Measuring crack width and spacing in reinforced concrete members

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Measuring crack width and spacing in reinforced concrete members

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ABSTRACT: Cracking behavior of reinforced concrete is usually understood by the cracking of a concrete prism reinforced with a central bar subjected to tension. Bending, which is majority of the real cases, is dealt in the Eurocode by an empirical adjustment of the coefficients. In this paper an experimental program is devised to study the structural size effect of reinforced concrete members on crack width and spacing. Bending tests are performed on three different sizes of beams which are geometrically similar in two dimensions. The main reinforcement ratio is constant in all the beams keeping the same number of bars. The cover to the main reinforcement is also scaled with the beam size. Crack width and cracks spacing are measured using digital image correlation technique. Strain in the main reinforcement is measured using embedded electric strain gauges. It is found that Eurocode underestimates the crack width and crack spacing. Measured values of crack widths show an important structural size effect, which is not accounted by Eurocode crack width formula.

1 INTRODUCTION

Serviceability limit states (SLS) for reinforced concrete (RC) structures are usually applied to ensure their functionality and structural integrity under service loading conditions. In current design codes (EC2 EN 1992), the serviceability limit states are defined by providing three control parameters (1) Limitation of stresses in the material (2) Control of crack width and spacing (3) Deflection (short term and long term) checks. The maximum stresses, deflections and crack sizes are computed from critical combinations of actual, applied loads (called service loads), in conjunction with the structure's geometry (type and location of reinforcement) and boundary conditions. However, it will be seen in this paper that the crack size also depends on material resistance to crack growth, which is not same as the material strength and which varies with the size of the structure. In this paper an experimental study is presented, in which three geometrically sized beams were tested in three point bending to obtain the experimental crack width and crack spacing, when the structure is subjected to service loadings.

2 CRACK CONTROL IN RC STRUCTURES

It is recognized that cracking in reinforced concrete members may be of two forms: (1) Cracking due to restraint provided by structure to volume change, and (2) cracking due to applied loads. In this paper only the cracking due to applied loads is discussed.

There are three principal elements in the provisions of crack control (EC2 EN 1992): (1) The provision of minimum reinforcement area (2) A method for calculating design crack width (3) Simplified rules which will avoid the necessity for explicit calculation of crack width in most normal situations.

2.1 *Design Crack width*

The approach almost universally used to explain the basic cracking behavior of reinforced concrete is to consider the cracking of a concrete prism reinforced with a central bar which is subjected to pure tension. Bending does influence the phenomena but this is dealt with in the Eurocode by an empirical adjustment of the coefficients.

According to Eurocode (EC2 EN 1992), the design crack width can be determined using the following expression

$$w_k = s_{r,\max}\left(\varepsilon_{sm} - \varepsilon_{cm}\right) \qquad (1)$$

where,

w_k = design crack width ; $s_{r,max}$ = maximum crack spacing ; ε_{sm} = mean strain in the reinforcement ; ε_{cm} = mean strain in concrete between cracks.

In the expression (1) ε_{sm} - ε_{cm} may be calculated as:

$$\varepsilon_{sm} - \varepsilon_{cm} = \frac{\sigma_s - k_t \dfrac{f_{ct,eff}}{\rho_{p,eff}}\left(1 + \alpha_e \rho_{p,eff}\right)}{E_s} \geq 0.6\frac{\sigma_s}{E_s} \qquad (2)$$

where

σ_s = stress in the tension reinforcement assuming cracked section ; $\rho_{p,eff} = A_s/A_{c,eff}$, which is the ratio of area of tension reinforcement (A_s) to the effective tension area of concrete around the steel ($A_{c,eff}$). However, $A_{c,eff}$ depends implicitly upon the concrete cover provided on the tension face. See details in EC2 EN 1992.

2.2 *Maximum final crack spacing*

When reinforcement is fixed at reasonably closed spacing (spacing ≤ $5(c+\Phi/2)$), according to Eurocode (EC2 EN 1992) the maximum final crack spacing can be calculated as:

$$s_{r,\max} = 3.4c + 0.425 k_1 k_2 \frac{\phi}{\rho_{p,eff}} \qquad (3)$$

where,

Φ = bar diameter ; c = concrete cover ; k_1, k_2 are coefficients depending upon steel-concrete bond properties and loading type respectively. See EC2 EN 1992 for details.

In equation (3) concrete cover c is explicitly introduced into the expression of the crack width as suggested by A. Beeby. He studied the influence of concrete cover over the transfer length (Beeby 2001). The transfer length increases monotonically with the increase of concrete cover. This effect is introduced in the calculation of crack spacing. Stress in the concrete around the reinforcement is directly dependant on the stress transfer length between concrete and steel. Since cracking occurs in concrete at the points where stress exceeds the tensile resistance of concrete, therefore, crack spacing is a function of concrete cover. In this study, concrete cover to height of the beam ratio is kept constant to take into account the effect of overall structure size on the crack opening and crack spacing.

2.3 *Analysis of test data*

It has been suggested that when analyzing the test data of crack width and crack spacing in reinforced concrete tensile members, following considerations should be made (Commentary to EN 1992):

- The materials used should be similar to the materials use today in the building structures. The low bound rebars, concrete qualities less than 20 N/mm^2 and steel qualities less than 400 N/mm^2 should not be used.

- The stress range should be serviceability range. For this purpose, results in the stress range in steel from 150 to 350 N/mm^2 should be considered for tests involving direct actions. For indirect actions, steel stress range up to the yielding stress of steel should be considered.

- To determine the crack spacing the number of cracks present at the last phase of the test is always considered since it is the closest to the stabilized cracking, as given by equation (3).

In the literature a very scarce data is found for the direct comparison between the calculated and the experimental crack widths.

3 SIZE EFFECT IN CONCRETE

Structural size effect is the central problem in predictions of fracture. Fracture tests are normally conducted on relatively small specimens and then this information is extrapolated to large structures.

The question of size effect has become a crucial consideration in the efforts to design concrete structures, for which there inevitably is a large gap between the scales of large structures (dams, reactor containments, bridges) and of laboratory tests. The size effect on structural strength is normally understood as the effect of the characteristic structure size (dimension) on the nominal strength of the structure when geometrically similar structures are compared (Bazant 2002).

In all quasi-brittle materials like concrete, fracture is preceded by a gradual dispersed microcracking that occurs within a relatively large fracture process zone ahead of the crack tip of a continuous crack. When a concrete structure is loaded, the strain energy produced by the applied load is converted to the energy consumed to create new fracture surfaces and the energy absorbed in the fracture process zone. For large-size structure the latter is negligible compared to the former, whereas for a small-size structure these can be comparable (Bazant 2002). Therefore, the larger the structure size, the lower the nominal strength. However, the concrete strength approaches a constant when the size of the concrete structure becomes very large.

3.1 *Size effect on crack width*

It is obvious that the cracking behavior is also influenced by structural size. A recent study has shown that the cracking in plain concrete is size dependant mechanism (Alam & Loukili 2009). It was observed that when geometrically similar specimens are tested under same loading and boundary conditions, the propagation of crack is not the same in large beams as it is in small beams. A numerical study (Ouyang & Shah 1994) of reinforced concrete based on fracture mechanics rules has also shown the cracking behavior to be size dependant. They calculated crack width in tensile members with constant central reinforcement and member length but varying cross sectional areas. They found that crack width decreases as the width of the member increases. Results were not compared with experimental data. They found that previously obtained experimental data is very scattered because crack width depends, not only on the geometry and loading condition of the structure, but also on the size of the structure. In the current design approach (Equations (1) & (2)), crack width is evaluated primarily using empirical methods that require some empirical constants. The size effect on the crack width cannot be accounted for by the conventional analysis unless additional empirical constants are used (Shah et al. 1995).

A limited amount of experimental data is available in the literature concerning the study of size effect on the crack width and crack spacing. Most of the results deal with the reinforced concrete members subjected to tension or having small dimensions(Commentary to EN 1992). In this paper an experimental program is devised to study the effect of structural size on the crack width and crack spacing. Three sizes of beams with geometrically similar length and height, but with constant thickness are tested in three-point bending. The tensile reinforcement ratio is kept constant; however, the concrete cover to the reinforcement was scaled according to the overall size of the beam. The aim of this study is to evaluate the concrete crack width and crack spacing expressions present in the Eurocode (equations 1-3) with the experimentally measured crack width and spacing.

4 EXPERIMENTAL PROGRAM

4.1 *Materials*

The concrete used to prepare the beams is made from Portland cement type 52.5, sand, aggregate & water using the mix proportions in Table (1).

Table 1. Concrete mix design details.

Cement (Portland 52.5)	312	kg/m^3
Sand	818	kg/m^3
Coarse aggregate (5 - 12.5 mm)	936	kg/m^3
Water	219	kg/m^3

The compressive strength of concrete is tested at 28 days using cylindrical specimens with diameter 10cm and height 20cm and is found to be 40 N/mm^2. Since the beams are reinforced with rebars, a super plasticizer with a dosage of 0.25% by weight of cement is added to increase the workability of fresh concrete.

The longitudinal reinforcement of beams is constituted of deformed bars with 10, 14 & 20 mm in diameter, while the transverse reinforcement is provided by deformed bars with 6mm in diameter. The steel bars in both cases are type $f_{yk} \geq 500$ MPa.

4.2 *Beams*

Three sizes of beams are tested. The dimensions of the beams are given in Table 2. The beams have a constant width (b = 100 mm), however, the length and height are scaled. Concrete cover at the tension face of the beam is also scaled with same proportion between different sizes of beams. The beams are reinforced with a constant reinforcement ratio by varying the diameter of the bars; however, the number of bars is kept constant. Steel stirrups are used in the area of high shear. Two hanger bars of 6mm diameter are used to support steel stirrups. These bars are cut where the stirrups are not provided (Fig. 1).

Table 2. Specimens geometry.

Beam		b	h	L	l	ρ	cover
		mm	mm	mm	mm	%	mm
Small	D1	100	100	400	300	1.99	10
Medium	D2	100	200	800	600	1.84	20
Large	D3	100	400	1600	1200	1.83	40

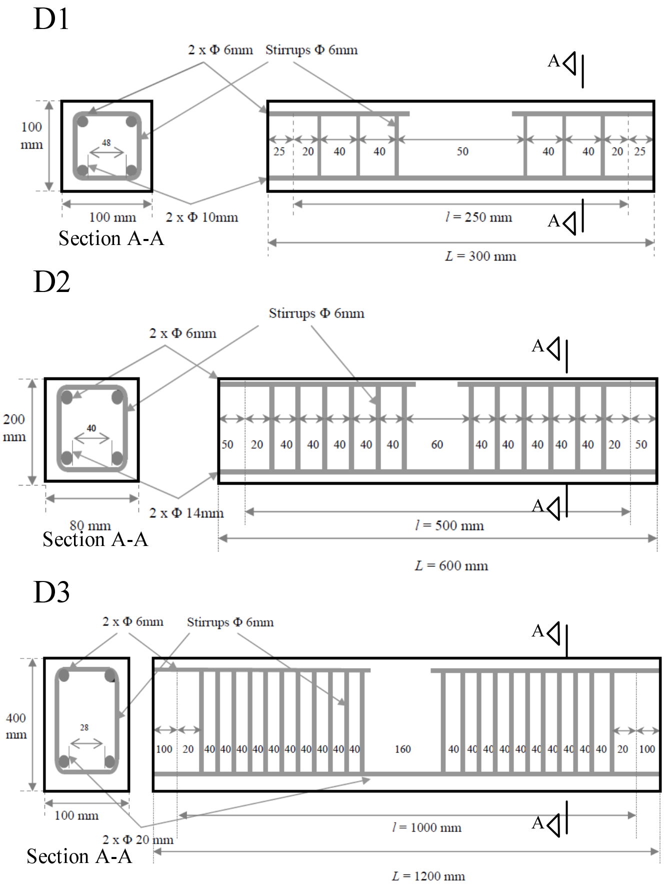

Figure 1*. Geometry and reinforcement details.
*The figure is not scaled.

4.3 *Test procedure*

All the experiments are performed using the same testing machine with controlled displacement. The test setup is shown in Figure 2. The load is applied at the mid span with a cylindrical jack, ensuring the point load. The load is transferred to the beam using a rubber pad, to avoid the concrete damage at the load point. The test is carried out using a constant vertical displacement rate of 0.5 mm/min. The displacement is measured using a laser sensor, which measures the displacement at the mid section of the beam under the load. The sensor is attached to a steel hanger, which is supported at the supports to take into account the settlement of beam at the supports.

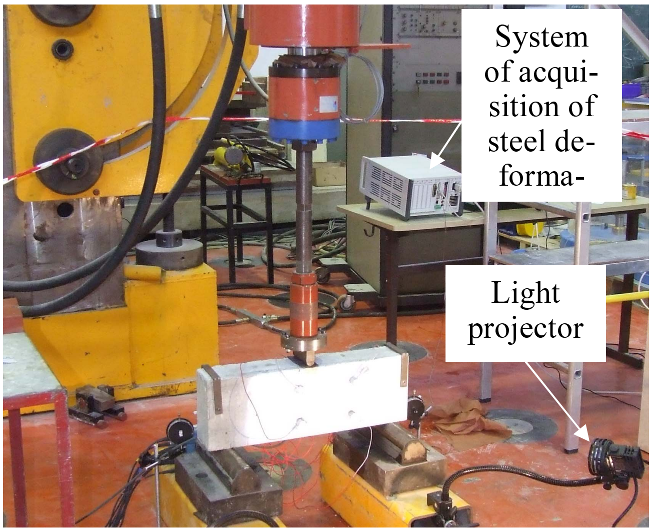

Figure 2. Test setup.

For each beam, two electric strain gauges are attached to the lower face of tension steel at mid span to measure the longitudinal strain in steel during the test (Fig. 3).

Results are discussed here for three point bending tests on three sizes of beams. After the fabrication, these beams were stored at 20°C and relative humidity of 50% for 24 hours. After the removal of molds, these beams were stored in 100% relative humidity for 28 days


Figure 3*. Strain gauges attached to the steel bars at mid span. *view before the pouring of concrete.

4.4 *Digital image correlation*

The measurement of crack width and crack spacing is carried out using a digital image correlation system. The digital image correlation is an optical method to measure the surface displacement field between two time instants. This technique has already been applied on concrete (Alam & Loukili 2009, Choi & Shah 1997, Lawler et al. 2001, Corr et al. 2007). It is based on the comparison of two images based on grayscale recorded before and after deformation. The first image is called the reference and the second is the deformed image. The displacement field is then determined through the movement of the subimage in an area defined as the correlation zone. The correlation consists of considering a segment (subimage) in the reference image and locating that segment (subimage) in the deformed image, where the maximum likelihood is achieved. In this study, a commercial software Vic2D is used to perform the image correlation. The size of subimage is taken as 29x29 pixels, which is regularly spaced in the reference image (of size 1392x1040 pixels) in the form of a grid. Each subimage in the reference image is correlated to the one in deformed image by calculating a correlation coefficient in the correlation area around the subimage. The resolution of the system depends directly on the distribution of gray levels which depends on the texture of the material. To obtain a random pattern, a speckle pattern of black and white paint is sprayed onto the surface of the specimen. The images on a single face of the specimen are captured using two digital cameras, which give 256 levels of gray intensity. Cameras are placed in such a way to film an area 15x10 cm by each camera at either side of the mid span. The mid span portion is filmed by both cameras. The mid span section is taken as the reference to relate the measurement values of the two cameras as shown in Figure 4.

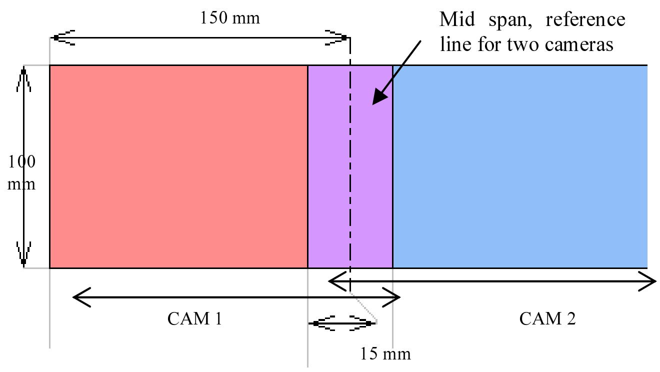

Figure 4. Camera zones for digital image correlation.

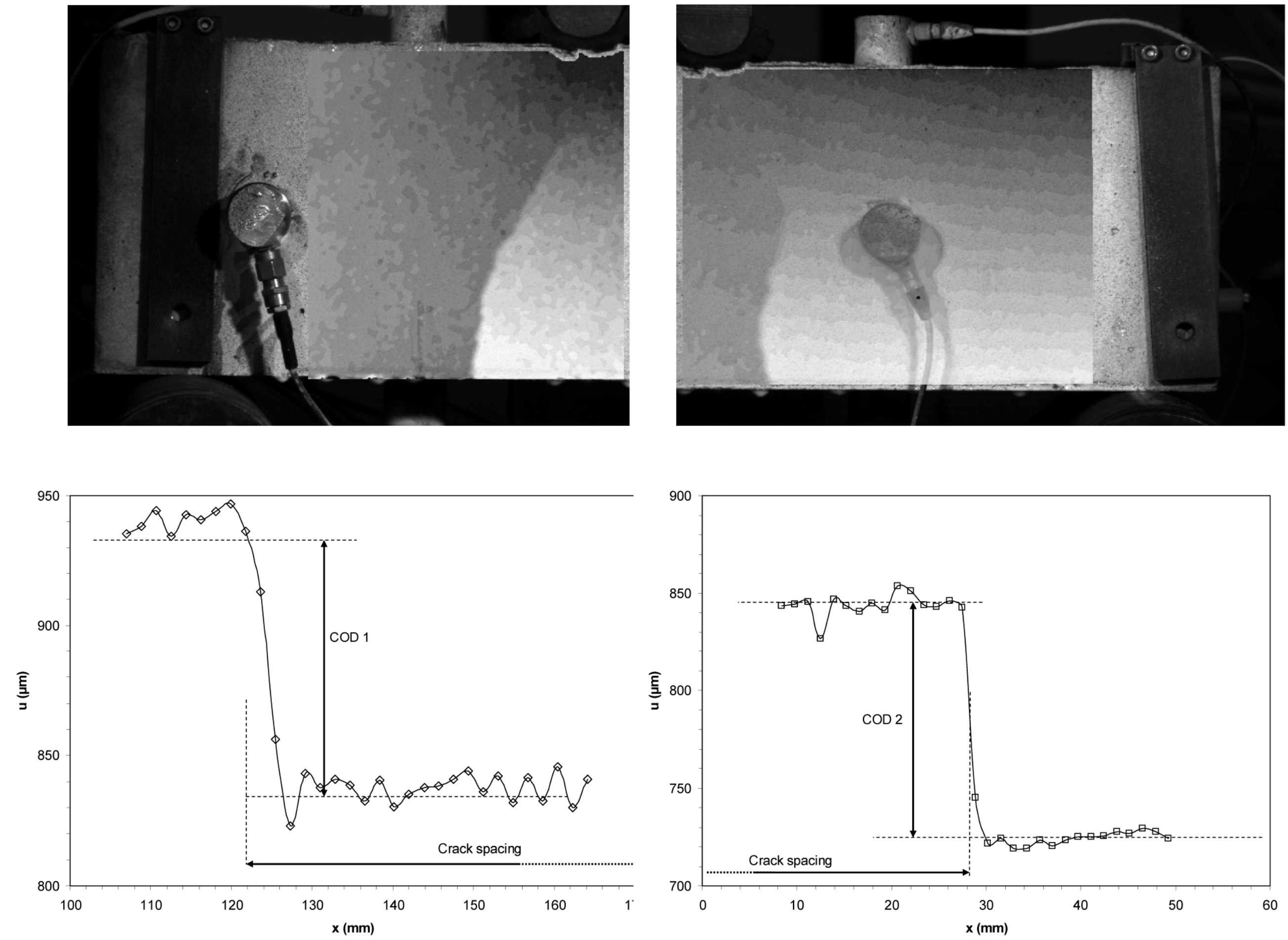

Figure 5. Measurement of crack opening displacement (COD) and crack spacing in small (D1) beam.

5 RESULTS AND DISCUSSION

The measurement of crack opening displacement (COD) and crack spacing by digital image correlation is presented in Figure 5. COD is measured as displacement jump on the surface of the beam. Multiple cracks are found, but only the maximum COD is considered in the further analysis

The crack width measured using digital image correlation technique is plotted against the crack width obtained using eurocode crack width formula (eq. 1) as a function of steel strain ε_{sm}. The crack width is measured at the mouth of the crack i.e. at the lowest fiber of the beam, where the crack width is maximum. The results are shown in Figure 6 for comparison. It can be seen that eurocode formula underestimates the crack width for all the three sizes. The difference between measured and calculated value exceeds when the strain is higher. Figure 4 shows the comparison for a stress range under yield limit of steel.

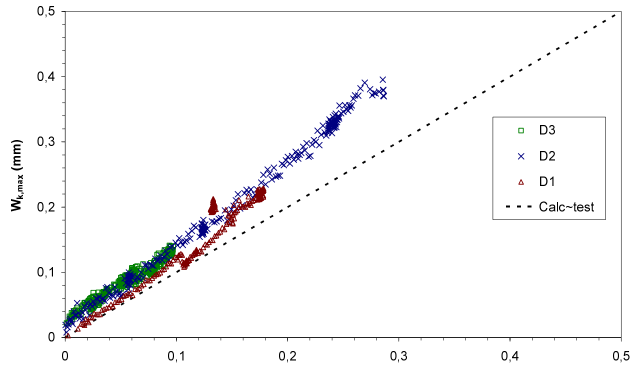

Figure 6. Comparison of experimental crack width ($W_{k,exp}$) and calculated maximum crack width ($W_{k,max}$) during crack formation stage (ε_{sm}< yield limit).

A more detail observation of the effect of size on the eurocode calculated crack opening is made in the Figure 7. It is clear that the calculated crack width is more or less comparable for small size beam but the error exceeds with size increases.

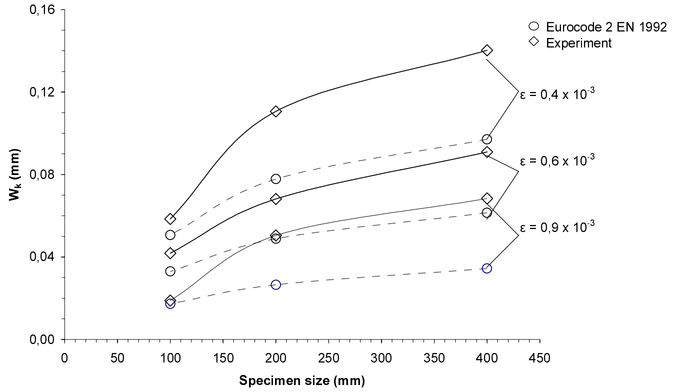

Figure 7. Size effect on experimental and calculated maximum crack width.

The crack width obtained from Eurocode formula does not take into account size effect. However, the values obtained are different for three sizes of beams. But, this should not be considered as size effect as the Eurocode formula depends only on the concrete cover and diameter of the bars, however, the true size effect is the effect of the dimensions of the structure on the overall fracture mechanism. As the structure becomes sufficiently large the size of the heterogeneity becomes negligible compared to the size of the structure and material follows a brittle failure. However, when the size of the structure becomes sufficiently small the size of heterogeneity becomes comparable to the size of the structure and the material and the material follows a ductile failure.

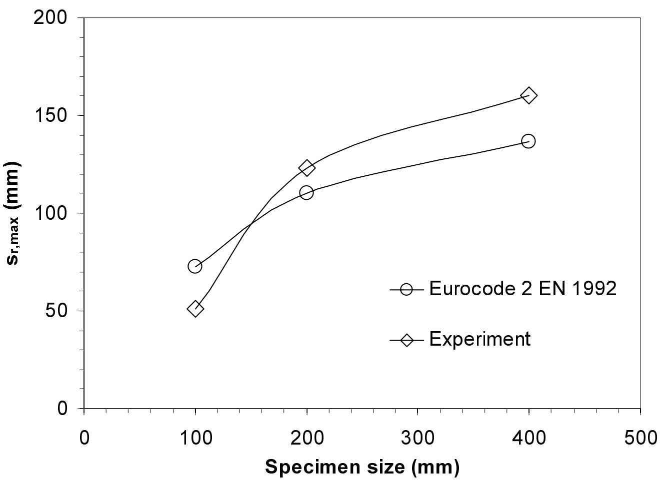

Figure 8. Maximum spacing of cracks, comparison of measured values with the calculated values.

The maximum spacing between cracks is also measured when steel stress was equal to 300 N/mm^2. This spacing is compared (Fig. 8) with the spacing obtained from the Eurocode formula (eq. 3). It is seen that is underestimated for the medium (D2) and large (D3) sized beam. The reason may be that the concrete becomes more brittle when the size of the beam increases. Thus the crack propagation is much faster (Alam & Loukili 2009) and energy release rate is higher in large structures (Kaplan 1961). However for small structures, crack propagation is much slower and strain energy is mainly released due to microcracking in the fracture process zone. Since the presence of reinforcement hinders the development of fracture process zone, more cracks are being formed to release the strain energy stored in the material.

6 CONCLUSION

An experimental investigation is performed to study the effect of structural size on crack width and crack spacing in reinforced concrete structures under service loadings. The results show that the measured values more or less agree with the calculated values at low strains and small beam size. But there is a significant size effect on the experimental crack width and crack spacing, which is not incorporated in the current Eurocode design formulas.

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