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Effect of confined concrete on compressive strength of RC beams

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Abstract. The results of experimental testing of the effect of confined concrete on compressive strength and ductility of concrete beam subjected to pure bending are presented. The effect of different stirrups forms and spacing, as well as different concrete strengths, on beam carrying capacity and ductility were analyzed. Ultimate strength capacity and deflection of concrete beam increase with the decrease in stirrups spacing. Stirrup form has a great effect on the ultimate carrying capacity and ductility of concrete beam. Stirrups which confined the region of concrete in the compression more contribute to greater compression strength of concrete than common stirrups at the perimeter of the entire cross-section of the beam.

Keywords: experiment; confined concrete; beam; compressive strength; stirrups effect

1. Introduction

Concrete in the axial compression confined by stirrups has greater ultimate strength and ductility than concrete with free lateral strain. Namely, stirrups decrease lateral strain of concrete element subjected to axial compression load, causing lateral compression in it. It leads to greater axial ultimate strength capacity and ductility of the concrete element. That effect is particularly expressed at columns subjected to axially compression load, where by increasing in lateral reinforcement can significantly increase the ultimate compressive strength of concrete and ultimate carrying capacity of confined concrete columns (Bing *et al.* 2001, Bousalem and Chikh 2007, Campione and Minafò 2010, Chung *et al.* 2002, Karim 2006, Liu *et al.* 2000, Němeček *et al.* 2005, Osorio *et al.* 2013, Park *et al.* 1982, Razvi and Saatcioglu 1999, Samani and Attard 2011, Yong *et al.* 1988). By an increase in the eccentricity of axial longitudinal compression load, the effect of stirrups on uniaxial ultimate compressive strength of concrete element is great reduced (Liu *et al.* 2000). Obviously, the smallest effect is in case of pure bending of concrete element. Experimental studies of stirrups effect on ultimate strength capacity of high-strength concrete beam subjected to pure bending, where beam failure occurs by concrete crushing in compression zone, are still preferred. Jang *et al.* (2009) have tested the beams that confined with standard rectangular closed stirrups. Hadi and Elbasha (2007), Hadi and Jeffry (2010), Hadi and Schmidt (2002), Jeffry and Hadi (2008) have tested the effect of different confinement shapes on the behavior of reinforced high-strength concrete beams. Results of testing proved that placing helixes with different

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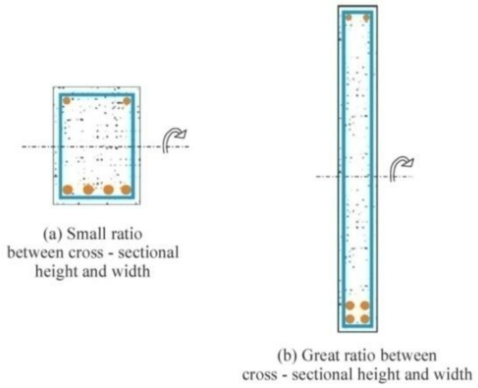

Fig. 1 Some forms of beam cross-section

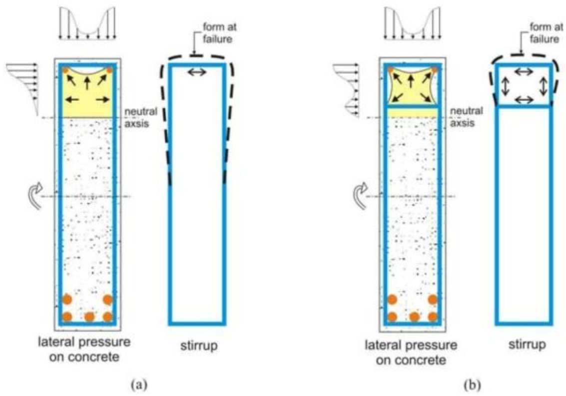

Fig. 2 Effects of stirrup form on lateral pressure of concrete and stirrup deformation at compression concrete failure of beam

diameters as a variable parameter in the compression zone of reinforced concrete beams improve their strength and ductility. The fact is that stirrups contribute to greater strength capacity and ductility of concrete beams subjected to pure bending. Also, the fact is that the stirrups effect will be greater for smaller spacing of stirrups. For the same amount of transverse beam reinforcement, by decrease in stirrups spacing leads to increase of the concrete compressive strength more than an increase in cross-sectional area of stirrups bar.

The form of beam cross-section also affects on the concrete ultimate compressive strength (see Fig. 1). Since stirrups induce lateral pressure on concrete and spatial stress state in the concrete element, different ultimate strength capacity and ductility shall be expected for beams with different height and width ratio of beam cross-section. The greater stirrups effect of is expected for smaller height and width ratio of beam cross-section.

The form of stirrup also affects on the concrete ultimate compressive strength (see Fig. 2). Common stirrups at the perimeter of the entire cross-section, as shown in Fig. 2(a), will provide in relatively small increase in ultimate compressive strength of concrete. Stirrups shown in Fig. 2(b) will provide greater lateral pressure on compressive zone of concrete and thus, greater ultimate compressive strength and ductility of the concrete. Number, spacing and diameter of longitudinal compression rebars, as well as maximum aggregate grain and other parameters, will also affect on the ultimate strength capacity and ductility of concrete beam.

This paper presents the results of the experimental testing of concrete beams subjected to pure bending, in which failure occurs by concrete crushing in compression zone. Effects of stirrups form and spacing, as well as concrete strength, on ultimate strength capacity and ductility of analyzed beams has been researched. For each case, three identical beam samples were made and tested. Presented test results are the averages of measured values. Description of the experiment carried out, obtained results and research conclusions are given hereinafter.

The aim of performed research was a confirmation of the existing knowledge and obtaining new ones on stirrups effect on strength capacity and ductility of concrete beams with compression failure of concrete.

2. Basic data of tested beams

The basic data of the experimentally tested beam are shown in Fig. 3. The beam length was 2.2 m, by span of 2.0 m, with a rectangular cross-section. The beam width was 60 mm, with variable height: at midspan 150 mm and by supports 500 mm. The beam height by the supports was adopted significantly greater than at the midspan, and with strong vertical and horizontal reinforcement at that length, in order to avoid shear failure of the beam by the supports and to achieve its failure at the midspan due to pure bending. Namely, the beam was loaded so that there were no shear forces at its middle length. The bottom zone of the beam was reinforced by strong longitudinal tensile reinforcement; thus, the beams failure was always occurred by concrete crushing in the upper compression zone at the length of beam height of 150 mm. The beam cross-section by the supports is shown in Fig. 4, and the beam cross-section at midspan in Fig. 5.

The effect of different stirrups types at beam midspan on its ultimate strength capacity and ductility was analyzed. Beams without stirrups, as well as beams with two types of stirrups (Fig. 6), were tested. Stirrups S_1 were the common ones, while stirrups S_2 were the same one with additional rebar welded laterally in the upper zone of the beam cross-section. It had been expected that stirrups S_2 would provide greater lateral pressure on concrete than stirrups S_1. It should have provided greater longitudinal compressive strength of concrete and therefore greater ultimate strength capacity of the entire beam.

Analyzed spacing of S_1 and S_2 stirrups, 5 mm in diameter, is shown in Fig. 7. Thus, beams without stirrups were tested, as well as those with stirrups S_1 and S_2 at 150 mm, 100 mm and 50 mm spacing. The rebars stirrups and other beam reinforcement were plain, made of steel with strength of 600 MPa and an elasticity modulus E_s = 200000 MPa (tested according to standards HRN EN ISO 15630-2 and HRN EN ISO 15630-3). Stirrups was positioned by their tying to the bottom zone longitudinal rebars and a soft wire of 2 mm diameter in the upper zone (its contribution to compressive strength of beam upper zone is negligible).

Three different compressive concrete strengths were analyzed: relatively low (f_c = 24.9 MPa), relatively medium (f_c = 35.2 MPa) and relatively high (f_c = 45.1 MPa), where f_c denotes uniaxial compressive strength of concrete, determined by the standard procedure (HRV EN 12390-3) on a cylinder of 150 mm diameter and 300 mm height. The concretes were prepared with classical Portland cement and lime aggregate of 8 mm maximum grain, and with water/cement ratio between 0.42 and 0.55. The concrete mixture proportions are given in Table 1. The parameters of analyzed beams (concrete strength, stirrups form and spacing) are given in Table 2. Therefore, a total of 21 different beam cases were analyzed. Since 3 identical samples were made for each

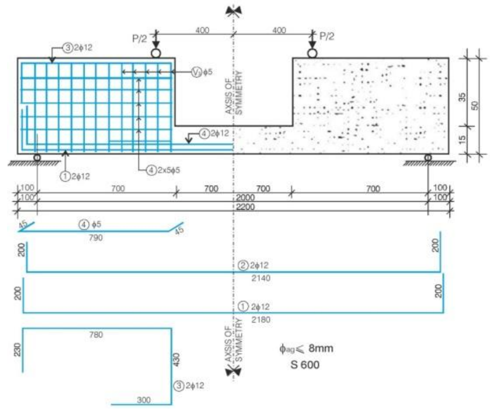

Fig. 3 The basic data of the experimentally tested beam

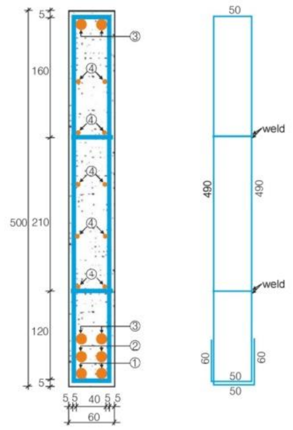

Fig. 4 Beam cross-section by the supports

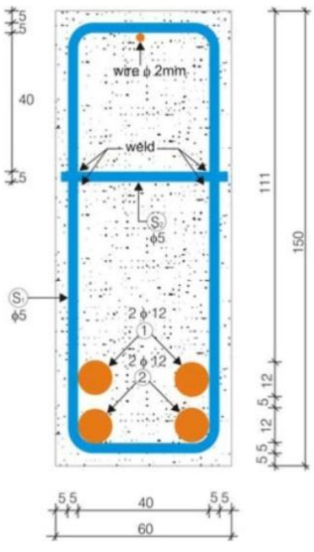

Fig. 5 Beam cross-section at midspan

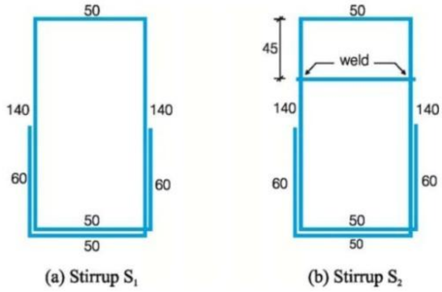

Fig. 6 Tested stirrup types (∅5 mm, *St* 600)

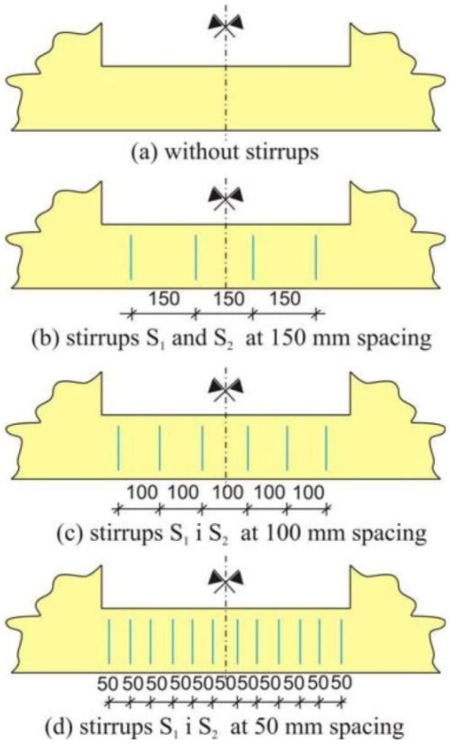

Fig. 7 Analyzed spacing of stirrups

Table 1 Mixture proportions of analyzed concrete

Uniaxial compressive strength of concrete f_c (MPa)	Mixture proportions					
	Coarse aggregate 4-8 mm (kg/m^3)	Fine aggregate 0-4 mm (kg/m^3)	Cement (kg/m^3)	Superplasticizer (kg/m^3)	Water (kg/m^3)	Total (kg/m^3)
24.9	721	1082	350	-	192	2345
35.2	734	1100	400	2	176	2412
45.1	716	1074	440	3.5	185	2418

Table 2 The parameters of analyzed beams

Uniaxial compressive strength of concrete f_c (MPa)	Stirrups spacing *e* (mm)	
	Stirrups S_1	Stirrups S_2
	without stirrups	without stirrups
24.9	150	150
35.2	100	100
45.1	50	50

beam cases, a total of 3 × 21 = 63 beams were tested.

If stirrups reinforcement percentage is analyzed, it can be observed that it had a wide range: from 0% (without stirrups) to 8.7% (stirrups spacing of 50 mm). It was expected that stirrups form, i.e., type of compression concrete zone enclosing, would have an effect on the compressive strength of concrete and so the ultimate strength capacity of the beam.

Concentrated load *P* was applied up to the beam failure with the increments of 5 kN. Before the beam failure, the force increments were decreased. Beam deflections, as well as concrete compression strains of the upper zone, were measured for each load increments at the beam midspan.

3. Experimental results

Deflections and strains were not measured after maximum strength capacity of the beam was reached. Measured values of the load (*P*) – deflection (Δ) relationship at beam midspan for adopted concrete compressive strengths are shown in Figs. 8-10. It can be observed following:

• Global characteristics of beam behaviour were practically almost non-dependant on compressive strength of concrete.

• Ultimate strength capacity and ductility of the beam depended on stirrups spacing and type. It increased with the decrease in stirrups spacing. Stirrups S_2 were more efficient than stirrups S_1.

• In comparison with the beam without stirrups, increase of ultimate beam strength capacity with stirrups S_2 at e = 50 mm spacing was about 15%, while ultimate beam deflections (ductility) were increased by about 20%.

• Beams with higher concrete compressive strength had higher ultimate strength capacity and smaller ductility than the beams with smaller concrete compressive strength. Relationships between respective strengths capacity and ductility of beams without stirrups and those with stirrups were practically equal for all adopted concrete compressive strengths.

• Beam behaviour was approximately linearly elastic up to about 0.35 f_c for f_c = 24.9 MPa, up to about 0.50 f_c for f_c = 35.2 MPa, and up to about 0.60 f_c for f_c = 45.1 MPa.

• In relation with the beams without stirrups, those with stirrups had some increase of the linear elastic zone, as well as greater ultimate strength capacity and ductility. Stirrups S_2 were more efficient than stirrups S_1.

The relationship between the concentrated load (*P*) and compressive concrete strain (ε) at the top of the beam at the midspan, as a function of compressive concrete strength, is shown in Figs. 11-13 respectively. Those diagrams are affine to those in Figs. 8-10, and also prove previously

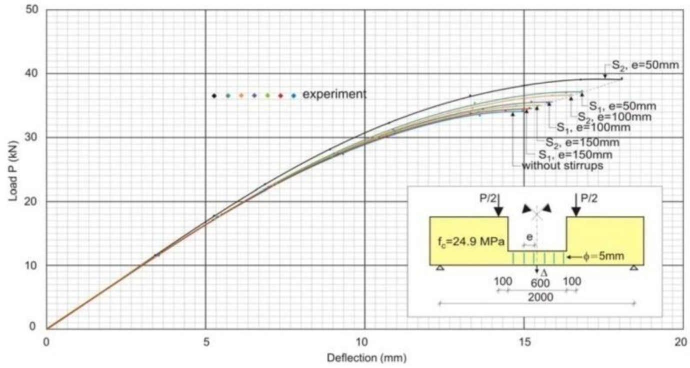

Fig. 8 Measured values of load (P) – deflections at midspan (Δ) relationship for beams made of concrete f_c = 24.9 MPa

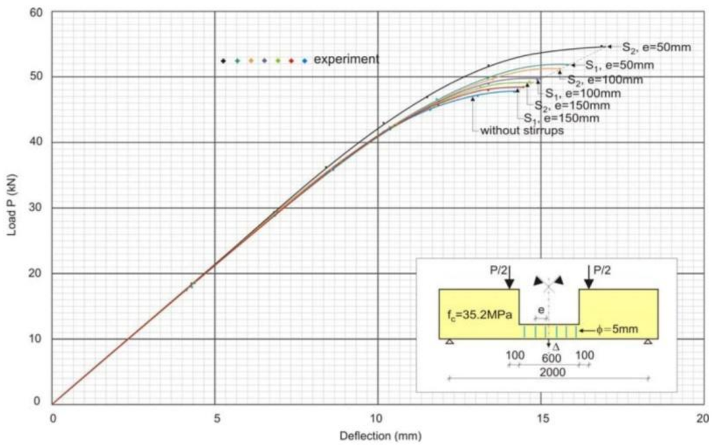

Fig. 9 Measured values of load (P) – deflections at midspan (Δ) relationship for beams made of concrete f_c = 35.2 MPa

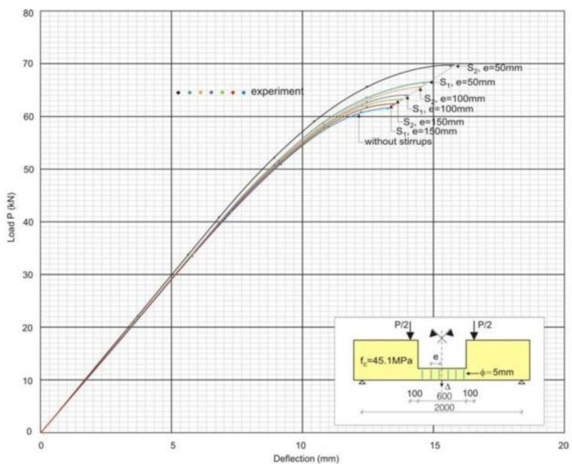

Fig. 10 Measured values of load (P) – deflections at midspan (Δ) relationship for beams made of concrete f_c = 45.1 MPa

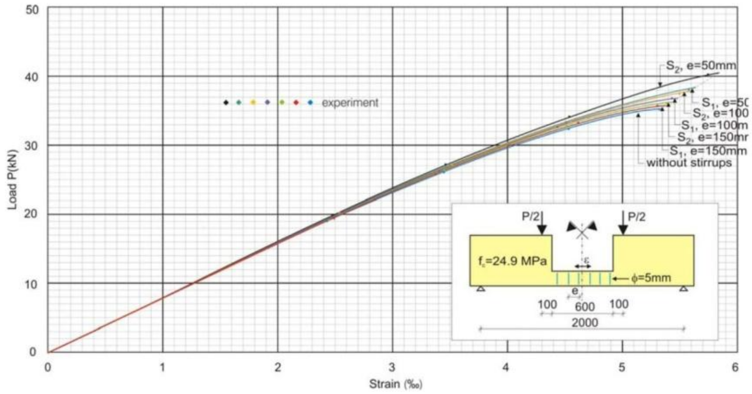

Fig. 11 Measured values of load (P) – concrete compressive strain at midspan (ε) relationship for beams made of concrete f_c = 24.9 MPa

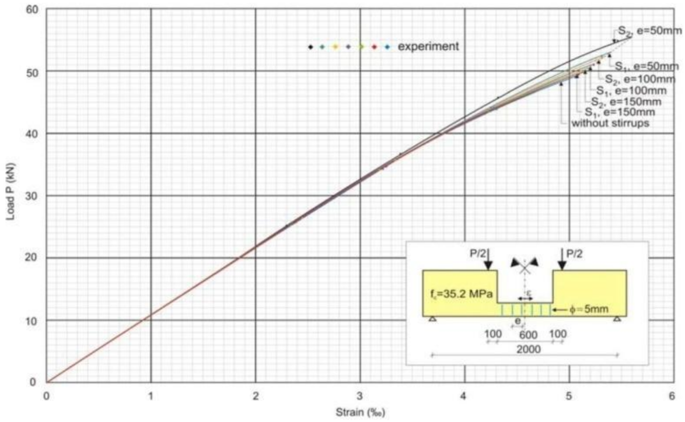

Fig. 12 12 Measured values of load (P) – concrete compressive strain at midspan (ε) relationship for beams made of concrete f_c = 35.2 MPa

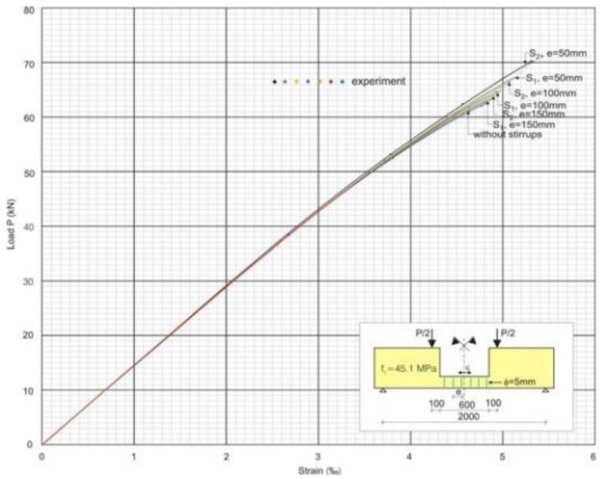

Fig. 13 Measured values of load (P) – concrete compressive strain at midspan (ε) relationship for beams made of concrete f_c = 45.1 MPa

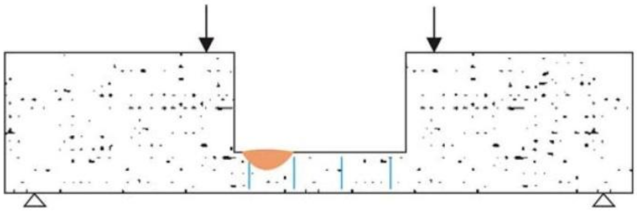

Fig. 14 Typical position of beams failure due concrete crushing

Fig. 15 Photographs of some beams after failure

listed observations.

Collapse of all beams was occurred by concrete crushing in the upper compression zone. Failure location has always been at the beam length of smaller height, i.e., at its connection with the length of greater beam height or adjacent to it. Typical position of beams failure due concrete crushing is schematically presented in Fig. 14. Photographs of some beams after the failure are shown in Fig. 15.

The smallest adopted stirrups spacing for analyzed beam was 50 mm, i.e. approximately the same as its width. In practice, stirrups spacing is often a lot smaller than beam width. It was expected that the advantage of stirrups S_2 in respect to stirrups S_1 in those cases with dense stirrups would be even greater. In this research the stirrups spacing had not been further deceased due to impossibility of concreting for such small beam cross-sectional size and small rebars spacing.

4. Conclusions

Ultimate strength capacity and ductility of tested concrete beams increase with the decrease in stirrups spacing. Stirrups form has a great effect on the ultimate carrying capacity and ductility of the beams. Stirrups that enclose concrete in compression zone are more efficient than common stirrups at the perimeter of the entire beam cross-section. Namely, in order to achieve higher compressive concrete strength and greater ultimate beam carrying capacity, vertical legs of common stirrups should be connected by horizontal lateral rebar approximately at the position of cross-sectional neutral axis, or the concrete compression region should be confined by the additional closed stirrup. In relation with the beams without stirrups, the tested beams with the greatest transverse reinforcement and closed stirrups in concrete compression zone had about 15% higher limit strength capacity and about 20% higher limit ductility (with still relatively high stirrup spacing in respect to beam width). The ratio of compressive strength and ductility characteristics of beams with stirrups, in comparison with those without stirrups, is practically non-dependent on concrete compressive strength. The beams made of concrete with higher compressive strength have higher carrying capacity and smaller ductility than beams made of concrete with smaller compressive strength. For the same percentage of lateral reinforcement, smaller stirrups diameter at smaller stirrups spacing is more efficient than greater stirrups diameter at greater stirrups spacing. In order to increase strength capacity and ductility of the beams with great ratio between their cross-sectional height and width, where failure occurs by concrete crushing, it would be favorable to enclose the compressive zone of the beam cross-section by additional stirrups. Especially, for greater ultimate concrete compressive strength, the compressive flange of the prestressed concrete beam should have the closed stirrups. An even greater effect of increasing the compressive strength of concrete can be enhanced by confining concrete in the compression zone of the beams using the helical reinforcement, and an even greater combination of the helical confinement and the rectangular ties.

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