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Experimental investigation on the shear capacity of RC beams with curtailed reinforcement

Henrik B. Joergensen*, Søren G. Hansen

Department of Technology and Innovation, University of Southern Denmark, Campusvej 55, 5230 Odense, Denmark

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ABSTRACT

In continuous beams with both positive and negative moments, curtailed reinforcement is often used to increase the bending capacity locally. In practice, it is normally considered as a safe assumption to neglect the curtailed reinforcement when calculating the shear capacity. However, some tests from the literature have indicated that the end of curtailed reinforcement may decrease the shear capacity. Not all shear models take this effect into account. These models tend to overestimate the shear capacity significantly.

This paper presents a large experimental study on the effect from curtailed reinforcement on the shear capacity of continuous beams without shear reinforcement.

The study shows that the curtailed reinforcement does not significantly influence the shear capacity. Beams with curtailed reinforcement have the same or only slightly reduced shear capacity compared to similar beams without curtailed reinforcement.

Different shear models ability to predict the test result are investigated. (1) Eurocode 2, that does not take the effect of curtailed reinforcement into account, overestimates the shear capacity of the tested beams by approximately 20%. (2) *fib* Model Code 2010, which account for the effect of the curtailed reinforcement, predicts the shear capacity of the tested beams with curtailed reinforcement quite accurately. However, since the shear capacity of the tested beams was not significantly affected by the presence of curtailed reinforcement, the model overestimates the shear capacity of similar beams without curtailed reinforcement by approximately 20%.

Based on the results presented in this paper, it is the authors' opinion that the reduced shear capacity should mainly be attributed to the continuous beam test setup rather than the curtailed reinforcement.

1. Introduction

Curtailed reinforcement is often placed in regions with hogging moments to increase the negative bending capacity locally. In practice, it is normally considered as a safe assumption to neglect the curtailed reinforcement when calculating the shear capacity. However, some tests from the literature have indicated that the end of curtailed reinforcement results in a decreased shear capacity.

In 1964, Leonhardt et al. [1] published a test series indicating that the ends of the curtailed reinforcement reduce the shear capacity of concrete beams without shear reinforcement. Although that the shear models that are available today are based on advanced and complex material mechanics, e.g. the Critical Shear Crack Theory (CSCT) [2], the Modified Compression Field Theory (MCFT) [3,4] and the Crack Sliding Model [5], the effect of curtailed reinforcement cannot be derived directly from the shear models. Therefore, when formulating the Swiss Code for Concrete Structures, SIA 262 [6] employing the CSCT, and the *fib* Model Code 2010 [7] employing the Simplified MCFT, the effect of the curtailed reinforcement was included empirically [2]. Both theories are strain-based and the longitudinal strain is increased in a zone near the curtailed ends by an empirical factor, which results in a decreased shear capacity. The American Building Code, ACI 318-14 [8], considers the effect as well. Here, the shear capacity is reduced with a factor 1.5 in a zone near the curtailed ends.

In 1999, Collins and Kuchma [9] published a test series that includes shear tests of beams with curtailed reinforcement and without shear reinforcement. Especially one test has attracted a lot of attention; the test was later known as the *Beam 8* test. *Beam 8* (specimen SE50A-45 in [9]) showed a significantly smaller shear capacity than predicted by some of the well-known shear models that do not take an effect of the curtailed ends into account, e.g. Eurocode 2 [10]. The aforementioned shear models that reduce the shear capacity in zones near the curtailed ends predict the shear capacity of *beam 8* much more accurate.

Contra-intuitively, the tested shear capacity of *Beam 8* indicates that adding curtailed reinforcement to a beam may reduce the shear capacity. If the end of the curtailed reinforcement reduces the shear

* Corresponding author.
E-mail addresses: hebj@iti.sdu.dk (H.B. Joergensen), sgh@iti.sdu.dk (S.G. Hansen).

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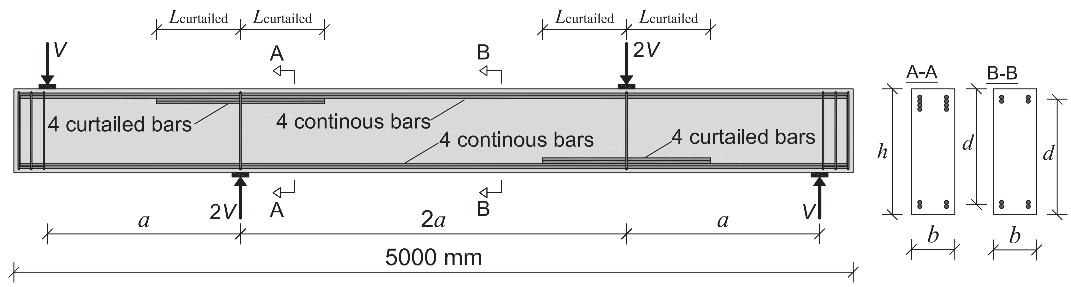

Fig. 1. Plane and sectional drawing of a typical specimen.

capacity, the normal practice of lapping reinforcement without consideration of the placement of the reinforcement ends could result in an unintended low shear capacity. Based on these potentially large impacts on the reliability of structural safety and the relative low amount of experimental evidence, the authors of the present paper recently published a test series studying the shear capacity of beams with curtailed reinforcement and without shear reinforcement, Joergensen and Hansen [11]. To test the influence of the curtailed reinforcement under well-known conditions, the beams were tested in a three-point-bending test setup, whereas the *Beam 8* test was conducted as a continuous beam test. The cross-sectional diameter and the length of the curtailed reinforcement were varied. The tests showed that the curtailed reinforcement did not significantly influence the shear capacity. Additionally, a comparison with shear models showed that Eurocode 2 [10] predicted the shear capacity quite accurately, for tests with and without curtailed reinforcement. Contrary, the shear models that include the effect of the curtailed reinforcement underestimated the shear capacity of beams with curtailed reinforcement.

The low shear capacity, found for *Beam 8*, may therefore be attributed to the continuous beam test setup. Although such tests on continuous systems are representative for actual structures, the number of tests found in the literature are very limited. Therefore, this paper presents an experimental programme to investigate the effect of curtailed reinforcement on the shear capacity of continuous concrete beams without shear reinforcement. To ensure that the effects found in the *Beam 8* test appear in the new tests, the experimental programme comprises 28 beams designed such that the *Beam 8* test is reproduced and appears as a standard test. To study the effects of the curtailed reinforcement, the beams are grouped in series where important design parameters are varied. The varied design parameters include; the bar diameter of the continuous and the curtailed reinforcement, the length of the curtailed reinforcement, the height of the beam and the concrete compressive strength. Finally, six beams without curtailed reinforcement are included for a direct comparison.

With respect to the role of cracking on the shear strength, the commentary text to ACI 318-14 [8] describes the effect of the curtailed reinforcement by: *"Flexure cracks tend to open early wherever any reinforcement is terminated in a tension zone. If the steel stress in the continuing reinforcement and the shear strength are each near their limiting values, diagonal tension cracking tends to develop prematurely from these flexure cracks"*. Additionally, it is well-known from the literature that the shear capacity is decreased by increasing crack width (see e.g. [2,3,12–14],). The actual effect of curtailed reinforcement on the crack formation and development has not been investigated previously. In this paper, the cracks are investigated by the means of Digital Image Correlation. The failure mechanisms and crack development are found to be similar for specimens with and without curtailed reinforcement.

All beams in the experimental programme of this paper failed in a shear failure. In all beams, sufficient flexural reinforcement was provided to ensure that the reinforcement did not reach its yield capacity. The present tests show that the original *Beam 8* and the new reproduction of the *Beam 8* have an almost identical shear capacity. However, the new tests also show that a similar beam without curtailed reinforcement have approximately the same shear capacity. This tendency was observed for comparable beams with three different heights.

Model Code 2010 [7] predicts the shear capacity for the new continuous beams satisfactory well when the effect of the curtailed reinforcement is taken into account. However, the shear capacity of the beams without curtailed reinforcement is overestimated since the tests show that the curtailed reinforcement does not significantly influence the tested shear capacity. The shear capacity, with and without curtailed reinforcement, is shown to be considerable lower than predicted by the Eurocode 2 [10]. It is the authors' opinion that the reduced shear capacity should mainly be attributed to the continuous beam test setup or other design parameters rather than the curtailed reinforcement.

2. Experimental programme

The experimental investigation comprised 28 continuous beams tested in a continuous four-point-bending test setup. The overall objective was to study the shear capacity in regions with curtailed ends. This section presents the design of the beams and the test setup.

2.1. Specimen geometry and material data

Fig. 1 shows a typical specimen whereas Table 1 shows the experimental programme and the geometrical and material data for all specimens. The experimental programme consists of seven series (E1–E7). In each series one design parameter is varied. Each series consists of 1–3 pair of identical specimens, e.g. Specimen E3a.1 and E3a.2 are identical and belong to series E3.

Specimens E1.1, E1.2, E7a.1 and E7a.2 are designed as reproductions of *Beam 8* (specimen SE50A-45 in Ref. [9]). The only difference is a small variation of the width, the concrete compressive strength and the reinforcement yield stress. With basis in the reproduction, important design parameters are varied in series E2 to E7. The varied parameters include; the height of the beam varying from 300 to 500 mm, the cross-sectional diameter of both continuous and curtailed reinforcement, the length of the curtailed reinforcement and the concrete compressive strength. Finally, identical specimens with and without curtailed reinforcement are tested for all height variations.

All specimens are cast with the same concrete recipe, except series E7. Specimen E7a.1 and E7a.2 were cast from a recipe that intentionally should give a higher concrete compressive strength whereas E7b.1 and E7b.2 were cast with a recipe giving a lower strength. All concrete recipes include a maximum aggregate size of 8 mm. The maximum aggregate size is almost the same as used in *Beam 8*, where maximum aggregate of 10 mm was used. Furthermore, 8 mm aggregate size is the normally used aggregate size of many precast concrete manufacturers in Denmark. From low to high concrete compressive strength, the water/cement ratio was 0.61, 0.46 and 0.39.

On the day of casting, concrete cylinders were cast for each concrete batch and stored together with the beams under a plastic sealing. After three days of curing, the beams and cylinders were demoulded. Both beams and cylinders were wrapped in plastic and stored together in the laboratory. On the day of beam testing, the uniaxial compressive