FURTHER STUDIES ON FLEXURAL CRACK CONTROL IN STRUCTURAL SLAB SYSTEMS

By EDWARD G. NAWY and KENNETH W. BLAIR

This paper is a consolidation of almost all available studies on the flexural cracking behavior of two-way action slabs and plates. An analysis is made of the test results of ninety two-way action slabs both rectangular and square and having various boundary conditions. Loads varied from concentrated load simulating column reaction on flat plates, to uniformly distributed load. Reinforcement used varied from smooth to deformed welded wire fabric to rebars. The clear spans of the test slabs ranged from 5 ft 8 in. x 5 ft 8 in. (1.724 x 1.724 m) to 5 ft 0 in. x 5 ft 0 in. (1.524 x 1.524 m) to 5 ft 0 in. x 3 ft 6 in. (1.524 x 1.067 m). Their effective depths ranged from 1.25 in. (3.17 cm) to 3.50 in. (8.89 cm), while the total thickness of the test slabs ranged from 2.5 to 4.0 in.

A fracture hypothesis is presented and a grid index is proposed as an indicator of the controlling flexural cracking pattern to be expected at loads up to 75-80 percent of the ultimate. It is shown that apart from the reinforcement stress level the major controlling parameter is the spacing of the reinforcement in the two orthogonal directions of a two-way action structural slab or plate. The diameter of the reinforcement and the concrete cover were the other parameters that influenced the behavior of slabs, but to a lesser degree.

Criteria are proposed for use by the design engineer in exercising crack control in two-way action slabs, plates, and flat plates of various boundary conditions. The proposed equation is applied to other large scale and full scale tests made by several investigators and found valid. The extent of the work is such that codification of the recommendations is possible for direct application in crack control design of structural slab systems.

Keywords: concrete slabs; cracking (fracturing); flat concrete plates; flexural strength; fracture properties; loads (forces); plates (structural members); reinforced concrete; reinforcing steels; research; restraints; serviceability; two-way slabs; welded wire fabric; yield-line method.

☐ Flexural crack control in reinforced concrete floor systems has become vitally important. Increased use of high strength reinforcement in concrete and the application of ultimate load procedures in the design of concrete structures require more attention to serviceability conditions, of which crack control is a major element. Since most framed floors are proportioned for two-way action, existing criteria[1] for crack control in beams cannot be safely applied to slabs.

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This paper is a consolidation of almost all available studies thus far on the flexural cracking behavior of two-way action slabs and plates. An analysis is made of the test results of 90 two-way action slabs, both rectangular and square and having various boundary conditions. The intent is to develop recommendations to the engineering profession for crack control in framed structural floor slabs and plates.

Loads applied to the test slabs varied from concentrated load, simulating column reaction on flat plates, to uniformly distributed load, accomplished by use of pressure rubber bags. The reinforcement in the various test series was varied from smooth to deformed welded wire fabric to rebars. The clear spans of the test slabs ranged from 5 ft 8 in. x 5 ft 8 in. (1.724 x 1.724 m) to 5 ft 0 in. x 5 ft 0 in. (1.524 x 1.524 m) to 5 ft 0 in. x 3 ft 6 in. (1.524 x 1.067 m). Their effective depths ranged from 1.25 in. (3.17 cm) to 3.50 in. (8.89 cm), while the total thickness of the test slabs ranged from 2.5 to 4.0 in.

The analytical part of the investigation was based on the fracture hypothesis previously formulated and tested by the first author,[2,3] giving a mathematical model which can predict the flexural cracking pattern in two-dimensional members. As a result, a basic equation for crack control in two-way action slabs and plates of varying degrees of restraint at the boundaries is proposed.

Through choice of the proper fracture coefficient, the designer can control the flexural crack width in the negative region of reaction zones of flat plates as well as in the negative and positive moment regions of two-way action slabs and flat slabs. A grid index is given as a guide for governing the primary failure pattern which controls the crack width.

CONTROL TESTS

High early-strength cement was used in the concrete mix of all the slabs. Crushed stone of maximum size 3/4 in. and graded local sand were used. The mix was vibrated with electric vibrators in the forms and the specimens were cured for varying periods, as shown in Table 1-A1 of the appendix. Six control cylinders 6 x 12 in. (15.24 x 30.5 cm) were taken from each slab mix, cured under the same curing conditions as the test slabs, and tested the same day that a corresponding slab was tested. Half the number of cylinders was tested in compression and the other half in tensile splitting.

Control specimens were also taken from the wire as well as the rebar steel reinforcement to establish their yield and ultimate strengths. Tables 1-A1 gives the yield strength for the various sizes and types of steel. A typical stress-strain diagram of representative reinforcement is given in Fig. 1-1.

TESTING PROGRAM

Eight series of two-way action slabs (90 slabs) were tested to failure in this research program. Details of their geometrical properties are given in Table 1-A1. The test series comprised the following.

Restrained Centrally Loaded Slabs (Series CSF1–CSK1)

Ten slabs were tested in this series. They were 7 ft 10 in. x 7 ft 10 in. (2.388 x 2.388 m) in over-all area, while the clear span was 5 ft 8 in. (1.724 m) in each direction. They were fully restrained on all four sides and the load was transmitted to the center of each slab through a hydraulic ram system over an area of 6 x 6 in. (15.24 x 15.24 cm). The slabs were reinforced with smooth welded wire fabric in two similar layers at top and bottom to provide for positive and negative moment. The size and spacing of the reinforcement were varied to extremes (see Table 1-A1).

Shear reinforcement was also provided in the form of horizontal mats and vertical cages over an area 24 x 24 in. (61.0 x 61.0 cm) at the center to prevent premature punching failure. The slabs in this series simulated column reaction zones in flat plate structures.

Simply Supported Centrally Loaded Slabs (Series SA1–SE3)

Twelve slabs were tested in this series. They were simply supported on all four sides on 2 in. (5.08 cm) wide supports. Corners were not held down. The over-all side length in each direction was 6 ft 2 in. (1.88 m) and the clear span was 5 ft 8 in. (1.724 m). They were reinforced with one layer of flexural reinforcement at the bottom whose sizes and spacings were varied to extremes. They were loaded in a manner identical to Series CSF1–CSK1, previously described. Shear reinforcement was also similar.

Uniformly Loaded Square Slabs Restrained on All Sides (Series WS1–WV7)

Thirty-nine slabs were tested in this series. They had an over-all area of 7 ft 0 in. x 7 ft 0 in. (2.134 x 2.134 m) and the clear span was 5 ft 0 in. (1.524 m) in each direction. They were fully restrained on all four boundaries, representing the interior panel of a multi-panel floor system. Uniformly distributed load was applied through a 3/8 in. thick rubber bag of size 5 ft 0 in. x 5 ft 0 in. (1.524 x 1.524 m). In slab tests WS1 through WS32, the bag was filled with nitrogen gas to develop the pressure, while in tests WV1 through WV7 water was used. Pressure was accomplished through a specially designed check-valve system.

Reinforcement was either deformed welded wire fabric of diameter ranging from 0.159 in. (4.0458 mm) to 0.331 in. (8.4074 mm) or #3 rebars (9.53 mm diameter). Two similar layers of two-directional reinforcement, one at the top and one at the bottom, were used in each slab to account for positive and negative bending moments. A central area 24 x 24 in. (61.0 x 61.0 cm) was removed from the negative reinforcement mat to eliminate the possible effect of compression steel on cracking in the positive moment region. The reinforcement diameter and spacing were varied to extremes to observe their effect on the flexural cracking behavior.

Total thickness was either 3 in. (7.62 cm) or 2.5 in. (6.35 cm), and the average effective depth varied between 1.21 in. (3.062 cm) and 2.62 in. (5.237 cm), as given in Table 1-A1. This series of tests could simulate in crack control study the behavior of an interior square panel of a multi-panel floor system.

Uniformly Loaded Square Slabs Restrained on Three Sides and Hinged on One Side (Series WV8–WV12)

Five slabs were tested in this series. They had properties similar to those of the previous uniformly loaded series, except that one side was a hinged support. Total thickness was 2.5 in. (6.35 cm) and the average effective depth was 2.0 in. (6.08 cm). Rubber bag pressure was developed through use of water. This series was intended to simulate a uniformly loaded square end panel of a multi-panel floor system.

Uniformly Loaded Square Slabs Restrained on Two Sides and Hinged on the Other Two (Series WV13–WV17)

Five slabs were tested to failure in this series. Their properties were similar to those of the previous uniformly loaded series (WV8–WV12), except that two adjacent sides were hinged supports. This series was intended to simulate a uniformly loaded square corner panel of a multi-panel floor system.

Uniformly Loaded Rectangular Slabs Restrained on All Sides (Series WV18–WV29)

Twelve slabs were tested to failure in this series. Each slab had a clear span of 5 ft 0 in. x 3 ft 6 in. (1.524 x 1.067 m). The total thickness was 2.5 in. (6.35 cm) and the average effective depth ranged between 1.21 in. (3.07 cm) and 2.0 in. (5.08 cm). Steel reinforcement was either deformed welded wire fabric of diameter ranging from 0.177 in. (4.495 mm) to 0.342 in. (8.687 mm) or #3 rebars (9.53 mm diameter). Reinforcing was in two similar layers on top and bottom, as in the previously described uniformly loaded square slabs. Load was applied through a rubber pressure bag 5 ft 0 in. x 3 ft 6 in. (1.524 x 1.067 m) in area and filled with water under a specially designed pressure control system. This series was intended to simulate an interior rectangular panel of a multi-panel two-way action floor system for crack control study.

Uniformly Loaded Rectangular Slabs Restrained on Three Sides and Hinged on One Side (Series WV30–WV33)

Four slabs were tested to failure in this series. Their size and reinforcement patterns were similar to those of the previous series WV18–WV29, but their total thickness had a constant value of 2.5 in. (6.35 cm) and an effective depth of 2.0 in. (5.08 cm). They also differed in that one of the four sides (the 5 ft 0 in. side) was a hinged support.

Uniformly Loaded Rectangular Slabs Restrained on Two Sides and Hinged on the Other Two (Series WV34–WV36)

Three slabs were tested to failure in this series. Their geometrical properties were generally identical to those of the previous series WV30–WV33 (see Table 1-A1), except that they differed in their boundary conditions. The slabs in this series had two adjacent edges restrained and the other two were hinged supports. They could reasonably simulate the corner panel of a multi-panel two-way action floor system for investigation of crack control behavior.

TESTING PROCEDURE

Load was generally applied in ten increments at intervals of approximately eight minutes between each two increments of load. Three minutes were allowed for the hydraulic pressure to stabilize itself before readings were taken. Deflection was measured with 4 in. travel dials located at the center of each slab and at quarter points both on the principal axes and the diagonals. Corner lift in those specimens which were simply supported was also measured. The deflection dials had an accuracy of 0.001 in.

The crack widths were observed with powerful illuminated microscopes of 0.001 in. accuracy. In the centrally loaded series, crack widths were read outside the 6 x 6 in. loading area and at each increment of load up to failure. Strain in the instrumented steel reinforcement was recorded through electric strain gages via a 96-channel electronic scanner recorder operating at a speed of one channel per second. The strain output was also monitored directly on a card punch system for prompt evaluation at the Rutgers Center for Computer and Information Services.

It was important to locate precisely the position of each reinforcement gage in the finished slab, so that direct correlation between crack width and steel stress could be made. This was accomplished through keeping an accurate record of the coordinates of each electric gage and maintaining these coordinates while placing the concrete. Accuracy of the applied load was maintained in the centrally loaded test slabs through use of proving rings. In the uniformly loaded slabs, bag pressure was read simultaneously on a mercury manometer and a calibrated pressure gage. Magnitude of restraint at the boundaries was measured through evaluating the degree of rotation of the edges using inclinometers.

FRACTURE HYPOTHESIS IN TWO-WAY ACTION SLABS AND PLATES

As proposed by the first author in References 2 and 3, stress concentration develops initially at the points of intersection of the reinforcement in the rebars and at the welded joints of the wire mesh, namely, at grid nodal points A_1, B_1, A_2, and B_2 in Fig. 1-2. This stress concentration causes plastic deformation of the concrete at these locations as a result of the energy imposed by the external load per *unit area* of slab. The bond between the bar or wire and the concrete at these locations is destroyed and active cleavages start to generate fracture lines towards the paths of least resistance. Planes of discontinuity, which are paths of least resistance, are the interaction surfaces between the reinforcement grid lines and the surrounding concrete gel, namely, A_1B_1, A_1A_2, A_2B_2, and B_2B_1. The resulting fracture pattern is a total repetitive cracking grid, provided the spacing of the nodal points A_1, B_1, A_2, and B_2 is close enough to generate this preferred initial fracture mechanism of orthogonal cracks narrow in width.

If the spacing of the reinforcing grid intersections is too large, the magnitude of the stress concentration and the energy absorbed per unit grid is too low to generate cracks along the reinforcing wires or bars. As a result, the principal cracks follow diagonal yield-line cracking in the plain concrete field (Fig. 1-2) away from the reinforcing bars early in the loading history. These cracks are wide and few.

This hypothesis also leads to the determination that surface deformations of the individual reinforcing elements have little effect in arresting the generation of the cracks or controlling their type or width in a two-way action slab or plate. This conclusion about the effect of surface deformations was also observed by University of Illinois tests.[4,5,6] In a similar manner one can also conclude that scale effect on two-way action cracking behavior is insignificant, since the cracking grid would be a reflection of the reinforcement grid if the preferred orthogonal narrow cracking widths develop.

Therefore, for control of cracking in two-way action floors, the major parameter to be considered is the spacing of the reinforcement in the two perpendicular directions. Concrete cover has only minor effect in such slabs, since it is usually of a constant small value of 3/4 in.

For a constant area of steel determined for moment in one direction, namely, for energy absorption per unit area of slab, the smaller the spacing of the transverse bars or wires, the smaller should be the diameter of the longitudinal bars. The reason is that less energy has to be absorbed by the *individual* longitudinal bars. If one considers that the magnitude of fracture is determined by the energy imposed per specific surface-volume of reinforcement (see Reference 7), then proper choice of the reinforcement grid size, namely, the distribution of the bar or wire intersections, together with the bar size, can control cracking into preferred orthogonal grids.

It must be emphasized that this hypothesis is important for serviceability and reasonable overload conditions. In relating orthogonal cracks to yield-line cracks, the failure of a slab *ultimately* follows the generally accepted rigid-plastic failure mechanism proposed by Johansen and extended by others.

Fig. 1-3a to 1-3f show typical cracking patterns of two-way action slabs. In comparing these slabs, it is seen that early development of extensive, closely spaced orthogonal cracking grids reflects the reinforcement grids whose locations are shown by the straight lines in the pictures. At failure, yield-line rupture mechanisms have to develop as seen in Fig. 1-3f.

As a result of the proposed fracture hypothesis, and on the basis of statistical analysis of the test data of the 90 slabs tested to failure, a basic cracking equation is proposed as follows:

$$w_{max} = K\,R\,f_s\,\sqrt{I}$$

where

w_{max} = maximum crack width at concrete face, in.

K = fracture coefficient dependent on loading and boundary conditions

R = cover ratio (1.25 on the average) = ratio of distance from neutral axis to tensile face of slab to distance from neutral axis to centroid of reinforcement grid

f_s = reinforcement steel stress (ksi) at service load level, and

I = Grid Index = $(\phi_1 s_2)/p_{t_1}$ (sq. in.), where ϕ_1 is diameter of reinforcing steel in direction "1" closest to concrete outer tension face, s_2 is spacing of reinforcing steel in direction "2" perpendicular to direction "1", and p_{t_1} is active steel ratio in direction "1" (see Notation).

Details of the fundamental formulation of the mathematical model resulting in Eq. (1) are given in Reference 3.

The grid index is proposed as an indirect measure of whether initial orthogonal narrow cracks or wide yield-line cracks control the behavior of a two-way action slab or plate. In summary, the parameters of Eq. (1) are based on the two-way action flexural cracking behavior in directions "1" and "2" as almost all slab systems are subjected to.

ANALYSIS OF TEST RESULTS

General

In analyzing the test results of the eight series of test slabs totaling 90 slabs, the geometrical properties of the concrete stretched cracked zones listed in Table 1-A2 of the appendix were applied to Eq. (1). A series of plots was developed in Fig. 1-4a to 1-4h, with the best lines of fit for each loading and boundary condition as shown. It is noted in all the diagrams that almost all the data fell within a 45 percent band of deviation about the best line of fit. It is also noted that the fracture coefficient K is inversely proportional to the degree of restraint at the supports.

Table 1-1 lists the values of K for the various loading and boundary conditions. Table 1-2 lists the observed and computed crack widths at reinforcement steel stress levels of 20 ksi (1406 kg/cm^2), 30, 35, 50, and 60 ksi (4219 kg/cm^2). The mean of the ratio of observed to predicted crack widths ranged between 0.844 and 1.088, in most cases less than but close to 1.0 at the 30 ksi stress level. This level can be generally considered as the upper bound limit of serviceability stress expected in normally loaded two-way action concrete structural floors, while 24 ksi (40 percent f_y = 60 ksi) is the more realistic level at present. The standard deviation ranged between 0.107 and 0.217 at this stress level. Such magnitude of deviation is not unexpected in the random phenomenon of cracking in concrete.[8]

Table 1-2 shows that the proposed cracking equation for two-way action slabs and plates generally overestimates the predicted crack width by 5 to 10 percent in the various cases. The ACI 318-71 Code[1] Z equation for crack control in beams (and one-way slabs) underestimates by considerably more than 62 percent the predicted crack width, whether in one-way slabs or in two-way action floors[9] of standard concrete cover. Hence these Code provisions cannot be safely applied to control cracking in two-way slabs, flat slabs, or plates, and could result in unrealistic values of reinforcement spacing in concrete floors. Eq. (1) of this investigation, on the other hand, can be equally applicable to one-way slabs using a K value of 1.6×10^{-5} shown in Table 1-1.

Centrally Loaded Slabs Series SA to CSK

In series SA, SE, CSF, and CSH, simulating column reaction zones of flat plates, the crack pattern followed closely the reinforcement pattern as seen in typical Fig. 1-3a, with the cracks being spaced at 4 to 4½ in. The Grid Index = $\phi s/p_t$ did not exceed 150 (see Appendix Table 1-A2) and the active steel ratio ranged between 0.75 and 2.0 percent. The yield mechanism developed drastically when the load was close to 80 percent of the collapse load. The widths of the orthogonal cracks which controlled up to that load level were narrow (see Table 1-2), and the yield-line cracks were also narrow as compared to crack widths in the other slabs in the centrally loaded group which had larger reinforcement spacings.

Series SB, SC, SD, CSG, CSI, CSJ, and CSK had reinforcement spacings varying between 8 x 8 in., 6 x 12 in., and 8 x 4 in. The grid indices ranged in value from 235 to 865 sq in., and the active steel ratio ranged from 0.19 to 0.5 percent. The yield-line mechanism in this series developed early in the loading history of each slab, namely, at about 35 to 50 percent of the ultimate load. Very few orthogonal cracks developed, and the widths of all the cracks were appreciably larger than the cracks developed in the previously discussed slabs (see Table 1-2). Fig. 1-3b is typical for centrally loaded slabs where yield-line cracking controlled throughout the loading range.

Square Uniformly Loaded Slabs Restrained on All Boundaries

Series WS1 through WS10; WS20-23; and WV1, 2, 4, and 5 can simulate an interior square panel of a multi-panel floor system. The reinforcement spacing was either 3 x 3 in. or 4 x 4 in., and their grid indices ranged between 78 and 327 sq in. The active steel ratio ranged between 0.48 and 1.17 percent. The dominant cracks were orthogonal and narrower than most of those discussed later. They were mostly an image of the reinforcing grid pattern. Fig. 1-3c is typical for crack width development in slabs whose grid index falls within this level.

Most of the others in the WS Series were reinforced with deformed welded mesh reinforcement at spacings of 4 x 8 in., 6 x 6 in., and 8 x 8 in., as given in Table 1-A1. Slab WV7 was reinforced with deformed #3 rebar (3/8 in. dia) spaced at 9½ x 9½ in. (24 x 24 cm). All these slabs developed dominant yield lines of considerably wide cracks early in their loading history. The values of the grid indices were generally in the range of 266 to 865 sq in. The use of deformed rebars did not reduce the crack widths, supporting the hypothesis that only the reduction in bar spacing can reduce the crack widths. Fig. 1-3d shows a typical slab in this category at failure, whether square or rectangular.

Uniformly Loaded Square Slabs Partially Restrained

Series WV8, 10, 11, 16, and 17 can simulate the end panels of multi-panel floor systems. The reinforcement spacing of 4 x 4 in. or 6 x 6 in. and their grid indices did not exceed 327 sq in. in value. The active steel ratio did not exceed 0.67 percent. Again, the dominant controlling cracking was orthogonal, narrow flexural cracking even though not all the edges were restrained, but one or two of the edges hinged.

Series WV9, 12, 13, and 15 had reinforcement spacing 8 x 8 in. for deformed welded fabric or 9½ x 9½ in. for deformed rebars (see Table 1-A1). The grid indices were in some cases in excess of 654 sq in. Wide yield-line diagonal cracks controlled early in their loading history and were very few in number, whether in the slabs reinforced with deformed welded fabric or deformed rebars.

Rectangular Uniformly Loaded Slabs Restrained on All Boundaries

Series WV19, 20, 21, 27, and 28 simulating a rectangular interior panel of a multi-panel floor system, had reinforcement spacings 3 x 3 in. or 4 x 4 in., and their grid indices ranged in value between 77 and 168 sq in. The controlling crack widths developed in these slabs and given in Table 1-2 at various stress levels were mainly orthogonal and narrow. A typical slab at failure is shown in Fig. 1-3e, giving a crack pattern reflecting the reinforcing pattern. The other slabs in this series developed wide diagonal yield-line cracks early in their loading history because of the high value of their grid indices.

Rectangular Uniformly Loaded Slabs, Partially Restrained

Series WV18 and WV22-26, simulating end panels of multi-panel floor systems, were reinforced with either deformed wires or 3/8 in. diameter deformed rebars at 8 x 8 in., 9½ x 9½ in., or 12 x 12 in. The grid index in WV23 had a high value of 1086 sq in., while the others in this group ranged between 327 and 653 sq in. It is seen from Table 1-2 that in the case of the widely spaced reinforcement, regardless of type, the crack width at the 20 ksi level was as high as 0.015 to 0.020 in. (0.6 to 0.8 mm). As predicted in the fracture hypothesis previously outlined, few very wide diagonal yield-line cracks developed early in the loading history and their number remained stationary up to failure.

Reinforcement in One Direction Only

Previous studies by the first author[10] included tests on one-way slabs where spacing of transverse reinforcement was up to 16 in. (40 cm). These tests, as well as those in References 4, 5, and 6, have shown that even if the spacing of transverse bars is infinite, cracks would develop at spacings not in excess of 12 in. (30 cm) for rational percentages of longitudinal steels. They have also shown that no significant difference exists in crack spacing whether the reinforcing element were smooth or deformed.

This is in conformity with the hypothesis previously presented, since concrete can withstand a tensile stress not in excess of 400 psi (28.1 kgf/sq cm) before fracture. Hence, in cases where only longitudinal steel is used, such as in the negative region of some flat plates or slabs, or in one-way slabs, a value of s_2 not exceeding 12 in. (30 cm) can be used in Eq. (1). This is also justified because the transverse spacing s_2 in Eq. (1) reflects essentially the spacing of cracks perpendicular to the spacing s_1 of the longitudinal steel closest to the concrete outer tensile fibers.

Comparison with Tests by Others

Limited crack width measurements in test results on two-way action slabs by other investigators are available. Those available involve only a few slabs in any research program, and in most cases either one or two per program. The crack control equation developed as a result of testing 90 slabs in the present investigation was applied to other large-scale and prototype tests listed in Table 1-3. Good agreement is found between the measured and the predicted crack widths, as seen from comparing values in Column 9 to those in Column 12 of Table 1-3 and from the closeness of the data points to the prediction line shown in Fig. 1-5. It can be concluded from this comparison that scale effect is insignificant in crack width evaluation in two-way action slabs and plates, and that the proposed equation gives reasonable prediction of flexural cracking behavior.

DISCUSSION SUMMARY

Summarizing the behavior of the 90 test slabs in this research program, it can be seen from the analysis of the test results that crack width development in