

Available online at www.sciencedirect.com**ScienceDirect**

Procedia Materials Science 3 (2014) 1977 – 1982

Procedia
Materials Sciencewww.elsevier.com/locate/procedia

20th European Conference on Fracture (ECF20)

Shear failure mechanism in concrete beams

Marta Słowik*

Lublin University of Technology, Nadbystrzycka 40, Lublin 20-618, Poland

Abstract

The aim of the paper is to investigate the shear failure mechanism and shear capacity in longitudinally reinforced concrete beams without transverse reinforcement. It has been found that the shear span-to-depth ratio and a beam size are important parameters which significantly affect the failure mode in the investigated members. The “size effect”, which is described in professional literature as a decrease of shear strength with the increase of the members depth, is not evaluated sufficiently enough. The effective length-to-depth ratio which has been identified in this paper, also has a considerable influence on the contributions of the shear resistance mechanism and thus the ultimate shear capacity. In the paper it has been shown that members characterized by the same shear span-to depth ratio but different effective length-to-depth ratio can fail in a different way.

© 2014 Elsevier Ltd. Open access under [CC BY-NC-ND license](https://creativecommons.org/licenses/by-nc-nd/4.0/).

Selection and peer-review under responsibility of the Norwegian University of Science and Technology (NTNU), Department of Structural Engineering

Keywords: Flexural concrete beams; diagonal crack; failure mechanism

1. Introduction

A shear carrying capacity of reinforced concrete members has been investigated experimentally and analytically by several researchers. It has been found that the shear failure mechanism in concrete members under bending which are reinforced longitudinally but have not transverse reinforcement significantly varies. The main important parameters which influence the shear failure, reported by CEB (1997), are the size of a member and the shear span-to-depth ratio (this parameter takes into account the ratio between bending moment M and shear force V occurring simultaneously in the same cross section $M/(Vd)$, and for three and four point bent test it may be calculated as a/d , where a is a distance between the applied force and the support and d is an effective depth of cross section).

* Corresponding author. Tel.: +48815384392; fax: +48815384390.

E-mail address: m.slowik@pollub.pl

Taking into account the most frequently described models for flexural-shear interaction, researchers divide beams on the basis of the shear span-to-depth ratio into deep beams of $a/d < 2.5$, in which the arch action takes place, and shallow beams of $a/d > 2.5$ where the beam action predominates. ASCE-ACI Committee 445 (1998) classifies beams into deep beams (when $a/d < 1.0$), short beams (when $1.0 < a/d < 2.5$), and ordinary shallow beams (when $a/d > 2.5$). It has been also recognized that, as members become deeper, the ultimate shear stress at failure v_{ult} becomes progressively larger than in slender beams.

Concrete beams with longitudinal reinforcement and without stirrups should be divided into short beams and slender beams but the beams' classification only on the basis of a/d is not sufficiently accurate because the beams of the same a/d but different size can fail in a different way. The rule of classifying members under bending should be modified and should include not only the shear span-to-depth ratio a/d but for example the effective length-to-depth ratio l_{eff}/d as well. This problem is discussed in the paper.

2. Experimental and theoretical investigations on size effect in shear

2.1. Examples of experimental investigations on size effect

The first evidence on the existence of the size effect in longitudinally reinforced concrete members subjected to shear was reported in sixties of 20-th century by Leonhardt and Walther (1962), Rüschi, Haugli, and Mayer (1962), Kani (1967). Then a number of experimental and theoretical studies were performed, for example by Walraven and Lehwalter (1994), Ozbolt and Eligehausen (1996), Karihaloo, Abdalla, and Xiao (2003) Wang, Xing, and Cao (2006), Sherwood, Bentz, and Collins (2007), Hassan, Hossain, and Lachemi (2008) and they confirmed that the influence of the member's size on the shear capacity is significant. In most of the performed experiments geometrically similarly scaled beams were tested and the size effect was investigated as the decrease of the shear capacity with the increase of the absolute members depth, see Fig.1.

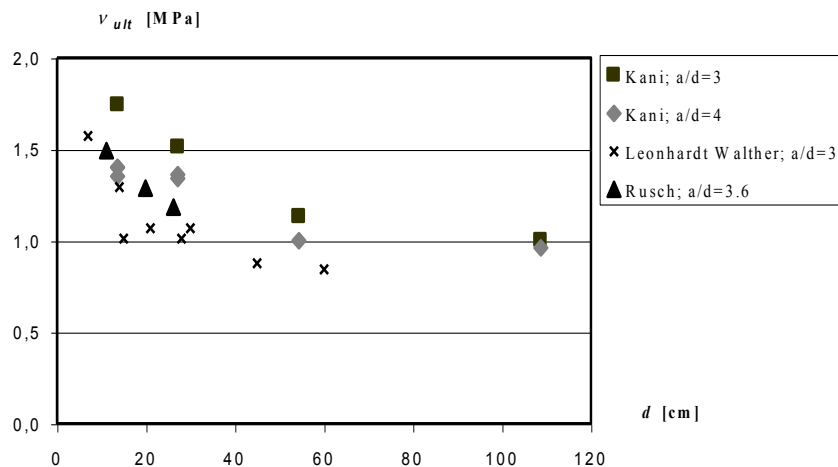


Fig. 1. The illustration of the decrease of shear capacity with the increase of the beams depth on the basis of test results.

2.2. The evaluation of size effect law

There is no general size effect law and the researchers are still working to elaborate the best procedure for shear design. Two major types of theoretical scaling laws for concrete structures have been proposed in professional literature. The first one, known as the Bažant's size effect law, presents a transition between the case when there is no size effect and the yield limit governs the capacity and the case of the maximal size effect when a brittle failure predominates. This theory was developed by Bažant and Kim (1984), Bažant and Kazemi (1991), Bažant and Planas

(1998) on the basis of fracture mechanics. The second type of scaling law, popularized by Carpinteri (1989), is based on a multifractal aspect of damage. This concept relies on homogeneity or inhomogeneity of the material and points that with the increase of the member size the aggregate size becomes relatively smaller and the size effect decreases.

Some codes consider the size effect in the equations for the shear capacity of members without transverse reinforcement, for example the Eurocode 2 (2004) and the *fib* Model Code (2010), whereas others do not, like the ACI 318 (2002). When the shear design equations are given in codes they allow to account for the size effect as a decrease of the design shear capacity with an increase of the member's depth.

2.3. Scope for the research

Although there is disagreement on how best to model the size effect, it has been generally agreed now that the main reason for this phenomenon lies in concrete cracking and structural energy release. Structures which exhibits a stable type of cracking exhibit the size effect as they are sensitive on the variation of fracture energy of concrete. There is no significant size effect in structures of an unstable crack growth and the failure depends mainly on the variation of the tensile strength of concrete. In longitudinally reinforced concrete beams a system of cracks exists and the type of stable or unstable cracks' growth depends on many parameters. The question arises: does the shear capacity depend only on the absolute depth of the member or does it depend on other dimensions, for example an effective length.

3. The influence of effective length on shear failure

3.1. Test procedure

The experimental investigation was performed to study the shear capacity and the character of shear failure in concrete beams reinforced longitudinally but without shear and compression reinforcement in dependence of an effective length l_{eff} . The beams were tested to failure under monotonic loading using a 6000 kN universal testing machine ZD600. A visual examination and surface displacement gauges were used to detect appearance of cracks. During the test, crack widths were measured directly by using handheld microscopes on one side of every beam and a bond between concrete and reinforcing steel bars was monitored.

3.2. Test specimens

Thirteen beams in two series were tested. All beams had the rectangular cross-section of the width $b = 0.12$ m, the total depth $h = 0.25$ m, and the effective depth $d = 0.22$ m. In the first series, five concrete beams were tested in a four-point bent test (beam S2, S3, S4, S5, OI-2). The beams were 2.05 m long and the beams' effective span during the test was $l_{eff} = 1.8$ m. The distance between the applied forces was different in every beam and the shear span-to-depth ratio a/d varied from 2.3 to 3.4. In the second series, eight concrete beams were tested in a three-point bent test (beam S1, S1k, S2k, S3k, S5k, OI-1, PI-1, PI-2). The beams had the different effective span l_{eff} , from 0.9 to 1.8 m and therefore the shear span-to-depth ratio a/d varied from 1.8 to 4.1. More details of the test specimens can be seen in Table 1.

The beams were made from the same concrete grade of the compressive strength $f_c = 35$ MPa, the splitting tensile strength $f_{ct,sp} = 3.5$ MPa, the Young's modulus $E_c = 41400$ MPa. The maximum diameter of aggregate was 16 mm. The beams were reinforced longitudinally by two deformed steel bars $\phi 18$ mm. The reinforcement ratio was $\rho = 1.8$ %. The steel bars in the beams of the symbol "S" were of 34GS category of the yield stress $f_y = 453$ MPa and the tensile strength $f_t = 698$ MPa. The bars in the beams of the symbol "O" and "P" were of RB500 category of the yield stress $f_y = 545$ MPa and the tensile strength $f_t = 631$ MPa.

3.3. Experimental results

The cracking shear force V_{cr} , was assumed as the force that caused the first diagonal cracking. The ultimate shear force V_{ult} , was taken as half the failure load read from the testing machine. The cracking and ultimate forces are given in Table 1.

Table 1. Details of test specimens and test results.

Beam	l_{eff} (m)	a/d	l_{eff}/d	V_{cr} (kN)	V_{ult} (kN)	V_{ult}/V_{cr}
S4	1.8	2.3	8.2	42.0	82.5	1.96
S5	1.8	2.5	8.2	40.5	40.5	1.00
S3	1.8	2.7	8.2	33.0	42.0	1.27
S2	1.8	3.4	8.2	37.5	42.0	1.12
OI-2	1.8	3.4	8.2	37.5	43.5	1.16
OI-1	1.8	4.1	8.2	37.5	45.0	1.20
S1	1.8	4.1	8.2	37.5	43.5	1.16
S5k	1.2	2.7	5.5	45.0	51.0	1.18
S3k	1.1	2.5	5.0	37.5	51.0	1.36
PI-2	1.0	2.3	4.5	37.5	71.0	1.89
S2k	1.0	2.3	4.5	45.0	75.0	1.67
PI-1	0.8	1.8	3.6	37.5	90.0	2.40
S1k	0.8	1.8	3.6	45.0	105.0	2.33

In the beams, as the first, flexural cracks formed within the mid-span. When the load reached approximately $F = 80$ kN the shear stress caused the appearance of diagonal cracks. The specimens exhibited two different modes of shear failure. The longer beams of $l_{eff} > 1.0$ m failed suddenly in shear, soon after the appearance of the diagonal crack. The shear transfer run along one major diagonal crack, which developed from the flexural crack at one side of the beam in the mid-span of the support zone when the load was close to the maximum. Also the bond failure between steel bars and concrete was observed in the form of the horizontal crack following the longitudinal reinforcement. The maximum measured crack width before failure did not exceed 0.1 mm. In short beams of $l_{eff} \leq 1.0$ m the failure process went in a different way. Two major diagonal cracks formed symmetrically at both opposite support zones of the beam when the load reached 50% of the maximum and they did not develop from the flexural cracks. The major diagonal cracks within shear span propagated towards the applied load and the support and their widths widened considerably up to 0.7 mm at failure.

3.4. Analysis of test results

In the performed experimental investigation, the diagonal failure took place in all tested beams. It was found that the ultimate shear capacity V_{ult} was considerably higher for the beams of $a/d = 1.8$ and 2.3, as compared with other beams of $a/d \geq 2.5$, whereas the diagonal cracking force V_{cr} was similar for all beams and did not depend on a/d (see Tab. 1). The obtained experimental results have confirmed that the shear capacity of the beams is significantly affected by the shear span-to-depth ratio a/d . Since the beams had different effective lengths while keeping the cross sections' length the same, it was possible to analyse the size effect as well. It was observed that with the increase of the beams' length the ultimate force decreased and, what is worth to notice, the size of the member influenced not only the shear strength but the character of failure in the investigated beams as well.

The size effect can be discussed when we compare the test results for the members of the same a/d but of different l_{eff} . For this purpose, the test data for two pairs of the beams were juxtaposed: the short beam S3k was likened to the longer beam S5 and the short beam S5k to the longer beam S3. The obtained ultimate shear forces for the short beams were by 26% higher compared to the longer beams of the same a/d . The distribution of cracks and the character of failure process differed in those two groups of members. In the longer beams more brittle failure

was observed. We can describe how sudden the failure was by means of ratio V_{ult}/V_{cr} . When it is 1.0 we have a brittle diagonal failure and with the increase of V_{ult}/V_{cr} we can observe a more steady damage process. For the longer beams S5 and S3 the V_{ult}/V_{cr} ratio is ratio was close to 1.0, whereas for the short beam S3k of $a/d = 2.5$ it was 1.4 and for the short beam S5k of $a/d = 2.7$ it was 1.2. The cracks patterns and the V_{ult}/V_{cr} ratios for the confronted beams are presented in Fig. 2.

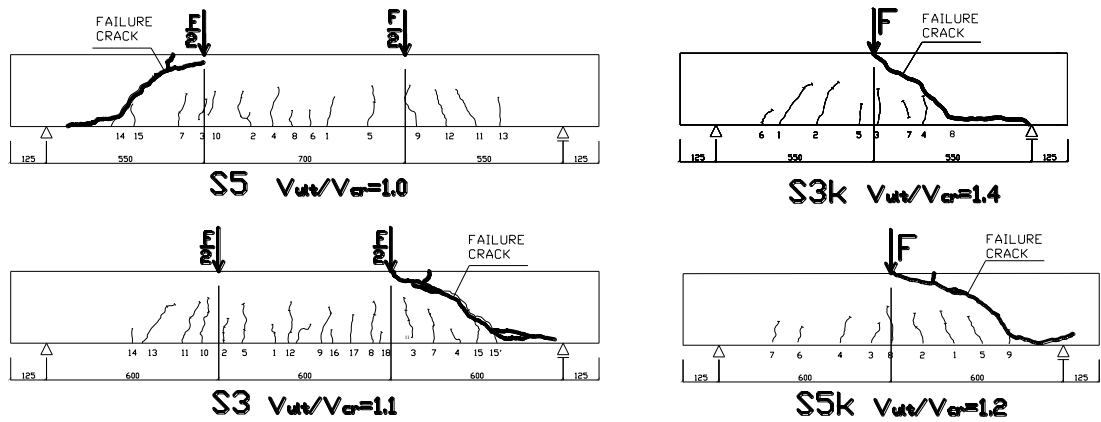


Fig. 2. Comparison of the longer beams with the short beams of the same a/d ratio.

It is difficult to verify the obtained test results with those published up to now as tests were not carried out with geometrically similar beams. In several studies addressing the size effect, the depth of the member was changed proportionally to the length whereas in the performed experiment the depth was kept constant. A new parameter is proposed in the analysis - the effective length-to-depth ratio l_{eff}/d , which can be also called the slenderness ratio.

In Fig. 3 the obtained test results are presented as the ultimate shear stress $v_{ult} = V_{ult}/bd$ versus l_{eff}/d and they are compared with the results from the experiment performed by Kani (1967). The test results indicate a considerable impact of the slenderness ratio on ultimate shear stress. Generally the results overlap and some insignificant differences are probably caused by the fact that in Kani's experiment the reinforcement ratio was greater ($\rho = 2.8\%$) and the compressive strength of concrete was lower ($f_c = 26.7$ MPa).

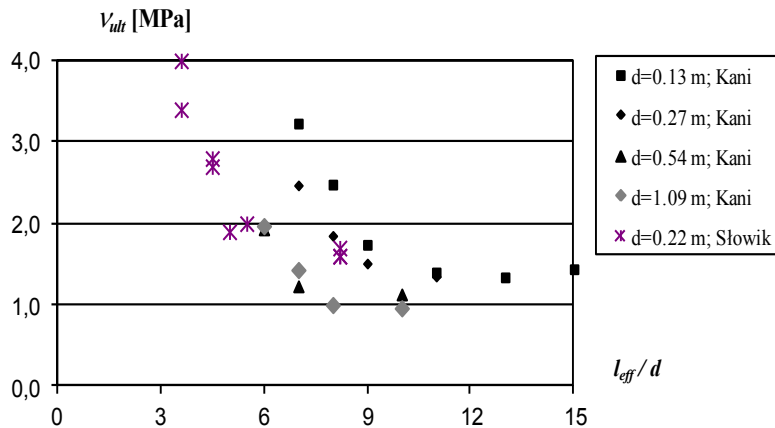


Fig. 3. Comparison of the test results with those obtained by Kani (1967).

4. Conclusions

The performed analysis showed that the diagonal shear failure exhibited the size effect. The failure process in investigated members was influenced by shear span-to-depth ratio as well as by the effective length-to-depth ratio. The shear span-to-depth ratio a/d is the primary parameter that significantly affects the shear strength in concrete members reinforced longitudinally and without shear reinforcement. This problem was discussed at length by Słowik and Nowicki (2012). The experiments presented in the paper have shown that the size of the member also exerted the influence on shear strength and mode of failure in the beams. In the tests reported in the literature, the “size effect” in shear was analysed taking into account two-dimensional similarity of specimens when the depth was proportional to the length of the member. From that view point, size effect was understood as the decrease of ultimate shear capacity along with the increase of beam’s depth. The performed tests have shown that the effective length-to-depth ratio l_{eff}/d , the parameter which has been identified in this paper, also affects the contributions of the shear resistance mechanism and thus the ultimate shear capacity.

Further research should be encouraged to analyse the effect of both shear span-to-depth ratio and the effective length-to-depth ratio on shear failure in concrete members reinforced longitudinally but without stirrups. The “size effect” is not only the problem of the member’s depth but of all dimensions: depth, effective length and width.

References

- ACI 318, 2002. Building Code Requirements for Structural Concrete (ACI318-02) and Commentary (ACI 318R-02). American Concrete Institute. pp. 1414.
- ASCE-ACI Committee 445, 1998. Recent approaches to shear design of structural concrete. *Journal of Structural Engineering*, ASCE 124 (12), 1375-1417.
- Bažant Z. P., Kim J., 1984. Size Effect in Shear Failure of Longitudinally Reinforced Beams. *ACI Journal*, September/October, 456-468.
- Bažant Z. P., Kazemi M. T., 1991. Size Effect on Diagonal Shear Failure of Beams without Stirrups. *ACI Structural Journal* 88 (3), 268-276.
- Bažant Z. P., Planas J., 1998. Fracture and Size Effect in Concrete and Other Quasibrittle Materials. CRC Press LLC, pp. 616.
- Carpinteri A., 1989. Size Effects on Strength, Toughness, and Ductility. *Journal of the Engineering Mechanics Division ASCE* 115 (7), 1375-1392.
- CEB, 1997. Concrete Tension and Size Effects. *CEB Bulletin* 237, pp. 253.
- Eurocode 2, 2004. Design of Concrete Structures. Part 1: General Rules and Rules for Buildings. EN 1991-1-1, European Committee for Standardization, pp. 225.
- fib, 2010. Model Code for Concrete Structures, First complete draft. *fib Bulletin* 56, Vol. 2, pp. 225.
- Hassan A.A., Hossain K.M., Lachemi M., 2008. Behaviour of Full-Scale Self-Consolidating Concrete Beams in Shear. *Cement and Concrete Composites* 30, 588-596.
- Kani G.N.J., 1967. How Safe Are Our Large Reinforced Concrete Beams? *ACI Journal/March* 1967, 128-141.
- Karihaloo B.L., Abdalla H.M., Xiao Q.Z., 2003. Size Effect in Concrete Beams. *Engineering Fracture Mechanics* 70 (7-8), 979-993.
- Leonhardt F., Walther R., 1962. Schubversuche an einfeldigen Stahlbetonbalken mit und ohne Schubbewehrung. *Deutscher Ausschus für Stahlbeton* 151, pp 83.
- Ožbolt J., Eligehausen R., 1996. Size Effect in Concrete and RC Structures; Diagonal Shear and Torsion. *Studi E Ricerche* 17, 37-68
- Rüsch H., Haugli F.R., Mayer H., 1962. Schubversuche an Stahlbeton Rechteckbalken mit gleichmässiger verteilter Belastung. *Deutscher Ausschus für Stahlbeton* 145, 4-30.
- Sherwood E.G., Bentz E., Collins M.P., 2007. Effect of Aggregate Size on Beam-Shear Strength of Thick Slabs. *ACI Structural Journal* 104 (2), 180-190.
- Słowik M., Nowicki T., 2012. The Analysis of Diagonal Crack Propagation in Concrete Beams. *Computational Materials Science* 52, 261-267.
- Walraven J., Lehwalter N., 1994. Size Effects in Short Beams Loaded in Shear. *ACI Structural Journal* 91 (5), 583-593.
- Wang W., Xing F., Cao Z., 2006. Experimental Study on Shear Failure Modes for Ultrahigh Strength Concrete RC Beams without Stirrups. *Journal of Shenzhen University Science and Engineering*, 23 (3), 189-194.