reinforcement ratio p) are shown in Fig. 1. As can be observed, each of the groups consists of two or three different reinforcement schemes: 4-bars reference and 16-bars (or 12-bars) alternative. During the previous tests [24,27] it has been shown that the effect of different distribution of bars is most evident in ties with a relatively low reinforcement ratio ($p \approx 1.5\%$). Therefore, two different covers (i.e. 30 mm and 50 mm) are considered in the reference ties with the lowest amount of reinforcement (Fig. 1). Six different bar diameters (Fig. 2) are used.

Gribniak and Rimkus [25] have developed specific equipment for anchorage of multiple bars as shown in Fig. 3. A general aim of the setup is to secure uniform distribution of the applied tension to the bars. The capability to monitor the deformation for each of the bars was another goal of the design. As can be seen in Fig. 3, the anchorage joints embrace two plates connected by a central bar that is connected to the tension device using a spherical hinge. The latter allows reducing a possible imperfection in applying the tensile load. The plates are perforated to fix and distribute the reinforcement bars within the concrete prism. Steel clamps are used for ensuring the confinement of the anchorage joints.

Length of the test specimen (Fig. 3) was limited by capacity of tensile machine. Thus, the length-to-width ratio of the ties was quite low. However, the authors' experience [24,28] indicates that the section area should be related with number of the reinforcement bars. Thus, the 150 × 150 mm section reinforced with four bars should be split into four segments (each of them associated with a single bar) that doubles of the actual length-to-width ratio. The trial tests [24,27] have also indicated that the cover is very important parameter for ensuring a uniform strain distribution in the concrete: depending on the bar diameter, width of the cross-section reinforced with a single bar should be equal to 60–80 mm. Otherwise, a deformation gradient in concrete, increasing with the cover, makes assumption of the similarity of mean strains of the reinforcement and concrete invalid. The trials also revealed that a relatively short (400–500 mm) concrete prisms with the limited cover might be representative for analysis of the cracking and tension-stiffening effects. The presented test equipment and specimens were designed by accounting the aforementioned conditions.