

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 criteria¹ 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.



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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 re-bars (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 = $(\phi_1 s_2)/p_{t1}$ (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_{t1} 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/cm²), 30, 35, 50, and 60 ksi (4219 kg/cm²). 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 Code¹ 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 floors⁹ 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 = ϕ_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 author¹⁰ 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

two-way action floors is a function of the grid index

$$I_1 = (\phi_1 s_2) / p_{t1} \quad (\text{or} \quad I_1 = \frac{s_1 s_2 t_b}{\phi_1} \cdot \frac{8}{\pi})$$

in the general crack control Eq. (1), where $w_{\max} = KRf_s \sqrt{I}$. The reinforcement spacing in the two perpendicular directions is a major parameter of this proposed index, while the diameter of the reinforcement and the active steel ratio are the two secondary parameters.

Application of the cracking equation to the test results was adequately tested both qualitatively, through observation of behavior as discussed, and quantitatively, through comparison of measured to predicted values, as in Table 1-2. The proposed fracture hypothesis was thus found valid and the proposed cracking equation safe to apply.

Also, for a constant area of steel determined for moment in one direction, the energy hypothesis that smaller spacings of transverse bars require smaller diameter of longitudinal bars was maintained in the design of the experiments. The test results are in conformity with this principle when comparisons are made for the developed crack widths and spacings of the test slabs for various combinations of diameter ϕ_1 with spacing s_2 , and diameter ϕ_2 with spacing s_1 . Bar or wire spacings not exceeding 6 to 8 in. (15-20 cm) force the generation of the preferred grid of numerous narrow orthogonal controlling cracks. To proportion the reinforcement in the two orthogonal directions for achieving this purpose, it is only necessary for the designer to evaluate the predicted possible maximum width w corresponding to a grid index I_1 in direction "1" closest to the concrete tensile outer fibers.

Furthermore, the predicted crack width $w = KRf_s \sqrt{I}$ of Eq. (1) can be presented in tabular as well as graphical form for the various fracture coefficients K describing the load and the boundary conditions applicable to the particular floor. Typical Fig. 1-6 gives a graphical solution of Eq. (1) at reinforcement stress level $f_s = 40$ percent $f_y = 24$ ksi for the K values of 1.6 to 4.2 described in Table 1-1.

A stress level of 40 percent of the yield strength of steel is chosen as the upper limit of serviceability stress to which a framed floor slab can be practically subjected at present. Steel of yield 60 ksi is commonly used today as reinforcement in floor slabs; hence 24 ksi level steel was used for constructing Fig. 1-6, while similar charts for higher stresses can be easily prepared. This diagram can be readily utilized for crack control evaluation with minimal computational effort, once the design engineer determines the maximum width of a flexural crack he can tolerate for the particular exposure condition. Table 1-4 summarizes acceptable permissible crack widths under various exposure conditions, discussed further by the first author in Reference 15 and also in Reference 1.

Eq. (1) was also verified by application to tests of both full-scale floors and smaller-scale models by other investigators. Very close agreement was obtained between the predicted and measured crack width values. Scale effect was found insignificant in two-way action, as predicted in the fracture hypothesis.

examples are given in the appendix to illustrate the simple application of the developed crack control hypothesis to structural slabs and plates.

CONCLUSIONS

1) Codification for crack control in two-way action slabs, flat plates and flat slabs is now possible as a result of this investigation. It is also necessary in view of increased use of high strength steel of 60 ksi yield or higher in slabs.

2) Crack control provisions for beams in the ACI Building Code 318-71 are inapplicable and unsafe to apply to two-way action floors. They also result in unrealistic and unsafe reinforcement spacings in one-way slabs having standard 3/4 in. cover.

3) The major parameter controlling the cracking behavior of a two-way system, apart from the reinforcement stress level, is the spacing of the intersecting bars or wires in the two orthogonal directions, while the diameter of the reinforcement and the active steel ratio are the two secondary parameters. Effect of the surface deformations of the steel is negligible.

4) Crack control is accomplished through development of numerous narrow orthogonal cracking grids reflecting the reinforcement grids, rather than through a few wide diagonal yield-line cracks. The grid index I is found to be a good indicator in proportioning the reinforcement spacings. Choice of the proper grid index value $I_1 = (\phi_1 s_2)/p_{t1}$ from Fig. 1-6 achieves this result.

5) Transverse spacing of the intersecting reinforcement in excess of an optimum value up to 8 in. (20 cm) approximately, regardless of the diameter of the reinforcement, leads to early development of wide diagonal cracks and no forced orthogonal fracture patterns are possible. Hence most efficient crack control in two-way action floor design can be achieved only through use of closely spaced small diameter and not through widely spaced large diameter reinforcement.

6) Scale effect is insignificant on crack width development in two-way action floor systems.

7) The proposed equation $w_{\max} = K R f_s \sqrt{I}$ predicts as a best fit the probable flexural crack width which can develop in a two-way action floor system. Values of the fracture coefficient K depend on the loading and boundary conditions and the ratio of short to long span, as given in Table 1-1. An average value of $R = 1.25$ can be used. Reinforcement stress f_s equivalent to 40 percent of the yield strength f_y can be used as a limit for acceptable serviceability conditions at present. The design engineer needs only to evaluate the predicted crack width corresponding to grid index I_1 in direction "1" closest to the concrete outer tensile fibers.

8) In plate regions where reinforcement in only one direction is sometimes used, and in one-way slabs with large spacing of transverse reinforcement, a value of s_2 up to 12 in. (30 cm), but not less than 8 in. (20 cm), can be inserted in the grid index parameter of the cracking equation; the larger the diameter ϕ_1 the larger is the s_2 value applicable within the 12 in. limit.

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TABLE 1—FRACTURE COEFFICIENT K IN EQ. $W_{\max} = K R f_s \sqrt{I}$ ^a

Loading ^b type	Boundary condition ^c	Span ratio ^d S/L	Fracture coeff. K
A	Square slab, 4 edges r.	1.0	2.1×10^{-5}
A	Square slab, 4 edges s.	1.0	3.1
B	Rect. slab, 4 edges r.	0.5	^e 1.6
B	Rect. slab, 4 edges r.	0.7	2.2
B	Rect. slab, 3 edges r. 1 edge h.	0.7	2.3
B	Rect. slab, 2 edges r. 2 edges h.	0.7	2.7
B	Square slab 4 edges r.	1.0	2.8
B	Square slab, 3 edges r. 1 edge h.	1.0	2.9
B	Square slab, 2 edges r. 2 edges h.	1.0	4.2

^a I = Grid Index = $(\phi_1 s_2 / p_{t1}) \text{ in.}^2$; f_s = reinforced steel stress (ksi). In cases where transverse steel is not used or when its spacing s_2 exceeds 12 in. (30.5 cm), use $s_2 = 12$ in. in the equation.

^bLoading type: A = concentrated; B = uniformly distributed.

^cBoundary condition: r. = restrained; s. = simply supported; h. = hinged.

^dSpan ratio: S = clear short span; L = clear long span.

^eK interpolated = 1.6×10^{-5} , as minimum for one-way slabs $\left(\frac{S}{L} \leq 0.5\right)$.

TABLE 1-2—CORRELATION OF OBSERVED AND COMPUTED MAXIMUM CRACK WIDTHS^a

Test no.	Slab des.	20 ksi			30 ksi			35 ksi			50 ksi			60 ksi		
		w _O	w _c	w _O /w _c	w _O	w _c	w _O /w _c	w _O	w _c	w _O /w _c	w _O	w _c	w _O /w _c	w _O	w _c	w _O /w _c
4 edges restrained, concentrated loading								Clear spans 5' 8" x 5' 8"								
								b _K = 2.1 x 10 ⁻⁵								
1	CSF1	.005	.0061	0.82	.008	.0092	0.88	.010	.0109	0.92	.022	.0153	1.44	.036	.0183	1.97
2	CSF2	.004	.0056	0.71	.007	.0085	0.82	.009	.0099	0.91	.014	.0141	1.00	.019	.0168	1.13
3	CSG1	.007	.0095	0.74	.012	.0143	0.84	.015	.0167	0.90	.028	.0238	1.18	.037	.0285	1.30
4	CSG2	.006	.0073	0.82	.010	.0109	0.92	.013	.0127	1.02	.021	.0182	1.15	.027	.0219	1.23
5	CSH1	.005	.0053	0.94	.009	.0079	1.14	.010	.0093	1.07	.016	.0132	1.21	.023	.0159	1.45
6	CSH2	.003	.0053	0.57	.004	.0079	0.51	.005	.0093	0.54	.007	.0132	0.53	.009	.0159	0.57
7	CSI1	.009	.0086	1.05	.014	.0129	1.09	.020	.0151	1.33	.044	.0215	2.05	.052	.0258	2.02
8	CSJ1	.006	.0065	0.92	.010	.0097	1.03	.013	.0113	1.15	.022	.0162	1.36	.035	.0195	1.80
9	CSJ2	.007	.0088	0.80	.011	.0131	0.84	.014	.0153	0.91	.022	.0219	1.01	.028	.0264	1.06
10	CSK1	.009	.0086	1.05	.013	.0129	1.01	.015	.0151	0.99	.023	.0216	1.11	.029	.0258	1.12
		w _O	Mean	} 0.842												
		w _c	S.D.													
							0.908			0.974			1.204			1.356
							0.179			0.204			0.322			0.454
4 edges simply supported, concentrated loading								Clear spans 5' 8" x 5' 8"								
								K = 3.1 x 10 ⁻⁵								
11	SA1	.012	.0085	1.41	.019	.0127	1.50	.024	.0148	1.62	.033	.0211	1.56	.039	.0225	1.73
12	SA2	.006	.0085	0.71	.010	.0127	0.79	.012	.0148	0.81	.019	.0211	0.90	.032	.0225	1.42
13	SA3	.009	.0085	1.06	.013	.0127	1.02	.016	.0148	1.08	.023	.0211	1.09	.034	.0225	1.42
14	SB1	.013	.0228	0.57	.023	.0342	0.67	.028	.0398	0.70	.044	.0569	0.77	.058	.0684	0.85

15	SB2	.007	.0155	0.45	.013	.0232	0.56	.015	.0271	0.55	.024	.0387	0.62	.036	.0465	0.77	
16	SC1	.021	.0248	0.85	.032	.0365	0.88	.038	.0425	0.89	.053	.0608	0.87	.064	.0744	0.86	
17	SC2	.029	.0238	1.24	.044	.0357	1.23	.056	.0416	1.35	.077	.0595	1.29	.093	.0714	1.30	
18	SD1	.020	.0164	1.22	.026	.0246	1.06	.029	.0287	1.01	.041	.0410	1.00	.051	.0492	1.04	
19	SD2	.017	.0170	1.00	.025	.0258	0.98	.029	.0301	0.96	.040	.0431	0.93	.050	.0510	0.98	
20	SE1	.013	.0185	0.70	.020	.0277	0.72	.024	.0323	0.74	.035	.0462	0.76	.051	.0555	0.92	
21	SE2	.006	.0054	1.11	.009	.0081	1.11	.012	.0095	1.26	.019	.0136	1.40	.026	.0162	1.61	
22	SE3	.006	.0077	0.78	.009	.0116	0.78	.012	.0135	0.89	.018	.0193	0.93	.025	.0231	1.08	
	$\frac{w_o}{w_c}$	Mean	} 0.925				0.942				0.988				1.010		1.173
	$\frac{w_c}{w_o}$	S.D.	} 0.295				0.264				0.302				0.279		0.328

4 edges restrained, uniform loading

Clear spans 5' 0" x 5' 0"

 $K = 2.8 \times 10^{-5}$

23	WS1	.009	.0070	1.28	.013	.0105	1.24	.016	.0122	1.31	.024	.0175	1.37	.036	.0210	1.72
24	WS2	.007	.0070	1.00	.010	.0105	0.95	.012	.0122	0.98	.017	.0175	0.97	.028	.0210	1.33
25	WS3	.006	.0071	0.85	.009	.0106	0.85	.011	.0124	0.89	.016	.0177	0.91	.033	.0213	1.55
26	WS4	.005	.0071	0.70	.009	.0106	0.85	.013	.0124	1.05	.021	.0177	1.20	.032	.0213	1.50
27	WS5	.009	.0133	0.68	.013	.0201	0.65	.015	.0234	0.64	.021	.0334	0.63	.028	.0400	0.70
28	WS6	.007	.0133	0.53	.009	.0201	0.45	.010	.0234	0.43	.019	.0334	0.57	.022	.0400	0.55
29	WS7	.008	.0067	1.20	.011	.0099	1.11	.013	.0116	1.12	.019	.0166	1.15	.027	.0201	1.35
30	WS8	.006	.0054	1.11	.009	.0814	1.11	.010	.0095	1.05	.014	.0136	1.03	.020	.0162	1.24
31	WS9	.008	.0099	0.81	.011	.0148	0.74	.013	.0173	0.75	.018	.0246	0.73	.027	.0297	0.91
32	WS10	.013	.0114	1.14	.019	.0172	1.10	.024	.0200	1.20	.034	.0286	1.19	.042	.0342	1.23
33	WS11	.014	.0117	1.20	.016	.0176	0.91	.020	.0211	0.95	.031	.0292	1.06	.035	.0352	0.99
34	WS12	.011	.0098	1.12	.017	.0146	1.17	.019	.0171	1.11	.034	.0244	1.40	.045	.0294	1.53
35	WS13	.030	.0288	1.04	.045	.0433	1.04	.052	.0506	1.03	.072	.0723	0.99	.092	.0865	1.06
36	WS14	.022	.0262	0.80	.031	.0393	0.79	.035	.0461	0.76	.051	.0663	0.78	.059	.0886	0.67
37	WS15	.019	.0137	1.39	.023	.0206	1.12	.026	.0240	1.08	.035	.0272	1.29	.042	.0326	1.29
38	WS16	.012	.0094	1.28	.014	.0141	0.99	.016	.0164	0.98	.023	.0234	0.98	.028	.0282	0.99

TABLE 1-2—CORRELATION OF OBSERVED AND COMPUTED MAXIMUM CRACK WIDTHS^a (CONT.)

Test no.	Slab des.	20 ksi			30 ksi			35 ksi			50 ksi			60 ksi		
		w _o	w _c	w _o /w _c	w _o	w _c	w _o /w _c	w _o	w _c	w _o /w _c	w _o	w _c	w _o /w _c	w _o	w _c	w _o /w _c
39	WS17	.011	.0094	1.17	.013	.0141	0.92	.014	.0164	0.85	.025	.0234	1.06	.033	.0282	1.17
40	WS18	.019	.0163	1.17	.028	.0246	1.04	.037	.0286	1.29	.047	.0410	1.15	.065	.0489	1.33
41	WS19	.014	.0135	1.04	.022	.0202	1.09	.024	.0236	1.02	.034	.0336	1.01	.044	.0405	1.09
42	WS20	.003	.0069	0.43	.006	.0104	0.58	.007	.0121	0.58	.013	.0173	0.75	.015	.0207	0.72
43	WS21	.005	.0069	0.72	.010	.0104	0.96	.013	.0121	1.07	.017	.0173	0.98	.020	.0207	0.97
44	WS22	.010	.0110	0.91	.017	.0165	1.03	.020	.0192	1.04	.026	.0274	0.95	.031	.0333	0.93
45	WS23	.016	.0117	1.37	.022	.0176	1.25	.023	.0206	1.12	.031	.0294	1.06	.037	.0351	1.06
46	WS24	.018	.0183	0.98	.026	.0267	0.92	.031	.0312	0.99	.045	.0455	0.99	.055	.0548	1.00
47	^c WS25	.015	.0131	1.15	.021	.0197	1.07	.026	.0229	1.14	.038	.0327	1.16	.045	.0393	1.15
48	WS26	.016	.0168	0.95	.025	.0250	1.00	.029	.0294	0.99	.039	.0412	0.85	.047	.0495	0.95
49	WS27	.011	.0126	0.87	.017	.0188	0.90	.021	.0220	0.96	.029	.0314	0.93	.036	.0378	0.96
50	WS28	.013	.0134	0.97	.021	.0201	1.00	.024	.0234	1.03	.034	.0335	1.01	.046	.0402	1.14
51	WS29	.017	.0218	0.78	.026	.0327	0.80	.031	.0381	0.81	.053	.0546	0.97	.076	.0654	1.18
52	WS30	.019	.0241	0.79	.029	.0361	0.80	.034	.0420	0.81	.049	.0604	0.81	.062	.0723	0.86
53	WS31	.012	.0116	1.03	.016	.0176	0.91	.018	.0204	0.88	.027	.0294	0.93	.036	.0348	1.03
54	WS32	.015	.0116	1.29	.019	.0176	1.08	.021	.0204	1.03	.032	.0294	1.09	.039	.0348	1.12
55	WV1	.008	.0077	1.31	.014	.0116	1.21	.017	.0135	1.26	.022	.0193	1.14	.027	.0232	1.16
56	WV2	.008	.0082	0.98	.011	.0123	0.89	.014	.0144	0.97	.021	.0206	1.02	.031	.0247	1.26
57	WV3	.013	.0149	0.87	.019	.0223	0.85	.021	.0261	0.81	.029	.0372	0.78	.035	.0447	0.78
58	WV4	.008	.0089	0.90	.010	.0134	0.75	.013	.0156	0.81	.018	.0223	0.81	.029	.0267	1.09
59	WV5	.013	.0082	1.59	.016	.0123	1.30	.018	.0144	1.25	.021	.0206	1.10	.022	.0247	0.89
60	WV6	.008	.0111	0.72	.015	.0167	0.90	.020	.0195	1.03	.036	.0278	1.30	.044	.0334	1.32
61	WV7	.011	.0175	0.63	.020	.0262	0.76	.025	.0307	0.81	--	--	--	--	--	--
		w _o	Mean	} 0.981												
		w _c	S.D.													
							0.946			0.967			0.996			1.097
							0.180			0.181			0.185			0.207

3 edges restrained, 1 edge hinged, uniform loading

Clear spans 5' 0" x 5' 0"

 $K = 2.9 \times 10^{-5}$

62	WV8	.007	.0080	0.88	.010	.0120	0.83	.013	.0140	0.93	.016	.0200	0.80	.021	.0240	0.87
63	WV9	.014	.0179	0.79	.018	.0253	0.71	.020	.0295	0.68	.029	.0422	0.69	.045	.0506	0.89
64	WV10	.010	.0092	1.08	.013	.0137	0.95	.014	.0160	0.88	.021	.0229	0.92	.028	.0275	1.02
65	WV11	.011	.0126	0.87	.015	.0190	0.79	.018	.0221	0.82	.025	.0316	0.79	.033	.0379	0.87
66	WV12	.018	.0182	0.99	.029	.0272	1.07	.035	.0318	1.10	--	--	--	--	--	--
	$\frac{w_o}{w_c}$	Mean	0.922				0.870			0.882			0.800			0.912
	$\frac{w_o}{w_c}$	S.D.	0.113				0.141			0.154			0.094			0.072

2 edges restrained, 2 edges hinged, uniform loading

Clear spans 5' 0" x 5' 0"

 $K = 4.2 \times 10^{-5}$

67	WV13	.024	.0233	1.03	.037	.0350	1.06	.044	.0408	1.08	--	--	--	--	--	--
68	WV14	.017	.0128	1.33	.023	.0190	1.21	.027	.0222	1.22	.040	.0317	1.26	.053	.0380	1.45
69	WV15	.021	.0224	0.93	.040	.0355	1.19	.054	.0391	1.38	--	--	--	--	--	--
70	WV16	.020	.0183	1.09	.027	.0275	0.98	.031	.0321	0.96	.046	.0457	1.00	.060	.0549	1.09
71	WV17	.017	.0132	1.29	.020	.0200	1.00	.022	.0232	0.95	.029	.0322	0.90	.036	.0398	0.91
	$\frac{w_o}{w_c}$	Mean	1.134				1.088			1.118			1.053			1.150
	$\frac{w_o}{w_c}$	S.D.	0.171				0.107			0.183			0.186			0.275

4 edges restrained, uniform loading

Clear spans 5' 0" x 3' 6"

 $K = 2.2 \times 10^{-5}$

72	WV18	.013	.0131	0.99	.018	.0197	0.91	.020	.0229	0.87	.027	.0328	0.82	.035	.0394	0.89
73	WV19	.007	.0069	1.01	.012	.0104	1.15	.014	.0122	1.15	.024	.0174	1.40	.034	.0208	1.64
74	WV20	.007	.0054	1.30	.009	.0081	1.11	.010	.0094	1.06	.015	.0134	1.12	.019	.0160	1.19
75	WV21	.007	.0076	0.92	.011	.0114	0.97	.013	.0133	0.98	.019	.0191	1.00	.023	.0229	1.00
76	WV22	.012	.0095	1.26	.017	.0142	1.20	.020	.0166	1.21	.026	.0237	1.10	.035	.0284	1.23

TABLE 1-2—CORRELATION OF OBSERVED AND COMPUTED MAXIMUM CRACK WIDTHS^a (CONT.)

Test no.	Slab des.	20 ksi			30 ksi			35 ksi			50 ksi			60 ksi		
		w_o	w_c	w_o/w_c	w_o	w_c	w_o/w_c	w_o	w_c	w_o/w_c	w_o	w_c	w_o/w_c	w_o	w_c	w_o/w_c
77	WV23	.015	.0192	0.78	.021	.0288	0.73	.025	.0335	0.75	.041	.0479	0.86	.050	.0575	0.87
78	WV24	.020	.0291	0.68	.023	.0436	0.53	.024	.0508	0.48	.032	.0727	0.44	.045	.0872	0.52
79	WV25	.011	.0122	0.92	.017	.0183	0.93	.020	.0214	0.93	--	--	--	--	--	--
80	WV26	.009	.0117	0.77	.014	.0175	0.80	.016	.0204	0.78	.025	.0292	0.86	.035	.0350	1.00
81	WV27	.007	.0061	1.15	.011	.0091	1.21	.013	.0106	1.22	.019	.0152	1.25	.024	.0182	1.31
82	^c WV28	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
83	WV29	.009	.0096	0.94	.012	.0144	0.84	.015	.0168	0.89	.020	.0240	0.83	.025	.0288	0.87
		w_o	Mean	} 0.983												
		w_c	S.D.													
							0.943			0.938			0.968			1.052
							0.176			0.188			0.235			0.227
3 edges restrained, 1 edge hinged, uniform loading								Clear spans 5' 0" x 3' 6"								
								$K = 2.3 \times 10^{-5}$								
84	WV30	.008	.0072	1.11	.009	.0109	0.83	.011	.0127	0.87	.016	.0182	0.88	.023	.0218	1.06
85	WV31	.013	.0122	1.07	.018	.0182	0.98	.021	.0214	0.98	.034	.0306	1.11	.044	.0367	1.20
86	WV32	.004	.0069	0.58	.006	.0104	0.58	.008	.0122	0.66	.015	.0174	0.86	.021	.0208	1.01
87	WV33	.012	.0128	0.94	.019	.0192	0.99	.024	.0224	1.07	--	--	--	--	--	--
		w_o	Mean	} 0.924												
		w_c	S.D.													
							0.844			0.894			0.951			1.088
							0.191			0.177			0.139			0.099

2 edges restrained, 2 edges hinged, uniform loading

Clear spans 5' 0" x 3' 6"

$K = 2.7 \times 10^{-5}$

88	WV34	.016	.0157	1.02	.025	.0235	1.06	.027	.0275	0.98	.038	.0392	0.97	.045	.0471	0.96
89	WV35	.007	.0079	0.89	.010	.0119	0.84	.012	.0138	0.87	.018	.0198	0.91	.024	.0237	1.01
90	WV36	.012	.0150	0.80	.019	.0225	0.84	.022	.0262	0.84	--	--	--	--	--	--
		$\frac{w_o}{w_c}$	Mean	0.902			0.916			0.897			0.939			0.984
			S.D.	0.111			0.127			0.074			0.042			0.035

^aLoad and boundary conditions defined in Table 1-1. w_o = observed; w_c = computed (in.). 0.01 in. = 0.25 mm.

^b K = Fracture coefficient.

^cNot included in analysis.

TABLE 1-3—TESTS BY OTHER INVESTIGATORS

Investigator ^a	No. tests	Scale	No. panels	Panel slab ft	Total slab thick., in.	Clear conc. cover, in.	Flexural reinforcement	Meas. crack width, in.	Steel stress level f_s , ksi	Value of K	Predicted crack width, in.
1	2	3	4	5	6	7	8	9	10	11	12
Guralnick-LaFraugh ¹¹	1	3/4	9	15 x 15	5 1/4	7/16	1/2" ϕ bars Top col. strip @ 6 3/8" x 6 3/8" Bot. mid. strip @ 12 1/2" x 12 1/2"	.005 negl.	8.3 2.7	2.45 2.45	.004 .002
Gamble-Sozen-Siess ¹²	2	1/4	9	5 x 5	2 1/2	3/4	Top: 1/8" sq. bars @ 2 3/4" x 2 3/4"	.005	19.3	2.2	.0045
Cardenas-Kaar ¹³ f_s evaluated from M- ϵ diagram	1	proto-type	2	13 x 13	5 1/2	3/4	Panel I: Top: 3/8" ϕ @ 6" x 6" Bot.: 6" x 6" D5.4/D5.4 WWF ^b Adjacent Panel I': Top & bot.: 6" x 6" D5.4/D5.4 WWF + 1/2" ϕ bars @ 6" x 6" on top col. strip	.008 .014	15 44	2.4	.008 .011
	1	1/2	1	6 x 6	5	3/4	Top & bot.: 6" x 6" D5.4/D5.4 WWF + 1/2" ϕ bars @ 12" x 12" top	.028	44	2.45	.025
Hopkins Park ¹⁴	1	1/4	9	5 1/2 x 5 1/2 central panel	2.02	13/64	Bot. mid. strip: 1/8" ϕ dia. @ 4 1/4" x 4 1/4"	.015	48.5	2.8	.0165

^aSuperscripts are reference numbers.^bD5.4 WWF = Deformed welded wire fabric. Area of single wire = .054 in.²; dia. = .2625 in.

TABLE 1-4—PERMISSIBLE CRACK WIDTHS VERSUS EXPOSURE CONDITIONS

Exposure condition	Maximum allowable crack width, in.*
Air or protective membrane	0.016
Humidity, air-water, soil	0.012
De-icing chemicals	0.007
Seawater and seawater spray; wetting and drying	0.006
Water-retaining structure	0.004

*0.001 in. = 0.025 mm.

APPENDIX

CRACK CONTROL DESIGN EXAMPLES

Example #1

The interior panel of a uniformly loaded two-way slab on beams has a span ratio $S/L = 1.0$ (where S = short span and L = long span). It is 5 in. thick. Find the size and spacing of negative reinforcement to satisfy normal exposure conditions. $R = 1.25$, $f_y = 60$ ksi.

Solution

- (a) From Table 1-1, required $K = 2.8 \times 10^{-5}$
 From Table 1-4, permissible $w_{\max} = 0.016$ in.

$$w_{\max}/R = \frac{0.016}{1.25} = .0128$$

From Fig. 1-6, Grid Index $I_1 = 370 \text{ in.}^2$

$$I_1 = 370 = \frac{\phi_1 s_2}{p_{t_1}} = \frac{s_1 s_2 t_b}{\phi_1} \cdot \frac{8}{\pi}$$

where t_b = cover to center of first steel layer. Try #4 rebars ($\phi = 0.5$ in.), assume $s_1 = s_2$, hence $t_b = 1.0$ in. hence,

$$370 = \frac{s_1^2 \times 1 \text{ in.}}{0.5 \text{ in.}} \cdot \frac{8}{\pi}, \text{ i.e., } s_1 = 8.5 \text{ in.}$$

- (b) From Crack Control Equation:

$$w = KRf_s \sqrt{I}$$

hence,

$$.016 = 2.8 \times 10^{-5} \times 1.25 \times .4 \times 60 \text{ ksi} \sqrt{I}$$

$$I = 370 \text{ giving } s_1 = 8.5$$

Therefore, for crack control, #4 @ 8½ in. is needed.

(ACI 318-71 Section 13.5.1 permits maximum spacing $2t = 2 \times 5 = 10$ in.)

Example #2

Solve Example #1 using deformed welded wire fabric as reinforcement.

Solution

$I = 370$ from before

Assume D3.6 gage and $\phi_1 = \phi_2 = 0.214$ in.

hence,

$$t_b = 0.107 + 0.75 = 0.857 \text{ in.}$$

$$I = 370 = \frac{s_1^2 t_b}{\phi_1} \cdot \frac{8}{\pi}$$

$$s_1^2 = \frac{370 \times .214 \times \pi}{8 \times 0.857} = 36.1 \text{ in.}^2, \text{ i.e., } s_1 = 6.02 \text{ in.}$$

Therefore, use 6 x 6 - D3.6/D3.6 WWFabric.

Example #3

Solve Example #2 if the span ratio $S/L = 0.6$.

Solution

From Table 1-1, $K = 1.9 \times 10^{-5}$ by interpolation

From Fig. 1-6, Grid Index $I_1 = 810$

(a) Trying #4 rebars:

$$810 = \frac{s_1^2 \times 1.0}{0.5} \cdot \frac{8}{\pi}$$

$$s_1^2 = 157, \text{ i.e., } s_1 = 12.5 \text{ in.}$$

Use #4 at 12 in. center to center each way.

(b) Trying deformed WWF size D3.6:

$$\phi_1 = \phi_2 = 0.231 \text{ in.}$$

$$s_1^2 = 36.1 \times \frac{810}{370} = 79.0 \text{ in.}^2 \text{ (from Ex. 2); } s_1 = 8.9 \text{ in.}$$

Use 9 x 9 - D3.6/D3.6 WWF.

Example #4

Find the size and spcing necessary for crack control at the negative region of the column reaction in a flat plate 7 in. thick and loaded uniformly. Span ratio $S/L = 1.0$, $R = 1.20$, $f_y = 60$ ksi. Concrete is subjected to normal exposure.

Solution

From Table 1-1, $K = 2.1 \times 10^{-5}$

From Table 1-4, permissible $w = 0.016$ in.

Hence,

$$w/R = 0.016/1.20 = 0.0133$$

From Fig. 1-6, Grid Index $I_1 = 700$

Assume $s_1 = s_2$

(a) Trying #4 rebars:

$$t_b = 0.25 + 0.75 \text{ in. cover} = 1.0; \phi_1 = 0.5 \text{ in.}$$

$$700 = \frac{s_1^2 \times 1.0}{0.5} \cdot \frac{8}{\pi}$$

$$s_1^2 = 137, \text{ i.e., } s_1 = 11.75 \text{ in.}$$

Use #4 at 12 in. center to center each way

(b) Trying deformed WWF size D3.0:

$$\phi_1 = \phi_2 = 0.195 \text{ in.}$$

$$t_b = 0.097 + 0.75 = 0.847 \text{ in.}$$

$$700 = \frac{s_1^2 \times 0.847}{0.195} \cdot \frac{8}{\pi}$$

$$s_1^2 = 63.5 \text{ in.}^2, \text{ i.e., } s_1 = 7.96 \text{ in.}$$

Use 8 x 8 - D3.0/D3.0 WWF.

Example #5

Solve Example #4 for severe exposure conditions.

Solution

From Table 1-4, permissible $w_{\max} = 0.012 \text{ in.}$

$$w/R = 0.012/1.2 = 0.010 \text{ in.}$$

From Fig. 1-6, Grid Index $I = 390 \text{ in.}^2$

(a) Trying #4 rebars:

$$s_1^2 = 137 \times \frac{390}{700} = 76.5 \text{ in.}^2, \text{ i.e., } s_1 = 8.6 \text{ in.}$$

Use #4 @ 8½ in. center to center each way.

(b) Trying deformed WWF size D3.0:

$$s_1^2 = 63.5 \times \frac{390}{700} = 35.5 \text{ in.}^2, \text{ i.e., } s_1 = 5.9 \text{ in.}$$

Use 6 x 6 - D3.0/3.0 WWF.

Note: For yield strength f_y value different from 60 ksi, either the crack control equation is to be directly used, or charts be prepared similar to Fig. 1-6.

NOTATION

- A_s = Area of tensile reinforcement in one direction per foot width of slab
 A_t = Concrete stretched area = $12(2t + \phi)$ for a 12 in. strip, defining the area of concrete stretched in tension
 d = Effective depth to center of one layer of reinforcement
 f'_c = Cylinder compressive strength of concrete, psi
 f_s = Tensile stress in steel reinforcement, ksi
 f'_t = Tensile splitting strength of concrete, psi
 f_y = Yield strength of reinforcement by 0.2 percent offset
 I_1 = Grid Index in direction "1" ($= \phi_1 s_2 / p_{t1}$) closest to outer concrete fibers
 I_2 = Grid Index in direction "2" ($\phi_2 s_1 / p_{t2}$) in direction perpendicular to "1"
 K = Fracture coefficient dependent on load or reaction type and on the support condition (See Table 1-1)
 p = Steel percentage = $A_s / 12d$
 p_t = Active steel ratio = A_s / A_t
 R = Cover ratio = ratio of distance from neutral axis to tensile face of concrete to distance from neutral axis to the center of gravity of reinforcement
 s = Spacing of reinforcement, in.
 $s.d.$ = Standard deviation (σ)
 t = Thickness of clear concrete cover, in.
 t_b = Thickness of concrete cover to center of reinforcement layer, in.
 w_c = Computed crack width in inches at concrete face, in.
 w_o = Observed crack width in inches at concrete face, in.
 w_{max} = Maximum crack width in inches at concrete face, in.
 ϕ = Diameter of reinforcing bar or wire, in.
 "1" = Direction of reinforcing elements closest to outer concrete fibers, for which crack control check is to be made

TABLE 1-A—GENERAL PROPERTIES OF SLAB TEST SPECIMENS^a

Test no.	Slab designation	Average slump, in.	Age at test, days	Cylinder compres. strength f'_c , psi	Cylinder split. strength f'_t , psi	Total center thickness, in.	Center d_1 , in.	Reinf. ^b wire gage or bar size	Reinf. dia. ϕ_1/ϕ_2 , in./in.	Reinf. spacing $s_1 \times s_2$, in.	Reinf. yield strength, 0.2% offset, in.	Center deflec. at ult. load, in.
4 edges restrained, concentrated loading						Clear spans 5' 8" x 5' 8"						
1	CSF1	5 1/4	195	5770	540	3.45	2.85	W8.6	0.331	4 x 4	86700	0.29
2	CSF2	3 3/4	12	5000	535	3.64	2.67	W8.6	0.331	4 x 4	86850	0.33
3	CSG1	3	12	4520	425	3.45	2.88	W8.6	0.333	8 x 8	85100	0.76
4	CSG2	3 1/4	9	4060	390	3.30	2.96	W8.6	0.333	8 x 8	78440	0.86
5	CSH1	2 1/2	9	3980	470	3.45	2.93	W4.7	0.244	4 x 4	83120	0.65
6	CSH2	1 3/4	10	5360	570	3.45	2.96	W4.7	0.244	4 x 4	82050	0.68
7	CSI1	2 1/2	17	5010	550	3.50	3.20	W4.7	0.242	8 x 8	80950	1.11
8	CSJ1	1 7/8	17	5710	560	3.40	2.95	W4.7	0.243	4 x 8	81900	0.70
9	CSJ2	1 1/2	17	5100	560	3.40	2.70	W4.7	0.243	4 x 8	83550	0.80
10	CSK1	2	16	4990	530	3.20	2.80	W5.4/ W2.9	0.262/ 0.192	6 x 12	88900	1.18
4 edges simply supported, concentrated loading						Clear spans 5' 8" x 5' 8"						
11	SA1	1 3/4	7	4420	365	3.85	3.20	W4.7	0.244	4 x 4	96600	1.62
12	SA2	9 1/2	14	4060	360	3.75	3.10	W4.7	0.244	4 x 4	88100	1.95
13	SA3	1 3/4	13½	5275	515	3.65	3.00	W4.7	0.244	4 x 4	80500	1.34
14	SB1	2 1/4	11	5660	450	3.60	2.55	W8.6	0.331	8 x 8	78900	1.42
15	SB2	3 1/2	12	4470	370	3.95	3.25	W8.6	0.331	8 x 8	78400	2.16
16	SC1	3 3/4	9½	4270	470	3.95	2.90	W4.7	0.244	8 x 8	80600	2.16

17	SC2	5 1/3	12	4500	470	3.60	2.60	W4.7	0.244	8 x 8	82700	2.34
18	SD1	2 1/2	11	5340	515	4.10	3.50	W5.4/ W2.9	0.263/ 0.192	6 x 12	94200	1.46
19	SD2	3	13	5300	540	4.00	3.40	W5.4/ W2.9	0.263/ 0.192	6 x 12	95700	1.50
20	SE1	3	12	5530	510	4.10	1.80	W8.6	0.331	4 x 4	84200	1.95
21	SE2	7 1/2	11	3810	410	4.10	3.75	W8.6	0.331	4 x 4	77600	1.38
22	SE3	6 1/2	11	4340	505	4.10	3.45	W8.6	0.331	4 x 4	82100	1.22

4 edges restrained, uniform loading

Clear spans 5' 0" x 5' 0"

23	WS1	8	86	3300	280	3.00	2.45	D4.6	0.242	4 x 4	83500	1.40
24	WS2	8	80	3300	280	3.00	2.45	D4.6	0.242	4 x 4	83500	1.48
25	WS3	3 1/2	42	4870	535	3.00	2.56	D2.0	0.159	4 x 4	86300	1.18
26	WS4	3 1/2	50	4870	535	3.00	2.69	D2.0	0.159	4 x 4	86300	1.52
27	WS5	2	32	5880	570	3.00	2.05	D2.0	0.159	4 x 4	86300	1.94
28	WS6	2	41	5880	570	3.00	1.90	D2.0	0.159	4 x 4	86300	1.50
29	WS7	8	64	2830	335	3.00	2.56	D2.9	0.191	4 x 4	93000	1.46
30	WS8	8	64	2830	335	3.00	2.56	D2.9	0.191	4 x 4	93000	1.38
31	WS9	7	53	4170	450	3.00	2.25	D2.9	0.191	4 x 4	93000	1.63
32	WS10	7	53	4170	450	3.00	2.25	D2.9	0.191	4 x 4	93000	1.68
33	WS11	7	55	4400	470	3.00	2.62	D4.6	0.242	8 x 8	67500	1.34
34	WS12	7	55	4400	470	3.00	2.62	D4.6	0.242	8 x 8	67500	1.42
35	WS13	7	55	4070	410	3.00	1.75	W8.6	0.331	8 x 8	83500	2.52
36	WS14	7	55	4070	410	3.00	2.00	W8.6	0.331	8 x 8	83500	2.60
37	WS15	7 1/2	40	3930	420	3.00	1.94	W2.1	0.162	4 x 4	72000	2.54
38	WS16	7	48	4530	420	3.00	2.32	W2.1	0.162	4 x 4	72000	1.72
39	WS17	7	48	4530	420	3.00	2.32	W2.1	0.162	4 x 4	72000	1.48
40	WS18	7 1/2	40	3930	420	3.00	1.87	W2.1	0.162	4 x 4	72000	1.96
41	WS19	6	49	4850	500	3.00	1.81	D2.0	0.159	3 x 3	81900	1.54
42	WS20	7	44	4420	440	3.00	2.25	D2.0	0.159	3 x 3	81900	1.54

TABLE 1-A1—GENERAL PROPERTIES OF SLAB TEST SPECIMENS^a (CONT.)

Test no.	Slab designation	Average slump, in.	Age at test, days	Cylinder compress. strength f'_c , psi	Cylinder split. strength f_t , psi	Total center thickness, in.	Center d_1 , in.	Reinf. ^b wire gage or bar size	Reinf. dia. ϕ_1/ϕ_2 , in./in.	Reinf. spacing $s_1 \times s_2$, in.	Reinf. yield strength, 0.2% offset, in.	Center deflec. at ult. load, in.
43	WS21	7	45	4420	440	3.00	2.25	D2.0	0.159	3 x 3	81900	1.37
44	WS22	6	49	4850	500	3.00	1.94	D2.0	0.159	3 x 3	81900	1.42
45	WS23	7	45	4190	430	3.00	2.25	D2.0	0.159	4 x 4	81900	1.55
46	WS24	7	45	4190	430	3.00	1.75	D2.0	0.159	4 x 4	81900	1.92
47	WS25	9 1/2	33	3800	360	3.00	1.87	D4.6	0.242	4 x 8	67500	2.46
48	WS26	9 1/2	32	2800	360	3.00	1.87	D4.6	0.242	4 x 8	67500	1.94
49	WS27	10	34	3550	390	3.00	2.12	D4.6	0.242	4 x 8	67500	1.92
50	WS28	10	34	3550	390	3.00	2.00	D4.6	0.242	4 x 8	67500	1.80
51	WS29	8	26	3800	425	3.00	1.75	D4.6	0.242	6 x 6	67500	2.24
52	WS30	8	27	3800	420	3.00	1.62	D4.6	0.242	6 x 6	67500	1.76
53	WS31	9	28	3780	390	3.00	1.25	D4.6	0.242	6 x 6	67500	1.84
54	WS32	9	65	3780	390	3.00	1.25	D4.6	0.242	6 x 6	67500	1.76
55	WV1	5	21	5590	580	2.50	2.00	D4.6	0.242	4 x 4	68300	2.22
56	WV2	5	28	5590	580	2.50	2.00	D2.9	0.191	4 x 4	68900	2.03
57	WV3	5 1/2	28	4810	500	2.50	2.00	D4.6	0.242	8 x 8	68300	2.20
58	WV4	6	32	5590	580	2.50	2.00	D2.0	0.159	4 x 4	68700	2.05
59	WV5	6	27	4990	530	2.50	2.00	D2.9	0.191	4 x 4	68900	2.04
60	WV6	6	34	4990	530	2.50	2.00	D4.6	0.242	6 x 6	68300	2.14
61	WV7	6 1/4	28	5660	570	2.50	2.00	#3	0.375	9½ x 9½	41600	2.04

3 edges restrained, one edge hinged, uniform loading						Clear spans 5' 0" x 5' 0"						
62	WV8	6 1/4	22	5590	570	2.50	2.00	D4.6	0.242	4 x 4	68300	2.02
63	WV9	5 1/2	28	5590	570	2.50	2.00	D4.6	0.242	8 x 8	68300	2.20
64	WV10	5 1/2	30	6080	660	2.50	2.00	D2.9	0.191	4 x 4	68900	1.94
65	WV11	6	36	6080	660	2.50	2.00	D4.6	0.242	6 x 6	68300	2.04
66	WV12	7	26	5660	550	2.50	2.00	#3	0.375	9½ x 9½	68300	2.20
2 edges restrained, 2 edges hinged, uniform loading						Clear spans 5' 0" x 5' 0"						
67	WV13	7 1/2	32	4100	410	2.50	2.00	#3	0.375	9½ x 9½	41600	2.56
68	WV14	6	34	4100	410	2.50	2.00	D4.6	0.242	4 x 4	68300	2.82
69	WV15	6	31	5200	590	2.50	2.00	D4.6	0.242	8 x 8	68300	2.30
70	WV16	6 1/4	33	5200	590	2.50	2.00	D4.6	0.242	6 x 6	68300	2.58
71	WV17	6 1/4	17	4780	530	2.50	2.00	D2.9	0.191	4 x 4	68900	2.28
4 edges restrained, uniform loading						Clear spans 5' 0" x 3' 6"						
72	WV18	4	7	3370	390	2.50	1.83	D9.2	0.342	8 x 8	62000	2.10
73	WV19	4	83	4200	400	2.50	1.92	D2.9	0.191	4 x 4	68000	1.77
74	WV20	7	24	3750	400	2.50	1.91	D2.5	0.177	3 x 3	91000	1.41
75	WV21	7	58	4280	380	2.50	1.66	D2.5	0.177	3 x 3	91000	1.64
76	WV22	6 1/2	53	5700	470	2.50	1.88	D4.6	0.242	6 x 6	91000	1.70
77	WV23	6 1/2	59	5700	520	2.50	1.83	D9.2	0.342	12 x 12	76000	2.28
78	WV24	5 1/2	18	5490	500	2.50	1.21	D9.2	0.342	8 x 8	62000	1.90
79	WV25	7 1/4	37	4780	530	2.50	2.00	#3	0.375	9½ x 9½	41600	1.86
80	WV26	6	35	5770	590	2.50	2.00	D4.6	0.242	8 x 8	68300	1.62
81	WV27	6	38	5770	590	2.50	2.00	D4.6	0.242	4 x 4	68300	1.56
82	WV28	6	22	5020	540	2.50	2.00	D2.9	0.191	4 x 4	68900	1.70
83	WV29	7	23	5020	540	2.50	2.00	D4.6	0.242	6 x 6	68300	1.70

TABLE 1-A1—GENERAL PROPERTIES OF SLAB TEST SPECIMENS^a (CONT.)

Test no.	Slab designation	Average slump, in.	Age at test, days	Cylinder compress. strength f'_c , psi	Cylinder split. strength f'_t , psi	Total center thickness, in.	Center d_1 , in.	Reinf. ^b wire gage or bar size	Reinf. dia. ϕ_1/ϕ_2 , in./in.	Reinf. spacing $s_1 \times s_2$, in.	Reinf. yield strength, 0.2% offset, in.	Center deflec. at ult. load, in.
3 edges restrained, 1 edge hinged, uniform loading						Clear spans 5' 0" x 3' 6"						
84	WV30	7	25	3930	440	2.50	2.00	D2.0	0.191	4 x 4	68900	2.05
85	WV31	6	26	3930	440	2.50	2.00	D4.6	0.242	8 x 8	68300	1.80
86	WV32	6	21	4950	520	2.50	2.00	D4.6	0.242	4 x 4	68300	1.80
87	WV33	6	22	4950	520	2.50	2.00	#3	0.375	9½ x 9½	41600	1.88
2 edges restrained, 2 edges hinged, uniform loading						Clear spans 5' 0" x 3' 6"						
88	WV34	6 1/2	21	4320	490	2.50	2.00	D4.6	0.242	8 x 8	68300	1.78
89	WV35	6 1/2	22	4320	490	2.50	2.00	D2.9	0.191	4 x 4	68900	2.00
90	WV36	6 1/2	14	4350	470	2.50	2.00	#3	0.375	9½ x 9½	41600	2.00

^aEdge support described in footnote to Table 1-1.

^bW = Smooth wire gage. D = Deformed wire gage. Number after letter W or D indicates area of cross-section in 0.01 in.² # = Rebar size.

Note: In slabs restrained at boundaries, the same pattern and amount of reinforcement used for the positive moment was also used for the negative moment.

TABLE 1-A2—PROPERTIES OF CONCRETE STRETCHED CRACKED ZONES

Test no.	Slab des.	Failure load P_u , lb	Concr. stret. area A_{t1} , in.	Concr. stret. area A_{t2} , in.	Cover factor R	Active steel ratio P_{t1} , %	Active steel ratio P_{t2} , %	Grid index $I_1 = \frac{\phi_1 s_2}{P_{t1}}$	Grid index $I_2 = \frac{\phi_2 s_1}{P_{t2}}$	Control. initial crack pattern O; YL*
1	CSF1	49700	18.38	22.36	1.50	1.407	1.155	94.1	114.7	O
2	CSF2	57600	18.49	22.34	1.40	1.433	1.189	92.4	112.6	O
3	CSG1	43400	17.67	21.84	1.20	.730	.598	358.2	445.2	YL
4	CSG2	40600	12.15	16.20	1.10	1.073	.808	248.1	329.6	YL
5	CSH1	41500	15.65	18.29	1.20	.881	.755	110.3	128.9	O
6	CSH2	41000	14.68	17.61	1.20	.940	.770	110.1	126.6	O
7	CSI1	37000	12.50	15.41	1.10	.556	.452	347.9	427.6	YL
8	CSJ1	41300	13.72	16.63	1.10	.993	.413	196.1	235.7	O-YL
9	CSJ2	41000	19.72	22.64	1.30	.706	.303	257.1	321.1	YL-O
10	CSK1	30900	11.90	15.05	1.10	.902	.191	349.7	603.1	YL
11	SA1	25000	18.52	21.45	1.20	.755	.652	129.1	150.0	O
12	SA2	23900	18.52	21.45	1.20	.755	.652	129.1	149.4	O
13	SA3	27000	18.52	21.45	1.20	.755	.652	129.1	149.4	O
14	SB1	18000	29.17	33.14	1.50	.442	.389	598.6	740.7	YL
15	SB2	22000	20.77	24.74	1.20	.621	.521	432.4	508.3	YL
16	SC1	13000	28.12	31.05	1.40	.249	.225	783.6	865.0	YL
17	SC2	12200	26.92	29.85	1.40	.260	.234	750.1	831.7	YL
18	SD1	12000	16.70	18.16	1.20	.648	.159	486.1	722.7	YL
19	SD2	14300	18.41	19.85	1.20	.588	.146	535.9	790.1	YL
20	SE1	27600	25.61	29.59	2.60	1.008	.873	131.4	151.8	YL

*O = orthogonal; YL = yield line.

TABLE 1-A2-PROPERTIES OF CONCRETE STRETCHED CRACKED ZONES (CONT.)

Test no.	Slab des.	Failure load P_u , lb	Concr. stret. area A_{t1} , in.	Concr. stret. area A_{t2} , in.	Cover factor R	Active steel ratio P_{t1} , %	Active steel ratio P_{t2} , %	Grid index $I_1 = \frac{\phi_1 s_2}{P_{t1}}$	Grid index $I_2 = \frac{\phi_2 s_1}{P_{t2}}$	Control. initial crack pattern O; YL*
21	SE2	53500	12.37	16.34	1.10	2.087	1.579	63.5	83.8	O
22	SE3	41000	19.57	23.54	1.20	1.319	1.096	108.9	131.0	O
23	WS1	119600	13.20	18.96	1.30	1.05	.73	92.4	132.8	O
24	WS2	104100	13.20	18.96	1.30	1.05	.73	92.4	132.8	O
25	WS3	98600	10.56	7.44	1.20	.57	.81	111.6	78.4	O
26	WS4	79600	7.44	10.56	1.20	.81	.57	78.4	111.6	O
27	WS5	104800	22.80	26.40	1.50	.26	.23	244.8	276.8	O-YL
28	WS6	105000	26.40	22.80	1.50	.23	.26	276.8	244.8	O-YL
29	WS7	81200	10.56	15.12	1.20	1.17	.58	65.2	131.6	O
30	WS8	84000	10.56	10.56	1.20	1.17	.58	65.2	131.6	O
31	WS9	73700	18.00	24.00	1.40	.48	.36	159.2	212.4	O-YL
32	WS10	82900	18.00	24.00	1.85	.48	.36	159.2	212.4	O-YL
33	WS11	85400	9.00	13.51	1.20	.77	.51	251.2	379.2	YL
34	WS12	81000	9.00	13.51	1.10	.77	.51	251.2	379.2	YL
35	WS13	105900	30.00	36.00	2.00	.43	.36	616.0	736.0	YL
36	WS14	109500	24.00	30.00	1.90	.54	.43	489.6	616.0	YL
37	WS15	74100	25.51	30.00	1.80	.25	.21	259.2	308.8	YL-O
38	WS16	63100	16.30	18.00	1.30	.39	.35	166.4	185.2	O-YL
39	WS17	65300	16.30	18.00	1.30	.39	.35	166.4	185.2	O-YL
40	WS18	65300	27.00	31.49	1.70	.23	.20	281.6	324.0	YL
	WS19	68300	28.49	33.00	1.80	.30	.24	159.0	198.9	YL

FURTHER FLEXURAL CRACK CONTROL

42	WS20	73000	18.00	15.00	1.30	.44	.53	108.6	90.0	O
43	WS21	73000	18.00	15.00	1.30	.44	.53	108.6	90.0	O
44	WS22	71900	25.51	22.46	1.60	.31	.36	153.9	132.6	O
45	WS23	68300	18.00	24.00	1.40	.33	.25	192.8	254.4	YL
46	WS24	62700	30.00	33.00	1.80	.20	.22	318.0	298.2	YL
47	WS25	84700	27.00	21.00	1.20	.26	.66	372.4	290.4	YL
48	WS26	74500	27.00	24.00	1.60	.26	.58	372.4	333.6	YL
49	WS27	79200	21.00	18.00	1.40	.32	.78	266.0	231.0	YL
50	WS28	84000	24.00	18.00	1.40	.29	.74	339.0	261.6	YL
51	WS29	73000	30.00	27.00	1.80	.31	.34	468.6	427.2	YL
52	WS30	70800	33.00	30.00	1.90	.28	.31	518.4	468.6	YL
53	WS31	68300	18.00	15.00	1.30	.51	.61	285.0	238.2	YL
54	WS32	77000	18.00	15.00	1.30	.51	.61	285.0	238.2	YL
55	WV1	81700	14.90	20.71	1.35	.926	.666	104.5	145.3	O
56	WV2	67700	14.29	18.88	1.30	.601	.455	127.1	167.9	O
57	WV3	63200	14.90	20.71	1.30	.463	.333	418.1	581.4	YL
58	WV4	63200	13.91	17.72	1.30	.427	.336	149.1	189.2	O-YL
59	WV5	69500	14.29	18.88	1.30	.601	.455	127.1	167.9	O
60	WV6	73000	14.90	20.71	1.30	.617	.444	235.1	327.2	O-YL
61	WV7	84000	16.50	25.50	1.35	.842	.545	423.1	653.7	YL
62	WV8	70500	14.90	20.71	1.35	.926	.666	104.5	145.3	O
63	WV9	57000	14.90	20.71	1.30	.463	.333	418.1	581.4	YL
64	WV10	66700	14.29	18.88	1.30	.801	.455	127.1	167.9	YL
65	WV11	76500	14.90	20.71	1.30	.617	.444	235.3	327.0	O-YL
66	WV12	70000	16.50	25.50	1.35	.842	.545	423.1	653.7	YL
67	WV13	65000	16.50	25.50	1.35	.842	.545	423.1	653.7	YL
68	WV14	74200	14.90	20.71	1.35	.926	.666	104.5	145.3	O
69	WV15	59000	14.90	20.71	1.30	.463	.333	418.1	581.4	YL
70	WV16	64000	14.90	20.71	1.30	.617	.444	235.3	327.0	O-YL
71	WV17	57200	14.29	18.88	1.30	.601	.455	127.1	167.9	O-YL

TABLE 1-A2—PROPERTIES OF CONCRETE STRETCHED CRACKED ZONES (CONT.)

Test no.	Slab des.	Failure load P_u , lb	Concr. stret. area A_{t1} , in.	Concr. stret. area A_{t2} , in.	Cover factor R	Active steel ratio P_{t1} , %	Active steel ratio P_{t2} , %	Grid index $I_1 = \frac{\phi_1/s_2}{P_{t1}}$	Grid index $I_2 = \frac{\phi_2/s_1}{P_{t2}}$	Control. initial crack pattern O; YL*
72	WV18	93200	16.10	24.31	1.45	.857	.567	319.3	482.5	YL
73	WV19	74300	14.29	18.88	1.40	.601	.455	127.1	167.9	O-YL
74	WV20	73600	14.12	18.37	1.30	.694	.533	76.5	99.6	O
75	WV21	70800	20.12	24.37	1.65	.487	.402	109.0	132.1	O
76	WV22	75600	14.90	20.71	1.40	.617	.444	235.3	327.0	YL
77	WV23	70600	16.10	24.31	1.45	.571	.378	718.7	1085.7	YL
78	WV24	83400	31.10	39.31	2.50	.443	.351	617.6	779.5	YL
79	WV25	77300	16.50	25.50	1.35	.842	.545	423.1	653.7	YL
80	WV26	67900	14.90	20.71	1.30	.463	.333	418.1	581.4	YL
81	WV27	80900	14.90	20.71	1.35	.926	.666	104.5	145.3	O
82	WV28	75800	14.29	18.88	1.30	.601	.455	127.1	167.9	O
83	WV29	73300	14.90	20.71	1.30	.617	.444	235.3	327.0	O-YL
84	WV30	51200	14.29	18.88	1.30	.601	.455	127.1	167.9	O-YL
85	WV31	47400	14.90	20.71	1.30	.463	.333	418.1	581.4	O-YL
86	WV32	72100	14.90	20.71	1.35	.926	.666	104.5	145.3	O
87	WV33	65500	16.50	25.50	1.35	.842	.545	423.1	653.7	YL
88	WV34	44300	14.90	20.71	1.30	.463	.333	418.1	581.4	YL
89	WV35	45600	14.29	18.88	1.30	.601	.455	127.1	167.9	O-YL
90	WV36	59600	16.50	25.50	1.35	.842	.545	423.1	653.7	YL



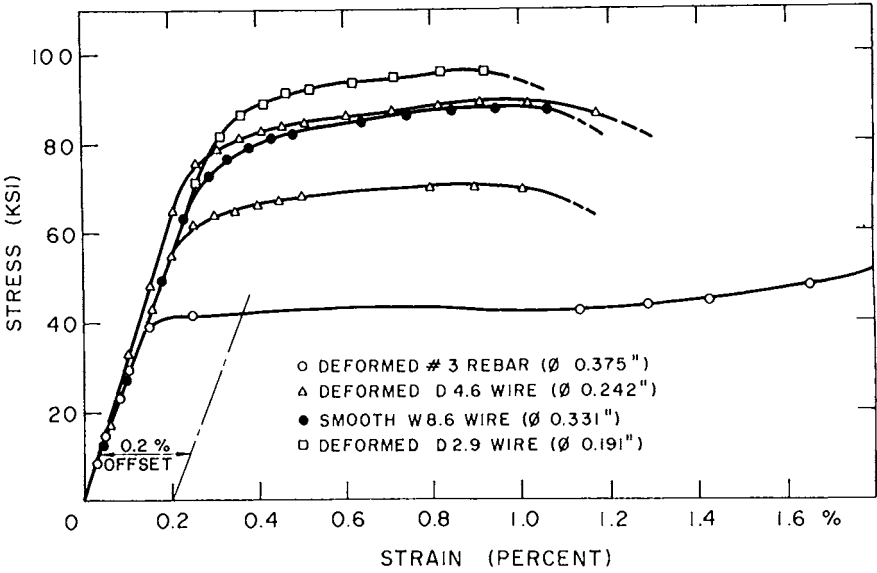


Fig. 1-1—Typical stress-strain diagram of reinforcement

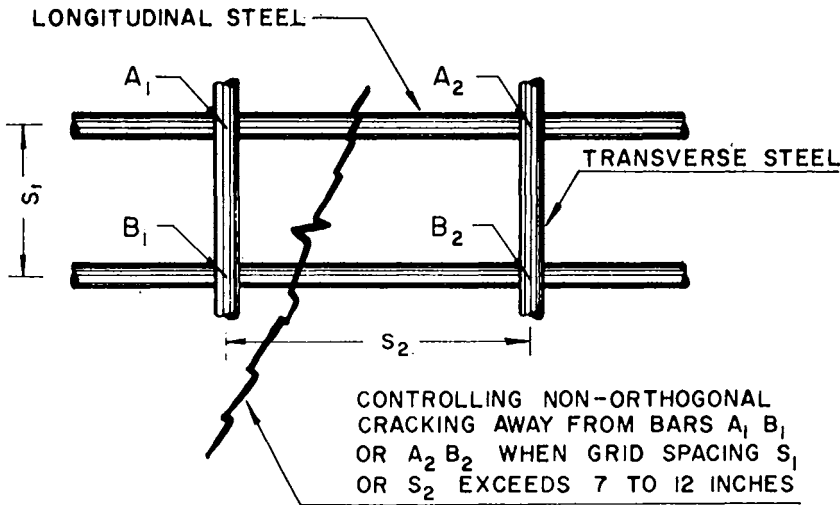


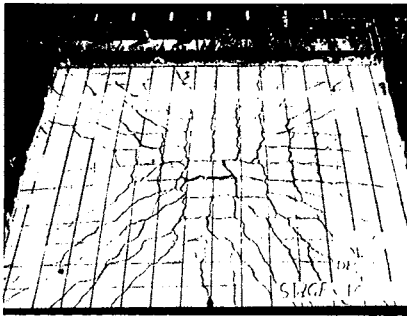
Fig. 1-2—Reinforcement grid unit



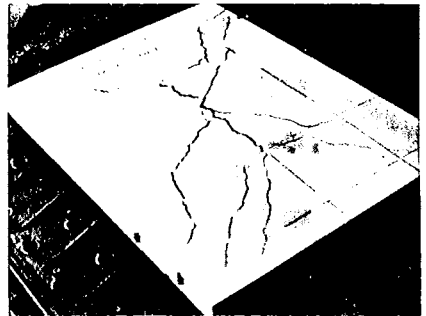
(a)



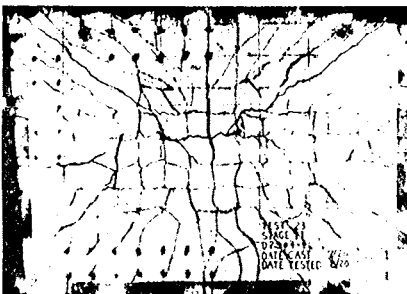
(b)



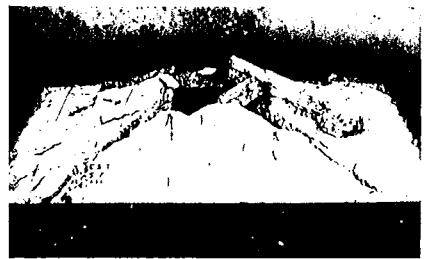
(c)



(d)

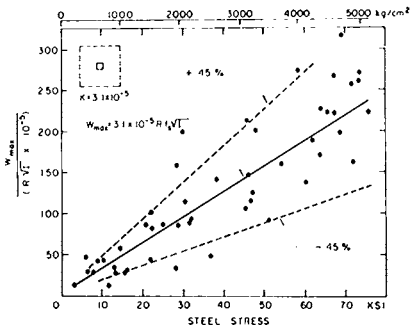


(e)

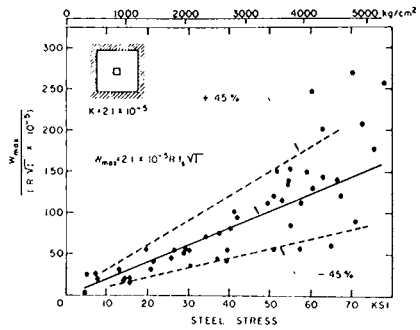


(f)

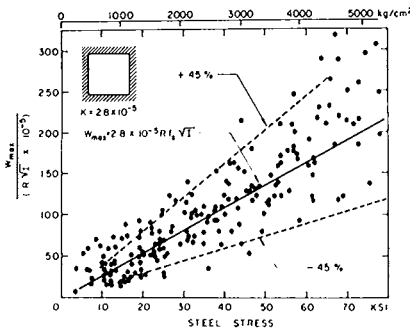
Fig. 1-3—Typical controlling cracking patterns. (a) Orthogonal: centrally loaded square slab. (b) Yield-line: centrally loaded square slab. (c) Orthogonal: uniformly loaded square slab. (d) Yield-line: uniformly loaded rectangular slab. (e) Orthogonal: uniformly loaded rectangular slab. (f) Slab at rupture.



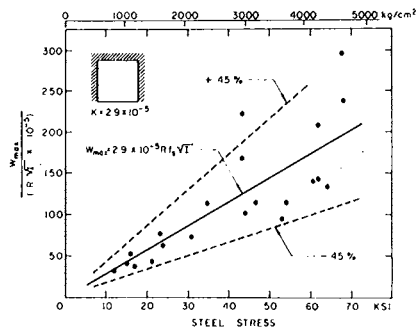
(a)



(b)

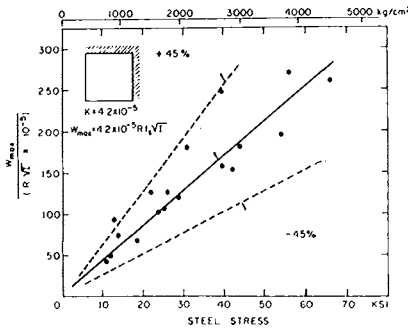


(c)

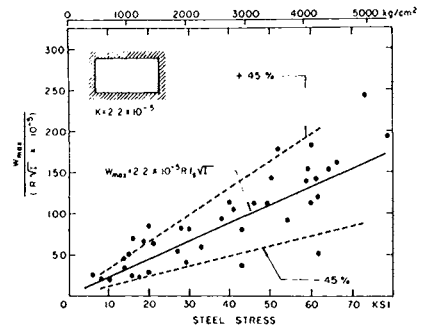


(d)

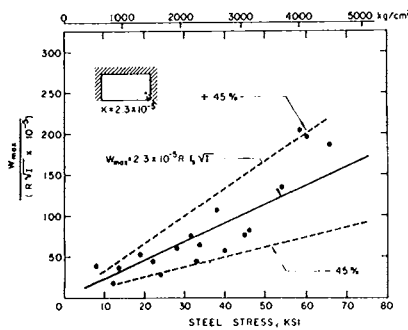
Fig. 1-4—Crack width vs. reinforcement steel stress. (a) Centrally loaded square slabs simply supported on all edges. (b) Centrally loaded square slabs restrained on all edges. (c) Uniformly loaded square slabs restrained on all edges. (d) Uniformly loaded square slabs restrained on three edges, hinged on one.



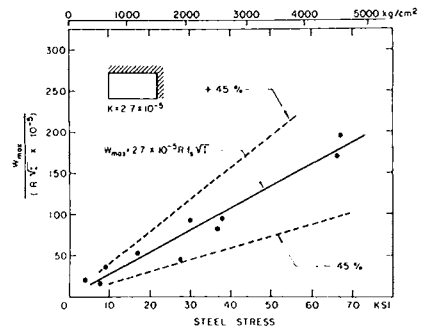
(e)



(f)



(g)



(h)

Fig. 1-4—Crack width vs. reinforcement steel stress. (e) Uniformly loaded square slabs restrained on two adjacent edges, hinged on the other two. (f) Uniformly loaded rectangular slabs restrained on all edges. (g) Uniformly loaded rectangular slabs restrained on three edges, hinged on one long edge. (h) Uniformly loaded rectangular slabs restrained on two adjacent edges, hinged on the other two

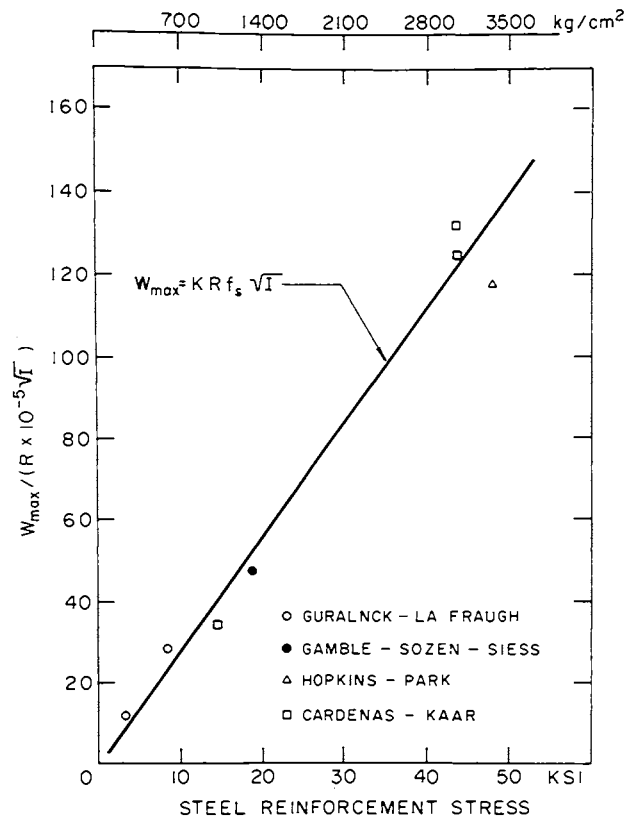


Fig. 1-5—Comparison with tests by others

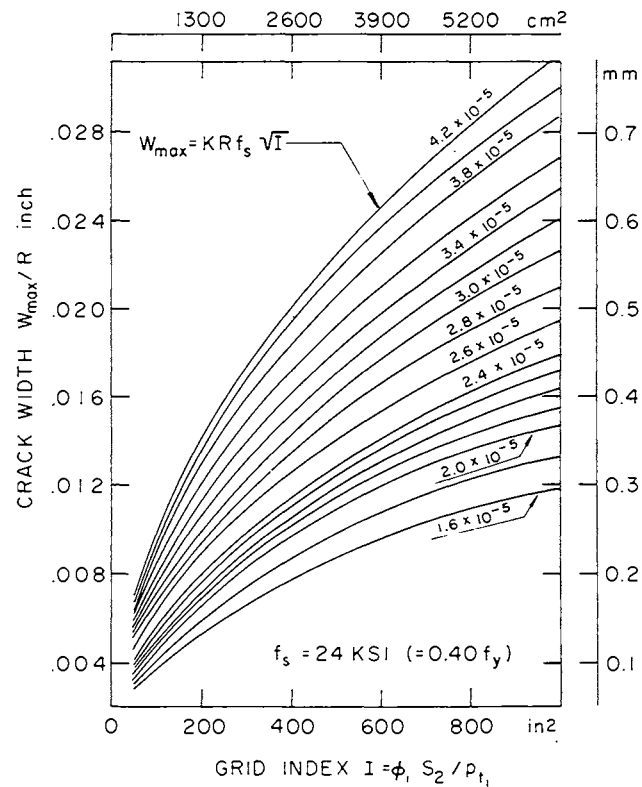


Fig. 1-6—Plots of grid index versus crack width at 24 ksi stress level for various load and support conditions

HUMAN RESPONSE TO CRACKING IN CONCRETE SLABS

By J. DÍAZ PADILLA and F. ROBLES

A technique is proposed for identifying and quantifying user needs in low-cost housing projects. This is done by correlating physical measures of the environment with psychological measures of the users. The method is illustrated with an attempt to develop acceptability criteria for cracking in concrete slabs.

Keywords: concrete slabs; cracking (fracturing); crack width and spacing; environments; psychology; reinforced concrete; research; residential buildings; serviceability.

□ A major economic and social problem is the development of low-cost housing. In a rational approach to the problem, housing may be conceived as a system and solutions may be obtained through the application of the techniques provided by systems engineering. With this approach, buildings are considered as consisting of a series of components and subsystems, combined in an orderly manner.

Housing is an extremely complex type of system since in considering the relations between the system, the users and the environment, it is necessary to take into account sociological and psychological parameters, which are difficult to evaluate. An especially difficult aspect is the identification and evaluation of user needs. This implies the establishment of serviceability criteria. In doing so, among other things, it is necessary to relate human response to the environment. Questions such as the following must be answered. What is the influence of living space on the well-being of the user? How much noise can be tolerated? How does an individual react to the visual characteristics of architectural surfaces?¹ What is the aesthetic significance of excessive deflections and cracking in reinforced concrete elements? To find answers to these questions it is necessary to obtain relationships between objective and subjective parameters employing physical and psychological measures.

Thus, for example, when we analyze the behavior of a structure under service loads we must establish when this behavior is "acceptable." This is not easy. In the present state of knowledge, the acceptability or non-acceptability of a structure's service behavior is based on the judgement of the engineer, that is, on subjective considerations. If it is desired to make a rational design in order to optimize the system, these considerations must be changed into objective ones. For this, as indicated above, tools for quantifying the parameters which influence the problem are necessary.

In this paper, a possible approach to the problem of relating human response to the cracking of slabs is suggested. A method of investigating the attitudes of users to cracking is proposed which should be of interest in establishing tolerable limits for crack widths. To illustrate the proposed approach its application to a

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typical low-cost housing project in Mexico City, the "Loma Hermosa" housing project, will be described. The buildings considered are three or four level structures consisting of masonry walls $5\frac{1}{2}$ in. (14 cm) thick which support two-way solid concrete slabs $3\frac{1}{2}$ in. (9 cm) thick. The underside of the slab is covered with plaster or a similar material applied directly to form the ceiling. The spans are very small, 9 ft 10 in. (3 m) wide by 12 ft $9\frac{1}{2}$ in. or 17 ft $2\frac{1}{2}$ in. (3.9 or 5.25 m) long so that minimum depth requirements govern the design. Consequently, the minimum reinforcement specified by the building code² is much more than the amount of steel needed for adequate strength. The possibility of relaxing minimum steel requirements is being considered,^{3,4,5} which of course raises the question of greater cracking. One of the objects of the Loma Hermosa research project was to investigate how much cracking users will tolerate as a first step in the development of rational design criteria for low cost buildings of the type described.

The research project outlined in this paper is a preliminary attempt to establish user needs and obviously is based on unrefined ideas which must be modified as the nature of the problem becomes more evident.

Before the results of the Loma Hermosa project are presented, some comments on the problems of designing for serviceability are offered and the techniques employed for quantifying damage and human response are reviewed.

SOME ASPECTS OF SERVICEABILITY DESIGN

From what has been said it is clear that one of the main difficulties of designing for serviceability consists in correctly identifying and evaluating user needs. Consider, for example, the different needs of the various people directly or indirectly involved in a building project, concerning cracking, deflection, durability, noise, or some other aspect.

The difficulty of defining needs becomes apparent when one attempts to analyze user reactions towards damage. To understand the nature of the problem,

we can plot a function $W = W(I)$ for different individuals and situations in which I represents a rating index used to measure a particular type of damage and W , a parameter that takes into account factors such as cost of repairs and human response (attitude). In this paper, this parameter shall be called "relative unhappiness" (the concepts of rating index and relative unhappiness will be discussed in the following sections). If, for simplicity, the lines joining key points are considered to be straight, graphs such as those shown in Fig. 2-1 are obtained. Obviously, for different situations, individuals, and damage indices, the relationships may change considerably.

Indices for Rating Damage (I)

To establish damage-relative unhappiness relationships, it is necessary to find a way of assigning arbitrary values to given degrees of damage.

In other words, indices of damage must be established. In the case of cracking, examples of indices for rating could be the maximum crack width, or the crack area divided by the area of the slab.

Rating indices should have two basic properties:

1. They should be predictable, that is, given the properties of the materials, the geometry of the element, and the construction method as well as the magnitude and the distribution of loads, there must exist reliable methods for predicting index values or their probability distribution.
2. They should correlate sufficiently well with the relative unhappiness.

Relative Unhappiness (W)

The importance of damage in the structure should be established according to the human response or attitude of the users (from indifference to strong reaction) and the cost of repairs ($0 \rightarrow \infty$).

In practice, these factors should be transformed to a single number representing the relative unhappiness caused by the damage under consideration. The lower end of the unhappiness scale will represent values of W corresponding to unnoticed unobjectionable damage, and the upper end, values corresponding to obvious and irreparable damage.

Applications of the $W = W(I)$ Function

Once a $W = W(I)$ function (with W expressed in money) has been established for a certain type of damage, and if the cost of different structural alternatives and the expected values of the damage indices are known, it is theoretically possible to find optimum solutions. However, such solutions are strictly valid only for conditions existing at a given time. The change in attitudes with time, for example, is extremely difficult to predict, so that it is a formidable task to develop models that take such changes into account. Notwithstanding this limitation, knowledge of the relationship between damage and relative unhappiness is useful when making decisions connected with design. In the conventional approach to design, user needs, or, in other words, the influence of the relative unhappiness of the user, are seldom considered in a rational way. On the other hand, if the function $W = W(I)$

is known, comparisons of different alternatives can be made in which relative unhappiness can be considered quantitatively through the expected value of this parameter given by

$$\int W(I) p(I) dI$$

where $p(I)$ = probability that I occurs.

This approach makes it possible to establish, in a more rational manner, the maximum limits of tolerable damage, and, in general, to facilitate the study of serviceability requirements in design.

A RATING INDEX FOR CRACKING IN SLABS

To establish relationships between relative unhappiness and damage it was seen that it is necessary to develop rating indices providing a simple quantitative measure of the damage in question. In the following paragraphs the procedure for developing such indices for rating the magnitude of cracking in slabs is described.

The complete configuration of cracking of 74 slabs was obtained and the length and width of the cracks at several points were measured.

A rating index called Index of Specific Cracking (ISC) was first proposed. This index can be expressed as

$$ISC = \frac{\sum_{i=1}^N (\text{average width} \times \text{length})_{\text{crack } i}}{\text{area of slab}}$$

where N is the number of cracks.

This index represents crack area per unit slab area and does not depend on the dimensions of the panel. It gives the same weight to the length and to the width of the cracks and does not take into account position, which was seen to be entirely random. From a practical point of view, the ISC is inconvenient as it involves a considerable amount of field measurement. Furthermore, it is difficult to develop models for predicting the ISC. In view of this, another index was chosen which required simpler measuring procedures, was easy to predict, and, at the same time, exhibited correlation with the ISC. The adopted index was the maximum crack width. The correlation between the two indices is shown in Fig. 2-2. An additional advantage of this index is that the crack width is the characteristic of cracking which first attracts a tenant's attention.

In the Loma Hermosa Housing project, cracking was evaluated by measuring the maximum crack width employing the ruler shown in Fig. 2-3.

QUANTIFICATION OF HUMAN RESPONSE

As mentioned previously, to study user response to damage such as cracking, methods of quantifying this response must be developed. The methods commonly

employed are based on psychological techniques.^{6,7} In this section, the procedure employed in the Loma Hermosa housing project to measure user's attitude (human response) towards cracking is outlined.

Attitude is defined as the degree of positive or negative feeling associated with some psychological object. In this connection, the quantification of human response or the measuring of attitude in research problems requires a scale of attitudes to measure the degree of feeling that individuals have with respect to a certain psychological object.

An attitude scale is simply a set of statements about the object under study. The construction of the scale, which probably is the most delicate step of the process, since the success or failure of an investigation depends on it, consists in the elaboration of statements according to a definite set of rules. The application of the scale consists in asking the individuals under investigation to react to these statements in some way, such as expressing an opinion on them or listing them according to the degree of agreement, so that through statistical procedures a number can be assigned to each individual which will be his rating or the measure of his attitude.

A great many methods of elaborating attitude scales exist. The only one which will be discussed here in some detail is the method of summated ratings (Likert's scale) which was the procedure employed in the Loma Hermosa project.

The attitude scale towards cracking consisted of the following nine statements:

1. "The cracks are proof that very bad materials were used in the construction of this apartment."
2. "The cracks bother me a lot, mainly because of the leaking caused by them."
3. "In case of an earthquake, the existence of cracks produces fear that the apartment will collapse."
4. "Cracks in any part of the apartment give the feeling of danger."
5. "Cracks make the apartment look very bad."
6. "Cracks annoy me."
7. "It is unpleasant to have an apartment with cracks."
8. "A cracked ceiling gives a bad impression of the apartment."
9. "When an apartment has cracks, it is because of its poor quality."

As can be seen, all the statements express an unfavorable reaction; that is, agreement with anyone of them indicates an unfavorable attitude and disagreement, a favorable one.

The method of summated ratings consists in measuring the degree of agreement or disagreement that the individuals under investigation feel towards each one of the statements which make up the attitude scale. For this purpose, the interviewed persons had to choose one of the following alternatives for each statement:

- Do you agree?
- (1) Strongly agree
 - (2) Agree
 - (3) Uncertain
 - (4) Disagree
 - (5) Strongly disagree

To assign numerical grades to attitudes, scalar values must be given to each one of the five categories for all the statements so that adding the scalar values representing the various reactions towards each statement, the attitude of each individual can be computed. The scalar values represent the relative positions of the different alternatives to the different statements in the psychological continuum.

The procedure used to obtain the scalar values is illustrated with a numerical example (Table 2-1) for the five categories of Statement 3. Relative frequencies are obtained in each of the five categories (Row 1) for a minimum of 200 data (269 data were obtained in the Loma Hermosa investigation) and the cumulative frequencies (Row 2) are computed in such a way that for the most favorable condition (complete agreement for favorable statements or, in this case, complete disagreement) the value 1.0 is obtained. Row 3 shows the sum of relative frequencies which fall below a certain category plus half the relative frequency corresponding to this category. The normal deviates,^{6,8} z , are shown in Row 4, z being the values of a random variable with normal distribution which define areas under the curve equal to the values of Row 3. This set of values can be used as a set of scalar values. Since we are interested in the relative values we add 0.820 to all the scalar values in order to have the value of zero in the most unfavorable position and thus z will always be positive.

To check whether the employed statements are sufficiently discriminating or not, (that is, if the mean attitude of a group with high attitude ratings differs significantly from that of a lower group), which is necessary for the scale to function adequately, the following procedure is used. For each statement the value of the variable t is obtained (Student- t distribution^{6,8}) for the 25 percent highest ratings and the 25 percent lowest ratings of all the individuals. The statement is accepted if the value of t is greater than or equal to 1.75. The t values obtained for the nine statements are shown in Table 2-2. As can be seen, all the statements have t values greater than 1.75 and thus, the scale is well constructed.

HUMAN RESPONSE DUE TO CRACKING IN SLABS

In the Loma Hermosa Housing project, an attempt was made to correlate a physical measure of the cracking in the slabs (the maximum crack width) with the response or attitude of the users.

Simultaneously with the measuring of cracking (as explained above) a series of data corresponding to one of the inhabitants of each apartment was collected. First, identification data were obtained (sex, education, and so on) and then Likert's scale was applied. Data were registered in codification sheets in order to rapidly convert the information to punched cards and to process it electronically.

With the exception of the initials of the project and the identification of the building's entrance, where alphanumeric characters were used, all the data were transformed into numbers. In the case of the age of the interviewed person or the apartment's area, numerical data are direct. With data such as educational level or type of building, it was necessary to have equivalences between characteristics and numbers. This treatment of the data made it possible to separate automatically groups with some common characteristics, and in some cases, how certain factors influence attitudes.

Six hundred and five questionnaires were obtained (that is, 605 apartments were inspected), of which 269 correspond to individuals living in apartments with cracked slabs. The data corresponding to apartments without ceiling cracks were not taken into account since it was assumed that they did not reflect the attitudes towards cracking (a fact which was later confirmed when mean attitudes of persons living in apartments without ceiling cracks were computed and unreasonable values were obtained). Once the scalar values for each response of each statement were computed (employing only the group of 269 data), attitudes were obtained by means of a computer program.

Mean attitudes were computed for different groups of individuals and tests of hypotheses concerning means were carried out (significance level $\alpha = 0.1$) to prove whether the existing differences in the means of the different groups were significant or not. Before these tests were carried out, the normality of the samples was checked by employing probability graph paper, and hypothesis tests for variance were made by means of an F distribution with $\alpha = 0.01$. Since, as attitude increases, dislike and annoyances diminish and since we are interested in relative values, attitudes were transformed and made relative to the largest numerical value so that they would go in the same direction as annoyances. It is important to mention that the neutral position is not known so that inferences of absolute nature are not possible.

The manner in which attitudes change when damages change was studied. Data were grouped into five categories corresponding to the five maximum widths of cracks found: 0.002, 0.004, 0.006, 0.008, and 0.01 in. (nominally 0.05, 0.1, 0.15, 0.20, and 0.25 mm) and an attempt was made to find some relationship between damages and attitudes. After the tests indicated above were carried out, the results given in Table 2-3 were obtained.

The results indicate that for the range of crack widths observed, only two groups of attitude were identifiable; group I, corresponding to very fine cracks with a maximum width of 0.002 in. (nominally 0.05 mm), and group II, corresponding to the rest of the observed cracks. In other words, the attitude of the users is the same although the widths of the cracks vary from 0.004 to 0.010 in. (nominally 0.10 to 0.25 mm). The increase in attitude is 23 percent of the attitude of individuals with very small cracks in their slabs.

From this point of view 0.010 in. (nominally 0.25 mm) can be defined as the maximum allowable width of cracks due to subjective considerations. This value happens to coincide with the current practice of maximum allowable crack width due to structural considerations.⁹ Since larger cracking was not observed, the existence of this type of correlation up to even higher values of the crack index is suspected but could not be proved.

When only subjective parameters were studied, it was found that the educational level plays an important role in the attitudes towards slab cracking. Table 2-4 shows how relative attitude changes with education.

If unity is taken to be the attitude of individuals of group I with a very high educational level or none at all, the fact of having some education results in greater attitude (dislike) when the cracks are small. In group II, only the individuals with relatively good educational background are less sensitive to slab cracking.

With occupation as a parameter, the educational level is reflected in an indirect manner (Table 2-5).

No influence was found in cracking attitude due to parameters such as the area of the apartment, the user's age, the number of persons living in the apartment or the type of building or apartment.

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TABLE 2-1—SCALAR VALUES

Do you agree?	Strongly agree	Agree	Uncertain	Disagree	Strongly disagree
(1) Relative frequency	0.41	0.16	0.07	0.12	0.24
(2) Cumulative relative frequency	0.41	0.57	0.64	0.76	1.00
(3) Midpoint of the cumulative relative frequency	0.20	0.49	0.60	0.70	0.88
(4) Z normal deviates	- 0.82	- 0.02	0.27	0.52	1.17
(5) $z + 0.82$	0.00	0.80	1.09	1.34	1.99

TABLE 2-2—STATEMENTS OF THE ATTITUDE SCALE;
t-VALUES

Statement no.	t values, group of 269 data
1	10.3
2	11.4
3	15.6
4	12.2
5	5.7
6	9.6
7	13.7
8	4.9
9	8.3