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Crack Width Investigation of Trapezoidal Precast Segmental Foundation

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Abstract: Maximum Crack width prediction formula proposed by various researcher indicates that each formula contains a different set of variables. This research presents a crack width investigation of trapezoidal precast segmental foundation under static loading. A literature review also suggests that there is no general agreement among various researcher on the relative significance of different variables affecting the crack width, despite the large number of experimental work carried out during the past few decades. An analytical method is developed to determine the concrete stress distribution near flexural cracks in reinforced concrete foundation and used to investigate the effects of various variables on width of cracks. The new formula is developed using a large number of curvature values calculated from the concrete and steel strains at various sections between adjacent cracks for a number of trapezoidal precast segmental foundation. The present method of incorporating the tension stiffening effect is verified by comparing calculated fracture mechanic and those measured by other researcher. The curvature values at sections between adjacent cracks are calculated using an empirical formula. Development of this formula is based on the curvature values calculated using the concrete and steel strains at various sections between successive cracks, for a number of composite precast foundation. Using the curvature values evaluated by the proposed formula, short-term deflections were determined for a large number of flexural members and the results were compared with those measured by other researcher. This comparison indicated that the present method of incorporating the tension stiffening effect in fracture mechanic calculations is acceptable. The results of this investigation showed that cracking was common for the bottom of precast segmental foundation under static loading; however, the crack width was usually within the design limits.

Keywords: Crack width, precast, foundation, formula, segmental

1. Introduction

Cracks in reinforced concrete structures can indicate major structural problems and detract from the appearance of monolithic construction. There are many specific causes of cracking.

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Cracking in reinforced concrete structures is unavoidable due to the low tensile strength of concrete. Wider cracks may not only destroy the aesthetics of the structure, but also expose steel reinforcement to the environment leading to corrosion. To control the crackwidth at the member surface, designers may use the guidelines prescribed in various building codes. These guidelines are based on certain crack width prediction formulas developed by various researchers.

Inspection of crack width prediction procedures proposed by various researchers indicates that each formula contains a different set of variables. A literature review also suggests that there is no general agreement among various researchers on the relative significance of different variables affecting the crack width, despite the large number of experimental work carried out during the past few decades. This is at least partly due to the differences in the variables incorporated by different researchers in their experimental work. Taking all the parameters in to account in a single experimental program is not normally feasible due to the large number of variables involved, and the interdependency of some of the variables. Analytical methods, on the other hand, can incorporate most of the variables without much difficulty. However, a literature search reveals that different researchers have concentrated on different sets of parameters in their calculation, to simplify the complex phenomenon of cracking in reinforced concrete. A major focus in this research is to incorporate as many parameters as possible in an analytical investigation.

Cracking in a reinforced concrete member also causes a significant increase in deflection. This is a result of the reduction of bending stiffness at cracked sections when the effect of tensile concrete below the neutral axis diminishes. However, at sections between successive cracks, some tensile stress is retained in the concrete around steel bars due to the action of bond, contributing to the bending stiffness of the member. This is called the "tension stiffening" effect. If the tension stiffening effect is neglected, the calculated defection may be overestimated by a large proportion. In simplified methods of deflection calculation, the tension stiffening effect is incorporated in a semi-empirical manner by using the effective moment of inertia method.

In analytical methods, the deflection is calculated using the curvature values, evaluated by adopting a non-linear stress-strain relationship for tensile concrete. This relationship allows the concrete to retain some tensile stress beyond the cracking strain. A new method is developed to evaluate the curvature values at sections between successive cracks by incorporating the bond force acting around steel bars in the calculation, instead of the concrete tensile force

2. Allowable crack widths in reinforced concrete

The maximum crack width that may be considered not to impair the appearance of a structure depends on various factors including the position, length, and surface texture of the crack as well as the illumination in the surrounding area. Crack widths in the range 0.25 mm to 0.38 mm may be acceptable for aesthetic reasons (Park & Paulay, 1975).

Table 1 - Setting Word's margins Maximum allowable crack widths.

Exposure condition	Maximum allowable crack width (mm)
Dry air or protective membrane	0.4
Humid, moist air or soil	0.3
De-icing chemicals	0.2
Seawater and seawater spray; wetting and drying	0.15
Water retaining structures	0.1

Crack width that will not endanger the corrosion of steel reinforcement depends on the environment surrounding the structure. Table 1. shows the maximum allowable crack widths recommended by ACI Committee 224 (ACI Committee 224, 1972) for the protection of reinforcement against corrosion. These values are taken as the basis for the development of rules prescribed in ACI 318 (ACI 318-89, 1990) for the distribution of tension steel to limit the crack width.

3. Causes of cracking

Cracks formed in reinforced concrete members can be classified into two main categories, namely cracks caused by externally applied loads, and those which occur independently of the loads (Wallenfelsz, 2006). Flexural cracks and inclined shear cracks are the two main types of cracks caused by external loads. Flexural cracks are formed in the tensile zone of the member and have a wedge shape, with the maximum crack width at the tension face and zero width near the neutral axis. Inclined shear cracks usually develop in thin-web beams when subjected to high shear forces (Wallenfelsz, 2006).

Internal micro-cracks fall into the other type of cracks caused by external load. These cracks occur as a result of high concrete stresses near the ribs in deformed bars, and are confined in the immediate neighbourhood of reinforcement without appearing on the concrete surface.

Cracks developed in restrained members due to concrete shrinkage or temperature change fall into the second category of cracks, which are independent of applied loads. In thin restrained members such as floor slabs these cracks may extend through the entire cross section, usually having an approximately uniform width. If the width of these cracks is not properly controlled, they may disrupt the integrity of the structure and reduce the bending stiffness considerably resulting in large deflections.

Table 2 - Crack widths formula proposed by various researchers.

No.	Investigator	Proposed Formula
1	Chi & Kirstein (1958)	$w_{max} = \frac{5\pi\phi}{E_s}\left(fs - \frac{428}{\pi\phi}\right)$
2	Broms (1965b)	$w_{max} = 2\,c\,\varepsilon_{s,ave}$
3	Broms & Lutz (1965)	$w_{max} = 4\,c_t\,\varepsilon_{s,ave}$
4	Venkateswarlu & Gesund (1972)	$w_{max} = \frac{2{,}4 \times 10^{-5}\phi\,(1462 - f_s)f_s}{1 + n\rho_m\,(662 - f_s)}$
5	Oh & Kang (1987)	$w_{max} = \{159\,(\phi_1)^{4{,}5} + 2{,}83(\phi_2)^{1/2}\} + (\varepsilon_s - 0{,}0002)\phi_2$
6	Beeby (1979)	$w_{max} = \frac{3\,a_{cr}\varepsilon_m}{\left(1 + 2\frac{(a_{cr} - c)}{(h - x)}\right)}$
7	Watstein, Parsons & Clark (1956)	$w_{max} = 1{,}29 \times 10^{-6}\left(\frac{h-d}{d}\right)\frac{\phi}{\rho}\left[2{,}56\,f_s - \left(\frac{1}{\rho} + 8\right)\right]$
8	Kaar & Mattock (1963)	$w_{max} = 1{,}57 \times 10^{-5} f_s\,\sqrt[4]{A_c}$
9	Gergely & Lutz (1968)	$w_{max} = \left[10{,}86\,\sqrt[3]{At_b}\,f_s\,\frac{h_2}{h_1}\right]10^{-6}$
10	Lan & Ding (1992)	$w_{max} = 1{,}41\,(2{,}7\,c + 0{,}11\,\phi/\rho_{te})\upsilon\;\;\varepsilon_s\,\psi$
11	Chowdhury & Loo (2001)	$w_{max} = 0{,}9\,\varepsilon_s\;\;(c - s_b) + 0{,}1\,(\frac{\Phi}{\rho})$
12	Ferry & Borges (1966)	$w_{max} = \frac{1{,}70}{Es}\left(1{,}5c + \frac{0{,}04\,db}{\rho_w}\right)\left(fs - \frac{0{,}75}{\rho_w}\right)$
13	Vis & Sagel (1987)	$w_{max} = 0{,}2\,\frac{ft'db}{\mu\,\rho_c}\,fs\,10^{-5}$
14	Hughes & Cifuentes (1988)	$w_{max} = 0{,}25\,\frac{ft'db}{\mu\,\rho_c}\,\frac{(1 + n\rho_c)}{(1 + 2n\rho_c)}\,\frac{fs}{Es}$
15	Rao & Dilger (1993)	$w_{max} = 2{,}55.\,10^{-6}\,fs\,dc\,(\frac{At}{As})^{0{,}5}$
16	Balazs (1993)	$w_{max} = 0{,}4\left[\frac{d_b}{\sqrt{f'_c}}\,\frac{f_s}{E_s}^{2}\right]^{1/1{,}4}$
17	Beeby & Narayanan (2000)	$w_{max} = 1{,}7\left(50 + k_1k_2\,\frac{db}{4\,\rho_e}\right)\frac{fs}{Es}\left[1 - \beta_1\beta_2\left(\frac{f_{sr}}{f_s}\right)^2\right]$
18	Padmarajaiah & Ramaswamy (2001)	$w_{max} = \frac{(D - x)}{(d - x)}\,\frac{4\,A_{cf}\,k_t\,\sigma_t}{k_b f_{bu}\,\Sigma\pi d}\,\frac{fs}{Es}$

Cracks belong to the construction method reinforced concrete. In many cases, structures can only be effectively designed by using the (cracked) state II. However, cracks also may endanger the structure. To ensure the protective alkaline environment to the steel enduringly, standards all over the world recommend higher concrete covers to achieve higher lifetimes. If the concrete cover were increased but the crack width could be kept small the hazards would be minimised. Potential hazards scenarios that are related to cracks are:

- uncontrolled deformation caused by steel yielding in the serviceability state
- easier access for chlorides and carbonisation to the steel as well as for oxygen, triggering corrosion
- weakened cross-section of steel following corrosion leads to a decreasing bearing capacity and larger steel strains
- internal pressure due to corrosion loads the bond area additionally leading to longitudinal cracking
- the foundation structures might be endangered by parting cracks and soil pressure in water-saturated cracks can destroy the cover during construction.

Because all internal processes cannot be simple described and are even worse to measure, common sense leads to the assumption to use the gaugeable crack width as scale for the endangerment of the structural member. It is possible to define limit states for serviceability corresponding to hazards to the proper functioning of the structure

Flexural cracks begin to occur when concrete stress in the tension face of a member reaches the flexural strength of concrete. After formation of a crack some elastic recovery takes place in concrete on the member surface, contributing to the crack width. However, some stress and strain is maintained in concrete surrounding the reinforcement due to the action of bond. This contributes to a reduction in the crack width near the bar compared to that at the tension face (Piyasena, 2002).

Flexural cracks in a varying moment region of a beam develop at a regular interval; however, in a constant moment region, these cracks develop at discrete intervals. Their locations depend partly on the occurrence and distribution of zones of local weakness in concrete, and therefore cracking is somewhat a random process (Piyasena, 2002). As a result, the exact locations of cracks in a constant moment region may not be predicted accurately. However, maximum and minimum spacing of adjacent cracks and the resulting maximum crack width may be predicted with sufficient accuracy by investigating concrete stresses developed in the tensile zone of a member.

The development of crack width (w) prediction formulas is usually based on calculated concrete stress distributions within the tensile zone of a member. Different researchers have used various simplified analytical procedures to determine the concrete tensile stress. While some analytical investigations are coupled with experimental works to verify the new prediction formulas, there are some investigations totally based on test results.

In most investigations, a uniaxial tension member has been used to simulate the conditions around steel bars in the constant moment region of a member. In experimental investigations, a concrete prism with a steel bar embedded along its axis is subjected to a tensile force applied to the two protruding ends of the bar. The resulting tensile cracks are considered to represent flexural cracks in a constant moment region of a beam. In analytical investigations the axial tensile stress distribution, developed in the concrete prism resulting from the bond force transferred from the steel bar, is calculated. This stress distribution is then used to predict the formation of new cracks in between existing cracks.

The literature review suggested that there is no general agreement among different researchers on the relative significance of various variables affecting the crack width, which sometimes leads to differing conclusions.

This is at least partly due to the absence of test data that describe the individual effects of each variable. Producing such a data set in the laboratory is expensive and time consuming because of the large number of variables involved, and due to the interdependency of some of the variables. A mathematical model capable of accurately predicting the spacing and width of cracks can be used to overcome this problem if it can include all variables involved in flexural cracking. This is not available at present, and is a main focus in this research.

Table 3 - Crack widths formula by various codes (AASHTO 2017).

No.	Code	Formula
1	CEB-FIP(1978) & NZS 3101 (1982)	$w_{max} = 1{,}7\left[2\left(c + \frac{s}{10}\right) + a_1 a_2 \frac{db}{\rho r}\right]\frac{fs}{Es}\left[1 - b_1 b_2\left(\frac{f_{sr}}{f_s}\right)^2\right]$
2	AASHTO (1996) & UBC (1997)	$w_{max} = \left[10{,}86\ \sqrt[3]{A t_b}\ f_s\ \frac{h_2}{h_1}\right]10^{-6}$
3	SNI 03-2847-2002 ACI 318-99 (1999)	$w_{max} = 11.\,10^{-6}\,\beta f_s\,\sqrt[3]{d_c\,A} \leq 0{,}30$
4	AS 3600 (2000)	$w_{max} = \frac{d_b f_s}{2\,\tau_m}\frac{1}{(1 + n\,\rho_s)}\frac{f_s}{2\,E_s}$
5	EC-2 (2000)	$w_{max} = 1{,}7\left(50 + k_1 k_2 \frac{db}{4\,\rho_e}\right)\frac{fs}{Es}\left[1 - \beta_1 \beta_2\left(\frac{f_{sr}}{f_s}\right)^2\right]$

4. Description of Test

To examine the crack width of a precast segmental foundation system on trapezoidal 12 foundation load tests were conducted. Concrete stress distribution patterns determined in formula are utilised in this experiment to predict the locations of cracks formed in a member when it is subjected to a gradually increasing load. Locations of primary cracks are determined based on the concrete stress distribution evaluated near the first flexural crack of the member. It is shown that the primary crack width in both constant and varying moment regions are governed by the slip length (bond length required to resist the steel stress increment at the first flexural crack). This prediction is verified by comparing the calculated and measured values of primary crack width in constant and varying moment regions.

Fig. 1 - Setting up of precast foundation test.

Fig. 2 - Precast foundation specimens.

Fig. 3 - Compression and Flexural test specimens.

The maximum crack width at a given load level is determined using the elastic extensions of steel and surrounding concrete. Using the present analytical procedure, the average maximum crack widths within constant moment regions are computed for 12 compression and flexural members at various load levels.

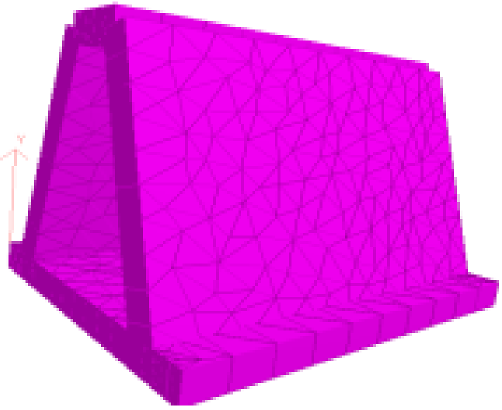

Fig. 4 - Finite element modelling.

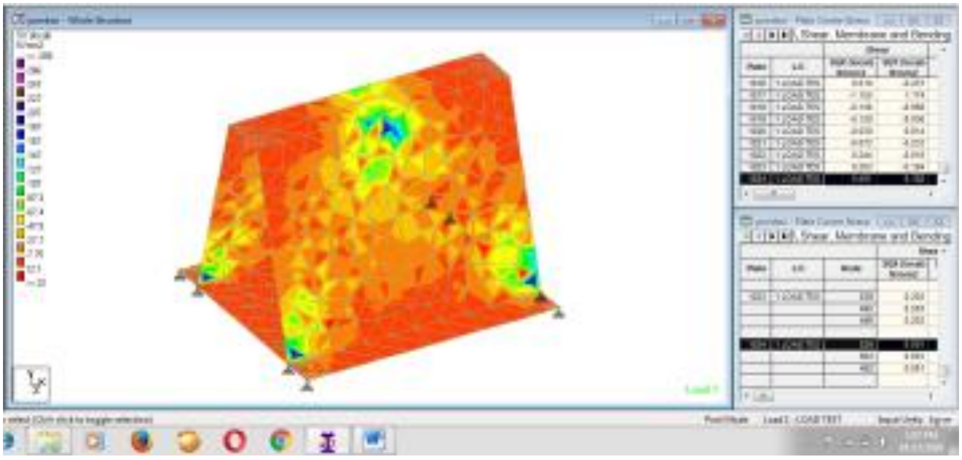

Fig. 5 - Analysis of precast foundation using software.

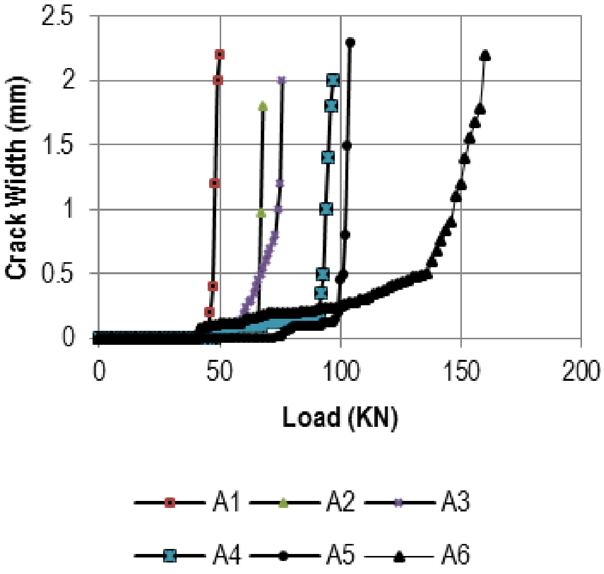

Fig. 6 - Variation of crack width and load level.

The accuracy of the proposed calculation method is verified by comparing the calculated width of cracks with the measured values

When a member is subjected to a gradually increasing load, the first flexural crack is developed at the location where the applied bending moment is equal to the cracking moment. Even in a prismatic member, the cracking moment may vary slightly along the length of the span due to the non-homogeneity of concrete and due to the presence of micro-cracks that may have occurred before the application of loading. Since the cracking moment M_{cr} is proportional to the flexural strength of concrete f_r, the possible variation of M_{cr} along the length of the slab is treated as a variation of f_r for convenience, in the following discussion.

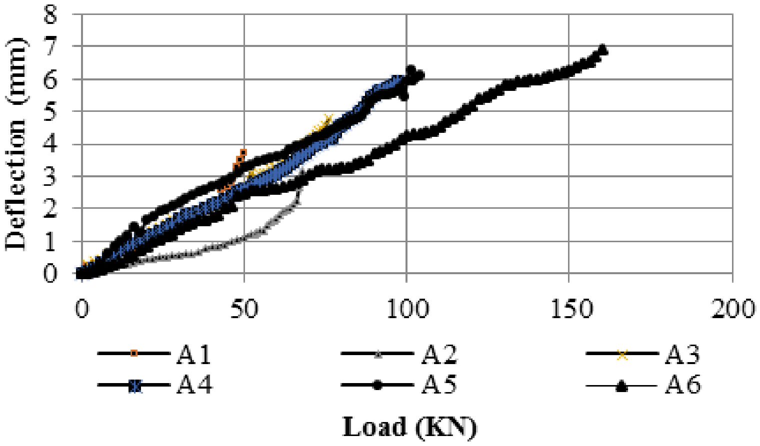

Fig. 7 - Variation of deflection with load for six types of reinforcement.

Consequently, it is assumed that a primary crack is formed when the calculated tensile stress f_{rc} at the tension face of the member reaches the flexural strength of concrete f_r.

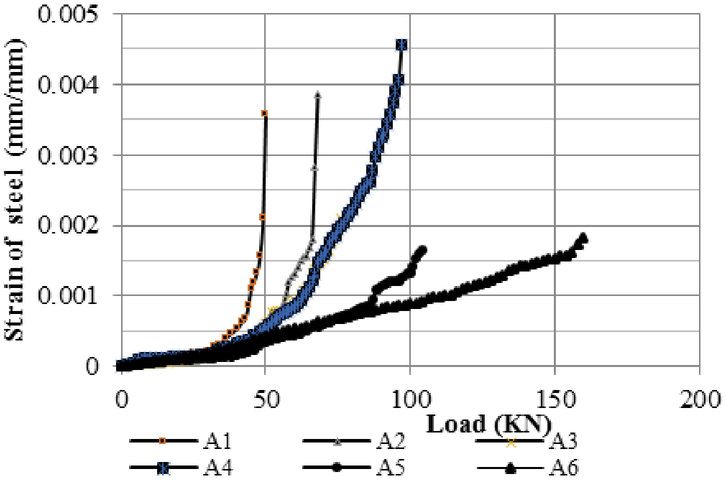

Fig. 8 - Variation of strain of steel with load level.

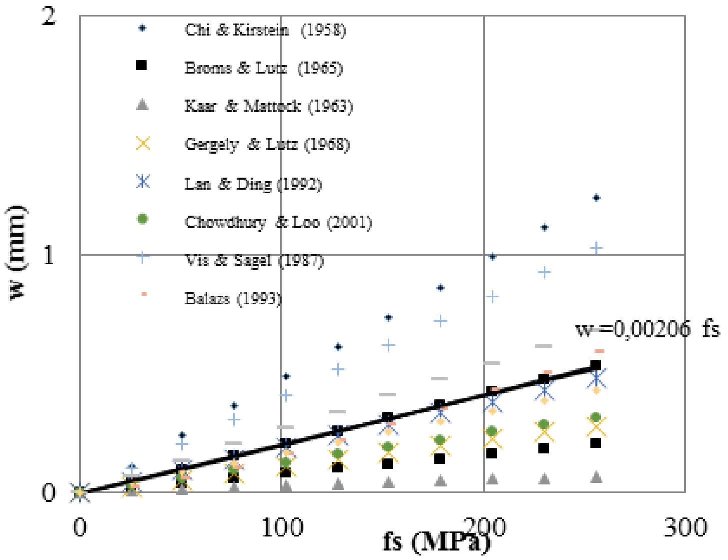

Fig. 9 - Variation of crack width (w) calculation with stress of steel (fs) for various investigators.

Crack widths in the critical regions were measured throughout the tests and provide important information regarding the onset of shear failure and concentration of failure along a single inclined crack plane. The single flexure-shear crack that ultimately resulted in shear failure was measured throughout all six tests (labeled tests A1, A2, A3, A4, A5 and A6).

Figure 6 shows measured crack widths for the six foundation tested. In the analysis approach the average crack width was determined as a function of the applied vertical load at midspan, with the assumption that the crack widths through the critical region would be approximately constant (this can be justified based on the tension-shift effect). The measured results in Fig. 6 demonstrate that this assumption was reasonable before the onset of shear failure.

Once shear failure started at displacements beyond peak force, the crack at a single critical location opened more than the other cracks, which tended to close or reduce in width. This critical location represents instability and localization of the response, and the final separation of the member occurred along this inclined failure plane. Theoretical and measured crack widths at the onset of shear failure were approximately the same for the three precast foundation at the critical crack location.

Figure 7 compares the deflections based on applied vertical load displacements and rigid-body geometry considerations with plastic rotations determined from summing the measured crack widths in Fig. 6. The similar results for all three decks demonstrate that all significant crack widths were measured accurately, as the measured deformation were found by summing individual load attributed to each considered crack.

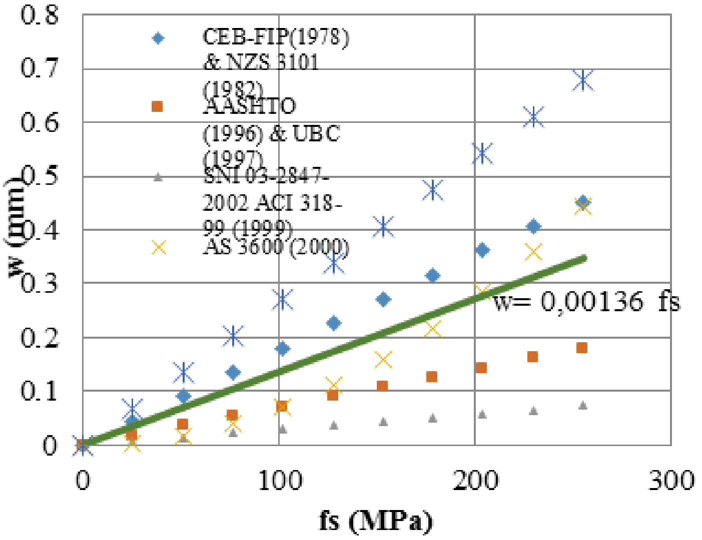

Fig. 10 - Variation of crack width (w) calculation with stress of steel (fs) for various codes.

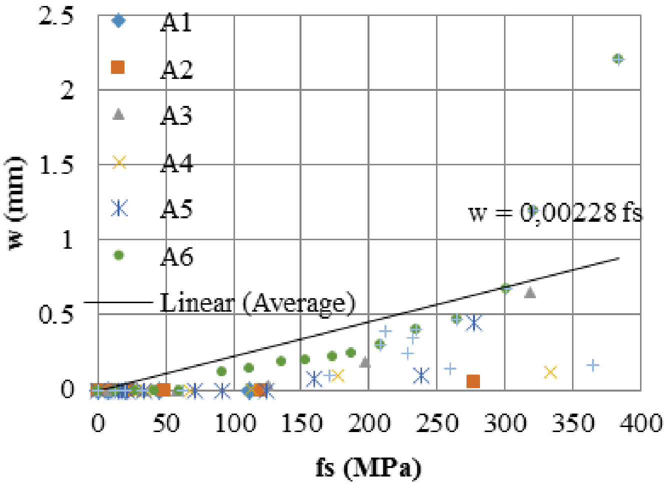

Fig. 11 - Variation of crack width (w) calculation with stress of steel (fs) by experimental results.

Theoretical plastic rotations were found based on the rigidbody geometry of a simple precast foundation with a concentrated plastic hinge at midspan. Similarly, based on this rigid-body model, displacements at midspan were determined from vertical load that were calculated from the measured crack widths. Midspan displacements derived from the measured crack widths compared well with the applied vertical displacements (Fig. 8). Overall, the results were similar, showing that most of the displacements came from three or four primary cracks, depending on the slab.

With the average crack width known from rigid-body geometry of the deformed test precast foundation, the concrete shear capacity can be determined directly from modified compression field theory. Necessary equations were developed to relate the vertical displacement at midspan, plastic rotation at the critical section, and average crack width through the critical region.

Although many investigations have been carried out on cracking of reinforced concrete flexural members, results of individual crack width are rarely available; only the average crack widths are reported most of the times.

Width of cracks in reinforced concrete members were determined using the calculated concrete stress distributions near flexural cracks. To calculate the stresses, a free body concrete block bounded by top and bottom faces and two transverse sections of the member was isolated and analysed using the spreadsheet.

Cracks initially formed in flexure, extending vertically from the extreme tension face of the concrete. As the load and displacement increased, the cracks extended up the section height. The first crack that formed was at the maximum moment location, directly under the applied load at midspan. This crack continued to widen and extend vertically with increasing displacement. At some point in the loading sequence, two additional flexural cracks formed, one on either side of the first crack. These two cracks were subjected to significant shear, and after widening and extending vertically they started to rotate toward the point of load application, becoming flexure-shear cracks.

An investigation in to the effects of various variables on the width of cracks revealed the following:

1. An increase in the width of the member or the concrete cover increases crack width if other variables are kept unchanged.
2. Concrete strength has no appreciable effect on the crack width, if other variables remain unchanged.
3. An increase in the number of bars, by reducing the bar diameter to have the same reinforcement ratio, will reduce width of cracks.
4. The steel stress at the cracked section will reduce the crack spacing while it increases the crack width.

5. Conclusion and Recommendation

Based on the results of a parametric study, simplified formulas were developed for the prediction of maximum crack width. A comparison of predicted crack widths for the flexural members and the measured values reveals that the proposed formulas perform adequately. In particular, the predictions of these formulas have almost the same accuracy as the results of the various investigators and various codes.

The proposed formula for precast trapezoidal precast segmental foundation is:

$$w_{max} = 3{,}38.\,10^{-4}\,\frac{(1+0{,}07.c)}{\left(1+\frac{16.n.\bar{\rho}}{3}\right)}\;p\;fs\;(mm) \qquad (1)$$

Where,

w_{max} = maximum crack width (mm)
c = depth of concrete cover (mm)
n = modular ratio of steel and concrete
$\bar{\rho}$ = reinforcement ratio
fs = stress of steel reinforcement (MPa)
p = precast modification factor

Analytical results of crack widths are greatly influenced by the assumed bond stress distribution and bond stress-bond slip relationship. The constitutive relationships proposed by different investigators vary considerably. Further research in to the measurement of bond stress and bond slip is proposed.

It was shown that the crack width increases with concrete cover. In spite of this, provision of a large cover is considered to be the most practical means of protecting the reinforcement against corrosion. Further research in to the effect of varying concrete cover on the crack width is proposed.

The proposed analytical procedure can also be extended to determine the increase in the crack width with time by incorporating the creep and shrinkage effects in the calculation of concrete and steel strains.

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