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Experimental verification of engineering procedures for calculation of crack width in concrete elements

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SUMMARY

The paper presents the results of experimental tests of cracking of the reinforced concrete elements exposed to tension and bending. Reinforcement type and quantity were varied as well as stress levels. Experimentally determined crack distances and widths were compared with the results of conventional engineering calculation procedures. The conclusions regarding the acceptability of the results of analyzed engineering calculations are given.

Key words: *cracking, crack width, crack distance, experimental results, engineering procedures, bending, tension.*

1. INTRODUCTION

Considering the existing accomplishments of engineering procedures for calculation of reinforced concrete structures, as well as the accomplishments of the state-of-the-art complex numerical analyses, it could be said that satisfactory accuracy of stress and strain calculations (ultimate bearing capacity) has been achieved, while calculations of deflection, especially crack state are still unsatisfactory. The basic reason for inadequacy of the procedures for crack calculation is in infeasible realistic modelling of very complex behaviour of concrete in cracking zones, as well as the relationship between the reinforcement and surrounding concrete (sliding of reinforcement).

For purposes of cracking control in reinforced concrete structures in everyday practice, only simplified engineering calculation procedures are used. Namely, there is still no commonly accepted theory of reinforced concrete element cracking that could reliably describe that complex phenomenon and determine crack width and distances with adequate accuracy. Therefore, almost all commonly used procedures are dominantly based on the results of experimental determination of crack widths and distances. They are also very simplified and adapted to everyday practice. Thus, the reliability of obtained results with regard to actual states is still questionable.

This paper firstly describes some of the most commonly used engineering procedures for crack width calculations in reinforced concrete elements. The results of those procedures are then checked on several experimental tests. The results of experimental tests of cracking of reinforced concrete elements exposed to tension and bending are presented. Then, the experimentally determined crack widths and distances are compared with those obtained by analyzed engineering procedures. In the end, the most important conclusions are given.

2. ANALYZED ENGINEERING PROCEDURES FOR CRACK WIDTH CALCULATION

The following commonly used engineering procedures for calculation of crack width in reinforced concrete elements exposed to tension and bending are analyzed according to:

- EUROCODE 2 [1]
- PBAB (Regulations on Technical Standards for Concrete and Reinforced Concrete) [2]
- Gergely-Lutz [3]
- ACI, Part 3-1999 [4]
- DIN 1045 [5]
- DIN 1045-1 [6]
- Creazza-Russo [7, 8]

The procedures are described in detail in given references and therefore will not be repeated here.

The diagram of experimentally determined crack widths on tested elements given in Section 3 also shows crack widths obtained by calculations according to the aforementioned procedures. It should be borne in mind that applied procedures are intended only for calculations of crack widths in elements under exploitation loads. A comparison between the calculated and experimentally determined crack width values is given in Section 4.

3. THE RESULTS OF EXPERIMENTAL TESTS OF CRACKING OF SOME REINFORCED CONCRETE ELEMENTS

Prismatic concrete elements exposed to bending and centric tension were tested. The same element geometry and concrete quality has been retained with a varying reinforcement type (deformed RA 400/500-2 and smooth reinforcement GA 500/560), bar diameter (ϕ8, ϕ10 and ϕ12 mm) and stress level (from small loads to breaking). Three identical samples were made for each characteristic test. The arithmetical mean of the obtained results for all three samples has been adopted as relevant. Crack widths and distances (position) were measured. The maximum crack widths for each load (stress) level are shown. Concrete with the maximum aggregate grain $\leq 16\ mm$ was used. Concrete was 90 days old at the moment of testing.

On the day of testing, the following mean concrete strengths were determined [2]:

$f_{cc} = 33.2\ MPa$ - compressive strength of a cube with *20 cm* edge

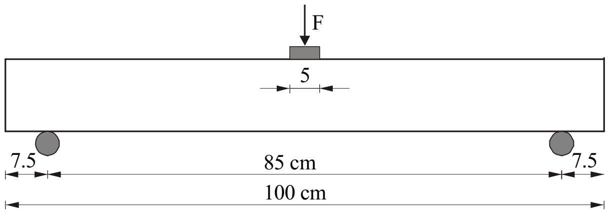
$f_{ct,b} = 2.8\ MPa$ - tensile strength at bending

$f_{ct,t} = 1.8\ MPa$ - tensile strength at centric tension

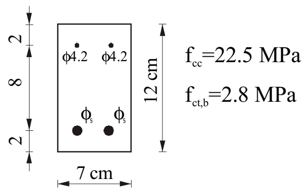
Except for crack widths experimentally determined on test samples, the given figures also show crack width values calculated according to engineering procedures given in Section 2. Only experimental test results will be reviewed in this section, while comparison between calculated and experimentally determined values will be given in Section 4.

3.1 Test results for beams exposed to bending

The basic characteristics of tested samples are given in Figure 1 [9]. Beams of *100 cm* length and *7/12 cm* cross-section exposed to bending were tested by loading with concentrated force at midspan. In the compressive zone the beams were reinforced with $2\ \phi 4.2$ (GA 500/560), while in the tensile zone the reinforcement consisted of two bars of diameter ϕ_S. Tension bar type (RA 400/500 and GA 500/560) and diameter (ϕ_S=*8 mm*, ϕ_S=*10 mm*, ϕ_S=*12 mm*) were varied. Thus, percentages of reinforcement were 0.844 % (2 ϕ8), 1.319 % (2 ϕ10) and 1.900 % (2 ϕ12).



a) longitudinal section



b) Cross-section

	Tensile bar diameter ϕ_s (mm)		
Ribbed reinforcement RA 400/500	*8*	*10*	*12*
Smooth reinforcement GA 500/560	*8*	*10*	*12*

c) Reinforcement

Fig. 1 Geometric characteristics of samples tested to bending

Beams were freely laid on two cylindrical bearings of *40 mm* diameter, the span being *85 cm*. The load was applied gradually at midspan, via a rigid base of *50 mm* width, with a relatively small force increase. The crack position and width were measured for each increase in force. The results obtained for deformed (RA 400/500) and smooth (GA 500/560) tensile reinforcement are given separately hereinafter.

3.1.1 Beams reinforced with deformed tensile reinforcement RA 400/500

Measured crack widths for reinforcement consisting of deformed bars are shown in Figure 2. The characteristic crack width w_k (which corresponds to measured maximum crack width) is shown with regard to applied force F and calculated reinforcement stress σ_s (determined with the assumption that concrete has no tensile bearing capacity and there is a linear stress-strength relationship for concrete).

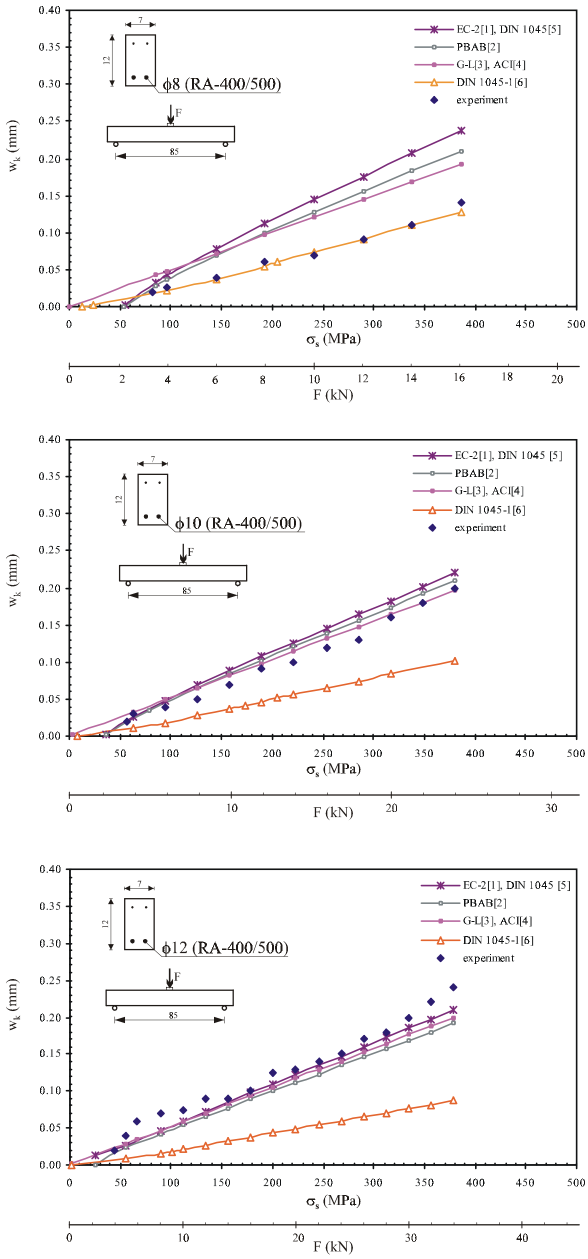


Fig. 2 Crack width in beams exposed to bending and reinforced with RA 400/500

The given figures show that, for more reinforced beams (ϕ12), the first cracks occur at lower reinforcement stresses, while for less reinforced beams (ϕ8) they occur at higher reinforcement stress levels. It can also be observed that, for the same stress level of tensile reinforcement, the crack widths are significantly greater for larger (ϕ12) than for smaller bar diameters (ϕ8). The test results prove the existing knowledge regarding the problems of cracking of reinforced concrete elements [10].

Since the greatest bending moments occur at beam midspan, the first cracks also occur in that zone. With the increase in load, new cracks occur almost symmetrical to the existing ones. With further increase in load, the cracks occur closer and closer to bearings, but also in the middle of the distance from the existing cracks. The first cracks are approximately perpendicular to the lower beam zone, while those closer to bearings are more inclined. With an increase in load, the neutral axis rises and cracks reach closer and closer to the upper beam zone. Due to a significant impact of shear, the beam break always occurred with the development of one dominant inclined crack. It was also observed that the first cracks were not always the widest ones. Namely, during the new cracks opening, the opening of the existing cracks can slow down (relative closing), with newly opened cracks often wider in the end. In some cases, there was a great deviation for the same samples, which proves the fact that reinforced concrete is non-isotropic material, its behaviour is strongly impacted by local factors.

The development of cracks (position of cracks) for beams reinforced in tensile zone with 2 ϕ12 - RA 400/500 is given in Figure 3. The mean distance between cracks s_{rm} has been calculated with regard to the total number of registered cracks and measured mutual distances in the lower beam zone.

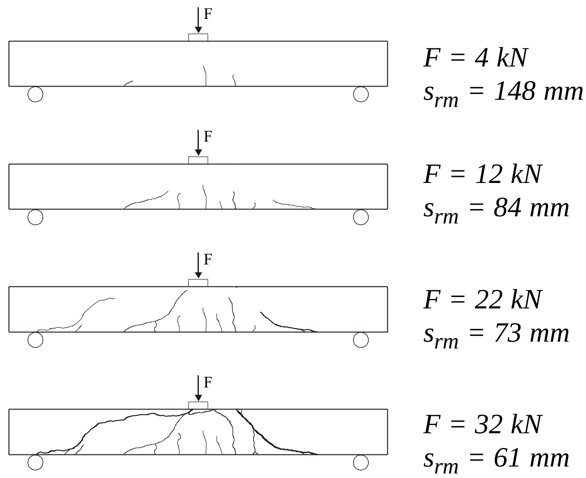


Fig. 3 Crack development in beam exposed to bending, reinforced with 2 ϕ12 (RA 400/500)

3.1.2 Beams reinforced with a smooth tensile reinforcement GA 500/560

For beams reinforced with a smooth reinforcement, the measured crack widths are shown in Figure 4. Based on the analyses of the obtained results, the analogue conclusions can be drawn as for deformed reinforcement. Thus, as in case of more reinforced beams (ϕ12), the first cracks also occur at lower stress levels, while for less reinforced beams (ϕ8) they occur at higher reinforcement stress levels. Also, for the same stress level of tensile reinforcement, the crack widths are greater for larger (ϕ12) than for smaller bar diameters (ϕ8). The crack development with a load increase is also similar to that for deformed reinforcement.

When crack widths measured on beams reinforced with deformed RA 400/500 and smooth reinforcement GA 500/560 are compared, it can be observed that the deformed reinforcement provides smaller crack widths for the same steel stress levels. It is a consequence of better adhesion of deformed reinforcement and concrete when compared with a smooth reinforcement, which has also been a common knowledge.

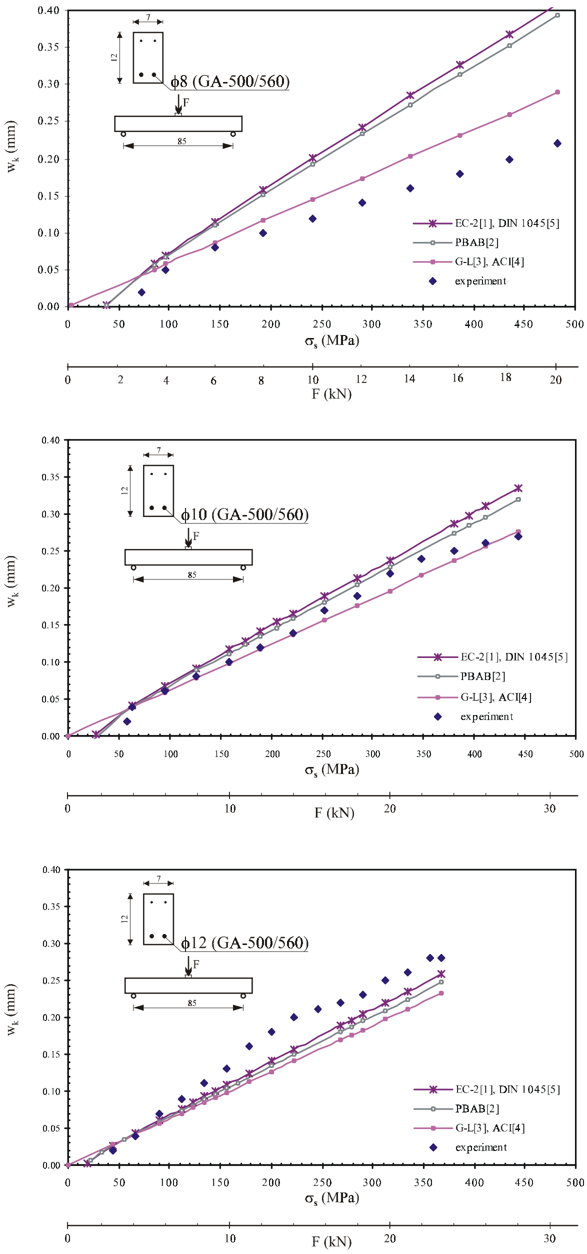
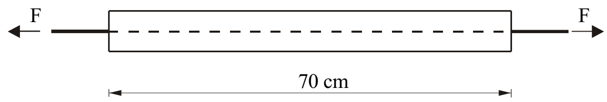


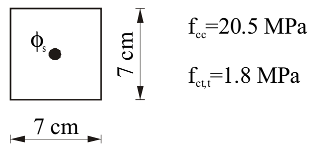
Fig. 4 Crack width for beams reinforced with GA 500/560 and exposed to bending

3.2 Test results for elements exposed to tension

The basic characteristics of test samples are given in Figure 5. Elements of *70 cm* length and *7/7 cm* cross-section were tested for centric tension. They were reinforced with one bar in the centroid of the cross-section. The reinforcement type (RA 400/500 and GA 500/560) and diameter (ϕ_s=8 mm, ϕ_s=10 mm, ϕ_s=12 mm) were varied. Thus, percentages of reinforcement were 0.422 % (ϕ8), 0.66 % (ϕ10) and 0.85 % (ϕ12).



a) longitudinal section



b) cross-section

	Bar diameter ϕ_s (mm)		
Ribbed reinforcement RA 400/500	*8*	*10*	*12*
Smooth reinforcement GA 500/560	*8*	*10*	*12*

c) reinforcement

Fig. 5 Geometric characteristics of samples exposed to tension

The elements were tensioned by a hydraulic press via reinforcement that extended from the beam faces. Since bars were not positioned ideally at the cross-section centroid, and eccentric fixing of bar extension in gripping jaw of the press was possible, additional stresses due to bending occurred in the elements. They were included in a manner that crack widths were measured at all four sides, with the arithmetical mean of measured results adopted as a relevant value. The results obtained for deformed and smooth reinforcement are given separately hereinafter.

3.2.1 Elements reinforced with deformed reinforcement (RA 400/500)

The obtained crack width results are given in Figure 6. Graphic presentation is analogue as for bending, with the reinforcement stress calculated according to the expression $\sigma_s = F/(\phi_s^2\pi/4)$.

Comparison of obtained results shows that similar conclusions can be drawn as for bending. There was a great non-concurrence of experimentally determined values for the same cases (same reinforcement), which also points to the presence of local impacts and eccentricity of longitudinal force. The development (position) of cracks in elements reinforced with ϕ 12 (RA 400/500) is given in Figure 7.

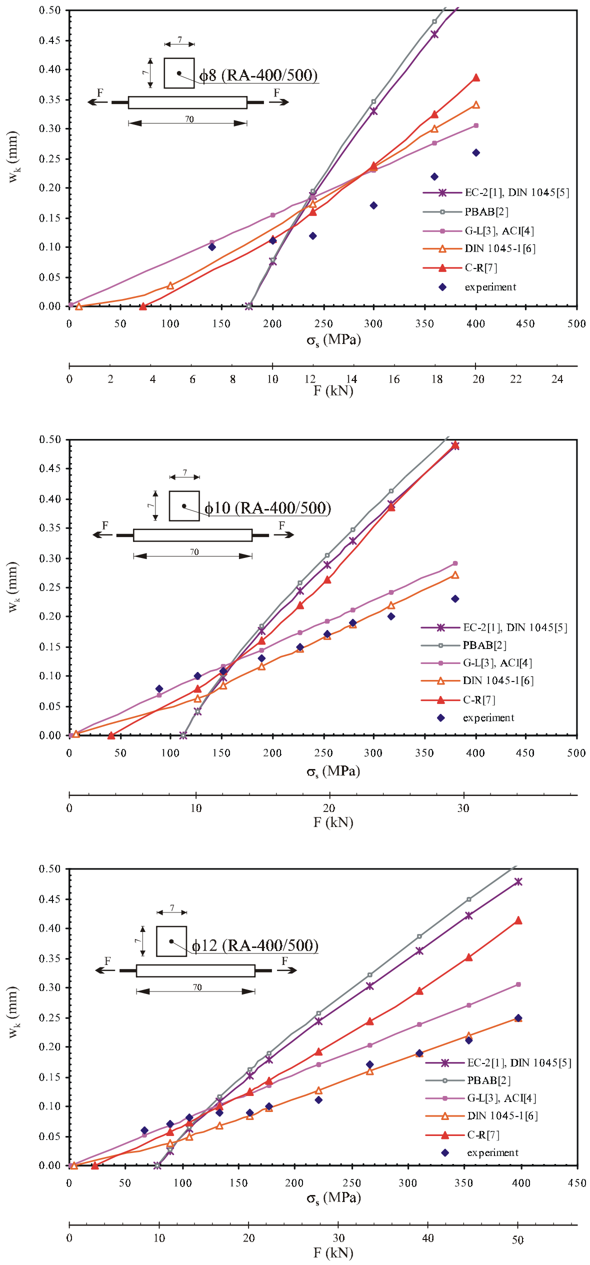


Fig. 6 Crack widths in tension elements reinforced with RA 400/500

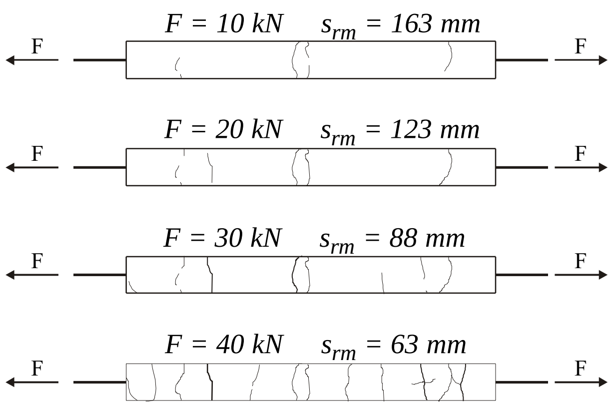


Fig. 7 Crack development in tensile element reinforced with ϕ 12 (RA 400/500)

3.2.2 Elements reinforced with a smooth reinforcement (GA 500/560)

The crack widths measured on tensile elements reinforced with GA 500/560 are given in Figure 8. The analysis of the results shows that analogue conclusions can be drawn as for tensile elements reinforced with a deformed reinforcement. The comparison of crack widths on elements given in Sections 3.2.1 and 3.2.2 also shows that, for the same stress levels, deformed reinforcement gives far smaller cracks than a smooth one, which has also been proved in practice.

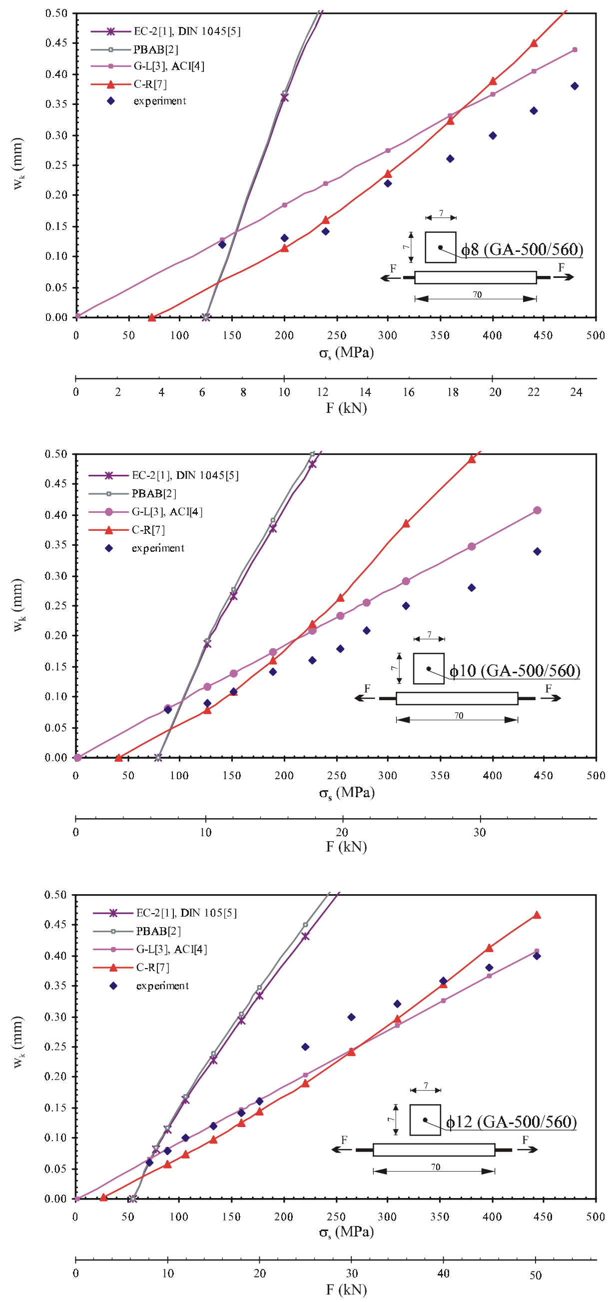


Fig. 8 Crack widths in tensile elements reinforced with GA 500/560

4. COMPARISON OF EXPERIMENTAL AND CALCULATED CRACK WIDTH VALUES

The crack width values, experimentally determined in Section 3, have been compared with crack width values calculated according to procedures given in Section 2. The results of the analyses are also given separately for beam bending and elements exposed to tension.

4.1 Beams exposed to bending

4.1.1 Beams reinforced with a deformed tension reinforcement (RA 400/500)

By comparing the experimentally determined and the calculated crack width values given in Figure 2, the following can be concluded:

- Crack widths calculated according to DIN 1045-1 [6] significantly differ from values calculated according to other procedures. It is mainly because of inadequate prognoses of the maximum distance between cracks according to this procedure. Thus, the calculation of crack width of elements exposed to bending according to DIN 1045-1 will be regarded as inadequate for the observed cases and discarded from further analyses. Respectively, the below mentioned conclusions assume that this procedure has not been considered.
- Engineering procedures for the crack width calculation according to EUROCODE-2 [1], PBAB [2], Gergely-Lutz [3], ACI-1999 [4] and DIN 1045 [5] give roughly equal crack width values.
- Calculated crack width values are, in general, greater than experimentally determined ones. The only exception is the most reinforced beam (ϕ12).
- Differences between calculated and experimentally determined values of crack widths decrease with the increase in beam reinforcement percentage i.e. increase in bar diameter.
- Calculations according to EUROCODE-2 [1] and DIN 1045 [5] give the greatest crack widths i.e. they are more on the safety side when compared with other calculation procedures.
- There is an equal concurrence between experimental and calculated results for exploitation and ultimate reinforcement stresses.
- Calculations according to Gergely-Lutz [3] and ACI-1999 [4] give crack width results for each load greater than zero. Therefore, crack widths obtained for the lowest load levels (before cracks appear) make no sense.
- Procedure for calculation of the beginning of the appearance of the first cracks is in good concurrence with experimentally determined values, except for the procedures according to Gergely-Lutz [3] and ACI-1999 [4].

4.1.2 Beams reinforced with smooth reinforcement (GA 500/560)

Based on the comparison between experimental and calculated crack width values given in Figure 4, the analogue conclusions can be made as in Section 4.1.1 for deformed reinforcement, with the following additions:

- Calculation according to DIN 1045-1 [6] has not been anticipated for smooth reinforcement.
- For the most reinforced beam (ϕ12), experimentally determined crack widths were somewhat greater than calculated values.
- In general, there is better correspondence between experimentally determined and calculated values for lower stress levels with regard to ultimate ones.

4.2 Elements exposed to centric tension

4.2.1 Elements reinforced with deformed reinforcement (RA 400/500)

Based on the comparison between calculation results and experimentally determined crack width values given in Figure 6, the following conclusions can be made:

- Unlike elements exposed to bending, the calculation according to DIN 1045-1 [6] provides the best correspondence between the calculated and experimentally determined crack widths for beams exposed to tension.
- There is a greater non-concurrence between calculation results and experimentally determined crack width values than for beam bending.
- For lower reinforcement stress levels, the procedures according to EUROCODE 2 [1] and Creazza-Russo [7] give smaller crack widths than the experimentally determined ones.
- For higher reinforcement stress levels (from medium exploitation to ultimate ones), all analyzed engineering procedures give greater crack widths than the experimentally determined ones.
- There is a great difference between the calculated values of crack widths according to different procedures.

4.2.2 Elements reinforced with smooth reinforcement (GA 500/560)

Based on comparison between experimental and calculated crack width values given in Figure 8, the analogue conclusions can be made as in Section 4.2.1 for deformed reinforcement, with the following additions:

- Calculation according to DIN 1045-1 [6] has not been anticipated for a smooth reinforcement.
- There is even greater non-concurrence between experimentally determined crack widths and those calculated by the applied engineering procedures.
- There are enormous differences among crack width values calculated according to different procedures.

5. CONCLUSIONS

Based on the comparison between the experimentally determined crack widths and the calculated values obtained by analyzed engineering procedures for beams exposed to bending and elements exposed to centric tension, the following can be concluded:

- The results of experimental tests of crack widths for elements exposed to bending and tension (with varying stress levels, reinforcement type and percentage - bar size), proved the existing knowledge regarding reinforced concrete behavior at cracking.
- There is a significantly better concurrence between calculated and experimentally determined crack widths for elements exposed to bending than for those exposed to tension.
- The results of crack width calculations according to analyzed engineering procedures differ less for beams exposed to bending than for elements exposed to tension.
- The analyzed engineering procedures for elements exposed to bending give crack widths that are mainly on the side of greater safety (reserves also include impact of reologic properties of concrete that have not been experimentally included here). For the most reinforced elements and lower stress levels of reinforcement, the calculated crack widths are somewhat lower than the experimentally determined values.
- For beam bending, there is a little difference between the calculated crack width values according to different procedures. Thus, it can be concluded that all analyzed procedures are equally accurate and acceptable in practice (an exception is a procedure according to DIN 1045-1 [6] that gave significantly smaller crack widths in comparison with other analyzed procedures and, therefore, its applicability remains questionable). One should be careful with more reinforced elements, taking into account that the real crack widths could be greater than the calculated ones.
- For elements exposed to tension, there are great differences between the calculated values of crack widths according to different regulations. Therefore, one should be careful when selecting a procedure. The procedures according to EUROCODE-2 for lower stress levels are on the safety side.

6. LITERATURE

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EKSPERIMENTALNA PROVJERA INŽENJERSKIH POSTUPAKA PRORAČUNA ŠIRINA PUKOTINA BETONSKIH ELEMENATA

SAŽETAK

U radu su prikazani rezultati eksperimentalnih ispitivanja raspucavanja armiranobetonskih elemenata opterećenih na vlak i savijanje. Varirana je vrsta i količina armature, te razina naprezanja. Utvrđene eksperimentalne vrijednosti širina i razmaka pukotina uspoređene su s rezultatima nekih uobičajenih inženjerskih postupaka proračuna. Navedeni su zaključci glede prihvatljivosti rezultata razmatranih inženjerskih proračuna.

Ključne riječi: *raspucavanje, širina pukotine, razmak pukotina, rezultati pokusa, inženjerski postupci, savijanje, razvlačenje.*