*- Technical Report -*

# A STUDY ON CRACKS IN BEAMS AND SLABS of EXISTING REINFORCED CONCRETE BUILDINGS AND PERPENDICULAR MARGIN LOADS

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ABSTRACT
Data was collected from field investigation reports attached to the earthquake resistance evaluation reports of existing reinforced concrete buildings. First, cracks in girders, beams, and slabs of existing reinforced concrete buildings were analyzed regarding their locations, widths, and patterns. Then, the perpendicular margin loads were expressed by the margin rates of loading to clarify the tendency of the margin rate of loading on girders, beams, and slabs of existing reinforced concrete buildings.
Keywords: existing building, crack, margin rate of loading, long-term allowable tensile stress

## 1. INTRODUCTION

Cracks in reinforced concrete buildings are generally revealed in cases of serious damage to buildings. Cracks that do not attract attention under general conditions of use seem to go unnoticed. However, even such complaint-free cracks, are subject to considerable tensile stresses, particularly the reinforcing bars at the crack locations.

Stresses on tension bars of bent reinforcement members are known to increase greatly due to concrete shrinkage due to drying [1]. In addition, the concrete shrinkage by drying of a wall body was reported to increase the stress on a tension bar to a significant level [2]. In other words, once a crack occurs, the stress on the tension bar at the location may become greater than the long-term allowable tensile stress.

To suppress the concrete crack width to approximately 0.2 to 0.3 mm, the Standard for Structural Calculation of Reinforced Concrete Buildings of the Architectural Institute of Japan is indirectly controlling cracks by keeping the tension bar stress under a long-term load within the long-term allowable tensile stress of 200 N/mm$^2$ or less. According to reports, this method has been validated well on the laboratory level but not enough on existing reinforced concrete buildings.

Crack width poses a problem under a long-term load that is the sum of the dead load and live load. The dead load, the self-weight of a building, hardly fluctuates, but the live load may fluctuate greatly depending on the use of the building. In general, the reinforced concrete buildings often have the cracks on the beams and the slabs, so on. Therefore, it is necessary to decide the magnitude of the live load not only from the aspect of the long-term allowable tensile stress but also the aspect of the crack.

To solve these problems, we should quantitatively clarify the correlations between the reinforcement stress and live load of the cracked member under a long-term continuous load. However, no such studies seem to have been conducted.

Therefore, data about cracked girders, beams, and slabs was collected from existing reinforced concrete buildings to clarify the following two points:

(1) Complaint-free cracks under general conditions of use and their widths

(2) Correlations between a crack and live load
Allowable stress is converted and defined as the perpendicular margin load. Then the margin between perpendicular margin load and design live load is studied.

## 2. DATA COLLECTION

### 2.1 Data Collection and Object Crack Width

In this study, data was collected from field investigations of earthquake resistance evaluation reports of existing reinforced concrete buildings in a certain prefecture. The evaluation reports were created on the basis of “Law Concerning the Promotion of Building Alterations for Earthquake Resistance.”

Reports of the field investigation state the crack conditions and widths. Crack widths are separated into three classes of 0.3 mm or greater, 0.2 mm, and 0.1 mm or smaller. For data collection, crack conditions and cross-sectional properties were extracted from cracks of 0.2 mm and 0.3 mm or greater in girders, beams, and slabs. Cracks of actual widths 0.3 mm or greater cannot be investigated from field investigation reports.

### 2.2 Data Collection Method

We collected data about cracks by noting the following points:

(1) A slab surrounded with girders is counted as one structure.

(2) The field investigation report states the lengthwise location, width, and direction of a crack in a girder or

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beam but not the vertical location. From the field investigation report, therefore, we cannot attribute a crack in a girder or beam to bending stress or drying shrinkage. For a slab, the field investigation report states a crack in the bottom face. We cannot tell whether a crack in the bottom face can also be seen from the top face.
(3) If floors of different uses adjoin at a girder or beam, the use of the floor with the greatest live load is taken as the room use necessary for estimating a design live load. If a slab is partitioned into several rooms, the use of the room with the greatest live load is taken.

### 2.3 Definitions of Terms

The main terms are defined here.

・Investigated member: Member that was investigated
・Cracked member: Member having a crack
・0.2 mm (0.3 mm) crack member: Member having a crack 0.2 mm (0.3 mm) wide
・Design live load: Live load based on the law
・Perpendicular margin load: Load converted by the equi-distribution load from the difference between the long-term allowable stress and the reinforcement stress estimated from a crack
・Margin rate of loading: Ratio of the perpendicular margin load to the design live load

## 3. CONDTIONS OF CRACKS IN GIRDERS, BEAMS, AND SLABS OF EXISTING REINFORCED CONCRETE BUILDINGS

### 3.1 Crack Widths of Cracked Members

(1) Numbers of cracked members in buildings

Of 256 reinforced concrete buildings in a certain prefecture, constructed in the period from 1936 until 1981, 52 (20% in total buildings) showed 0.2 mm or greater crack in girders, beams, and slabs. The buildings were 49 schools and 3 hospitals (health centers). For all buildings that showed cracks, Table 1 lists the total number of members, the number of investigated members, the number of 0.2 mm crack members, and 0.3 mm or greater crack members.

As Table 1 shows, the percentage of 0.3 mm or greater crack members among the 0.2 mm or greater crack members was 88% for girders, 88% for beams, and 64% for slabs.

(2) Tendency of crack width by members

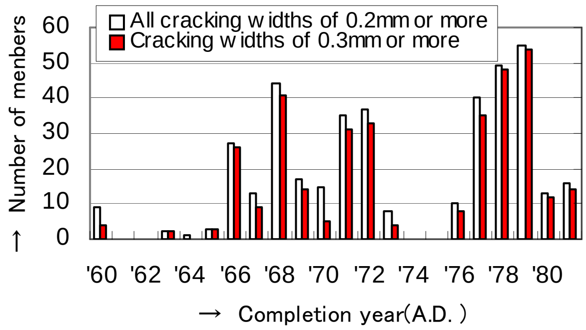
According to the year of construction, crack locations were classified into girders, beams, and slabs. Then the cracked members were classified by crack width into two groups of 0.2 mm or greater crack members (including 0.3 mm or greater crack members) and only 0.3 mm or greater crack members. Fig. 1 (1) to (3) shows the results of the classification.

From the figure, we see that 0.3 mm or greater crack member account for nearly 90% of the girders and beams with 0.2 mm or greater cracks. Once a crack occurs, the crack width almost never remains at 0.2 mm.

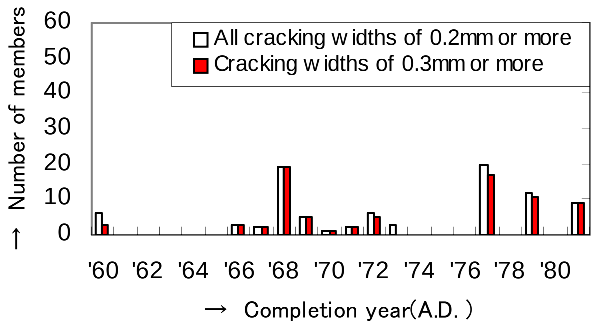
Table 1 Details of the crack member in 52 buildings

| Name of member | Number of all members | Number of investigated members | Number of crack member | | |
|---|---|---|---|---|---|
| | | | A. 0.2mm or more | B. 0.2mm | C. 0.3mm or more |
| Girder | 5109 | 2913 | 394 | 50 (0.12) | 344 (0.88) |
| Beam | 1534 | 865 | 89 | 11 (0.12) | 78 (0.88) |
| Slab | 3208 | 1302 | 207 | 75 (0.36) | 132 (0.64) |

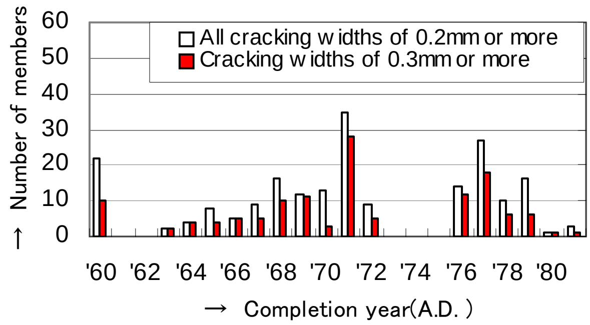
Note 1 : The number of all members is a total of 52 buildings.
Note 2 : A value in ( ) of a B column and the C column is the ratio for A




(1) Girder




(2) Beam




(3) Slab

Fig.1 Tendency of the crack width that occurred to each member

Even among slabs with 0.2 mm or greater cracks, 0.3 mm or greater crack members account for more than 60%.

### 3.2 Crack Locations and Patterns by Member

The crack conditions of the members were reviewed and the crack patterns were roughly classified into basic and compound patterns. A basic pattern indicates the crack conditions of a member with a single crack only. The basic patterns were further classified by crack location or direction. A compound pattern is composed of several basic patterns. A member with several cracks can be expressed by a compound pattern.

(1) Girder and beam

The basic crack patterns of girders and beams were distinguished by three crack locations (one end, center, or both ends). Table 2 gives the numbers of cracked members of the basic and compound patterns. For the girders and beams, the field investigation reports state many vertical cracks. As mentioned earlier, we cannot tell whether a crack is located at the upper or lower end of a beam.

From this table, we see that girders and beams usually show only a single 0.2 or greater crack on one end or at the center and seldom show more than one cracks. Once a crack occurs, it seems that no more cracks occur.

(2) Slab

Structures of Slabs surrounded by girders are classified into three basic types (slab with no beam, slab with one beam, and slab with two beams). Fig. 2 shows the basic pattern of the cracked slabs.

Fig. 3 shows the distribution of the number of cracked members of the basic pattern.

The cracked slabs of the basic pattern accounted for 77% of all the cracked slabs, indicating the high proportion of this pattern.

Since several cracks occurred, the number of compound patterns was 21. However, the number of slabs belonging to each pattern was 1 or 2. As in the girders and beams, the slabs did not seem to suffer from several cracks.

The same figure shows that there are considerably many cracks appeared and they are represented as NA, NB, OA, OB, TB and TD. According to this, it is found that cracks generally tend to occur around the corner due to the shrinkage caused by drying.

Bending stress is the main factor for cracks in the top face at the ends and in the bottom face at the center. For the basic patterns shown in Fig. 3, ND, NG, OD, OE, OG, TE, TH and TL may be the cracks caused mainly by bending stress. Bending stress was the cause of only 19% of cracked slabs of both the basic and compound patterns. Considering these slabs, there are not many cracks attributable to bending stress.

## 4. PERPENDICUIAR MARGIN LOAD

### 4.1 Effectiveness of Analysis

In this analysis, by using the margin rate of loading, the correlation between the width of crack, the long-term load and the design live load in existing reinforced concrete buildings is examined.

However, "cracks more than 0.3mm" assumed uniformly as 0.3mm. Furthermore, the actual size of cross-sectional size is unknown. This is because the cross-sectional size which is mentioned in the report of the field investigation states only the data of the structural calculation document. The thickness of cover is also uncertain in many cases. Therefore, there are a lot of limits in these results of the analysis since such uncertain sectional quantity and the thickness of cover that is specified by the Building Standard Act are

Table 2 Crack pattern of both the girder and the beam and the number of the members

| basic pattern of the crack | | |
|---|---|---|
| A | B | C |
| ●——— | ——●—— | ●———● |

| | | Crack pattern | number of the members |
|---|---|---|---|
| Girder | basic pattern | A | 217 |
| | | B | 143 |
| | | C | 7 |
| | combined pattern | A+B | 25 |
| | | B+C | 2 |
| | Total | | 394 |
| Beam | basic pattern | A | 48 |
| | | B | 34 |
| | combined pattern | A+B | 7 |
| | Total | | 89 |

Note 1 : A black circle shows the position in which the crack occurs.

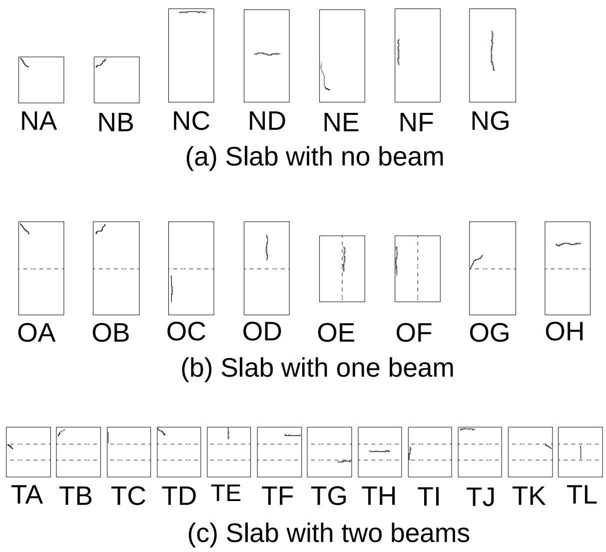



Fig.2 Basic crack pattern of slab

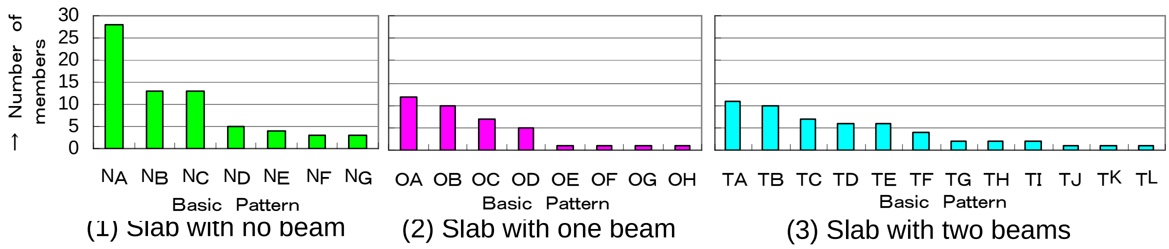



Fig.3 Number of slabs to each crack pattern

applied.

Therefore, it is very important to verify these results by using definite data in further study.

### 4.2 Margin Rate of Perpendicular Margin Load

If a crack occurs, the tension bar stress at the location changes to a stress by the crack as well as the existing long-term load. If an additional perpendicular load makes the tension bar stress reach the long-term allowable stress, the perpendicular load is called the perpendicular margin load. In other words, this load is converted by the equi-distribution load from the difference between the long-term allowable stress and the reinforcement stress estimated from the crack.

A formula was created to calculate the reinforcement stress that is generated on a girder, a beam, or a slab by the equi-distribution load vertically imposed on the face. The perpendicular margin load is when the reinforcement stress in the formula is equal to the remaining stress expressed by Eq. (1).

$$f_v = f_t - f_{tc} \tag{1}$$

where,

$f_v$ : Remaining stress on reinforcing bar

$f_t$ : Long-term allowable stress

$f_{tc}$ : Reinforcement stress by crack

The reinforcement stress by crack $f_{tc}$ was calculated from the crack width by using the Guidelines for the Design and Construction of Pre-stressed Reinforced Concrete (Type III PC) Structures [3].

The margin rate of loading defined by Eq. (2) indicates how much load each member can accept until the reinforcement stress at the crack location reaches the long-term allowable stress.

$$\eta = \frac{w_A}{w_L} \tag{2}$$

Where,

$\eta$ : Margin rate of loading

$w_A$ : Perpendicular margin load

$w_L$ : Design live load

The perpendicular margin load on a girder or a beam was calculated by assuming a crack at an end.

A slab cannot be handled equally as a girder or a beam because it has two directions. Here, a perpendicular margin load on a slab is defined as follows:

(1) If there is a crack parallel with the short side, the perpendicular margin load is either the load when the reinforcement stress on the short-side end reaches the allowable stress or the load when the reinforcement stress on the long-side end reaches the allowable stress, whichever is smaller.

(2) If there is a crack parallel with the long side near the center, the perpendicular margin load is either the load when the reinforcement stress at the location reaches the allowable stress or the load when the reinforcement stress on the long-side end reaches the allowable stress, whichever is smaller.

(3) If there is a crack near the long-side end, the perpendicular margin load is the load when the reinforcement stress on the long-side end reaches the allowable stress.

### 4.3 Assumptions for Calculation

(1) The crack widths and positions comply with the investigation data of existing reinforced concrete buildings. If an earthquake resistance evaluation report says "0.3 mm or greater crack," the crack width is assumed to be 0.3 mm.

(2) The crack width $w_p$ stated in a report is regarded as not the average crack width but the maximum crack width $w_{\max}$ .

(3) From the field investigation reports, we cannot tell whether a crack is located at the top edge or bottom edge. Here, such a crack is assumed to be located at a tension edge.

(4) The compressive strength of concrete and the cross-sectional properties of the reinforcement bar comply with data given in the field investigation reports.

(5) The thickness of coverage is assumed to be 40 mm for a girder or beam and 20 mm for a slab.

(6) The drying shrinkage strain $\varepsilon_{sh}$ is assumed as 200μ for the girder or the beam and 300μ for the slab. These values were adopted based on the Standard for Structural Calculation of Reinforced Structures [1]. The effectiveness of these values is indicated in the Recommendations for Design and Construction of Partially Prestressed Concrete (Class Three of Prestressed Concrete) Structures [3].

(7) A girder or a beam is assumed to be secured on both ends, and the design live load and perpendicular margin load are assumed to show a hexagonal equi-distribution load.

(8) A slab surrounded with girders or beams is counted as one, and an equi-distribution load is assumed to be on the slab**.**

(9) For the reinforcement stress at a crack location, the following Eq. (3) is used for approximation.

$$M = \frac{7}{8} a_t \sigma_t d \tag{3}$$

Where, $M$ : bending moment

$a_t$ : Area of section on reinforcing bar

$\sigma_t$ : Reinforcement stress

$d$ : Effective depth

### 4.4 Members Used for Study

For this study, girders and beams satisfying the following conditions were used as members:

(1) The crack width near an edge is 0.2 mm or greater.

(2) There is no bearing wall above or below the girder or beam.

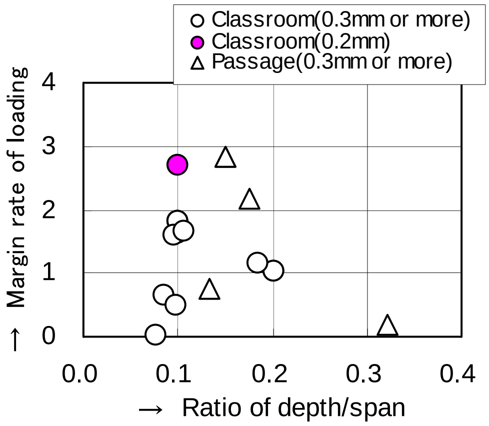



Fig.4 Outside girder

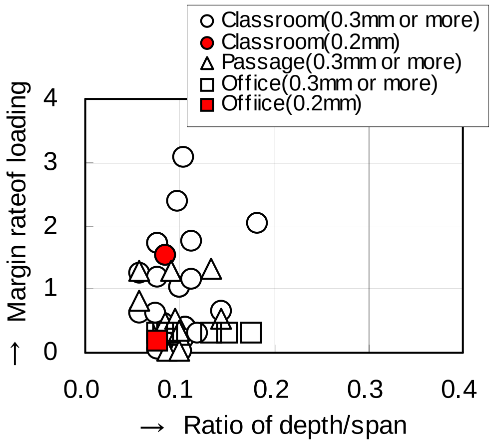



Fig.5 Inside girder

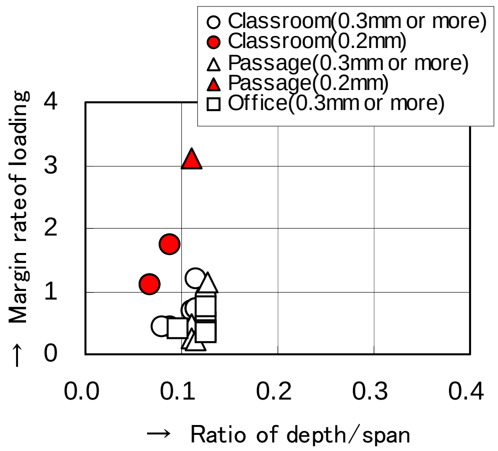



Fig.6 Beam

(3) The crack is of Pattern A or C among the basic patterns shown in Table 2 or of a composite pattern containing Pattern A.
(4) The cross-sectional dimensions and reinforcement arrangement are known and the length of the member is about 4 m or longer.

The slabs used in the study were 2.5 m or longer on the short side with a crack parallel to the side (as shown in Fig. 2, this would include the basic types of ND, NG, OD, OE, OG, TE, TH, and TL or any compound type containing the basic types), whose thickness and reinforcement arrangement were known.

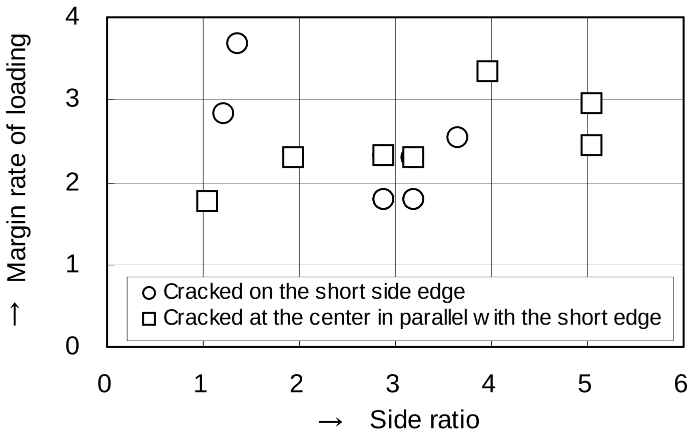



Fig.7 Margin rate for Design live load

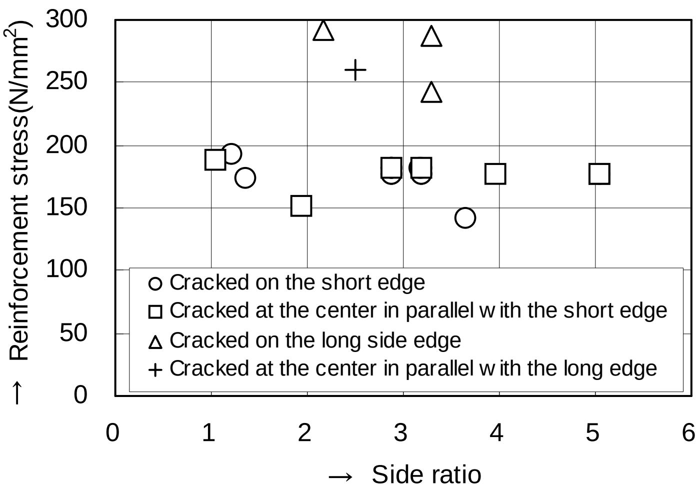



Fig.8 Reinforcement stress at crack location

Regarding girders, the stress on the tension bar at an edge calculated from the crack width exceeded the long-term allowable stress (up to approximately 10% over the long-term allowable stress) in 14 of the members. Likewise, 4 slabs showed a stress beyond the long-term allowable stress.

Therefore, the perpendicular margin load was studied for 65 girders. There were 18 external girders around buildings and 47 internal girders inside buildings. The perpendicular margin load beam was also studied for 25 beams and 20 slabs.

## 5. CORRELATIONS BETWEEN PERPENDICULAR MARGIN LOAD ON CRACKED BENT MEMBER AND DESIGN LOAD

Figs. 4 to 6 show the margin rates of loading of external girders, internal girders, and beams. The horizontal axis indicates the ratio of depth to span. The margin rate of loading is distinguished by the room use and crack width. A numeric value in the legend indicates the crack width at the end of a member.

The margin rate of loading is over 1 for members with 0.2 mm or greater crack, except for one member. For the stress on the tension bar at the end of a member to reach the long-term allowable stress of 200 $N/mm^2$, the perpendicular load should be greater than the design live load.

The margin rate of loading reaches approximately 3 for members with 0.3 mm crack but the rate is mainly in the range from 0.5 to 1.2. Therefore, if a perpendicular load approximately equal to the design live load is imposed on a member with a 0.3 mm crack, the stress on the tension bar at the end of a member reaches the long-term allowable stress of 200 $N/mm^2$. This tendency is especially notable for beams.

Fig. 7 shows the margin rates of loading on slabs. The horizontal axis indicates the side ratio (long-side length / short-side length). Primarily, slabs with two beams were measured and their side ratio was more than 2.

The calculated slabs had either a crack on the short-side end or one at the center parallel to the short side. Consequently, the margin rate of loading ranged from approximately 1.7 to 3.7. There was still a great margin for the stress on the tension bar on the long-side end to reach the long-term allowable stress of 200 $N/mm^2$.

Fig. 8 shows the reinforcement stresses of slabs at the crack locations, including slabs for which the stresses at the crack locations exceeded the long-term allowable stress. In all of the four slabs cracked on the long-side end or at the center parallel to the long side, the reinforcement stress at the crack location exceeded 200 $N/mm^2$ and a load greater than the design live load could not be imposed.

## 6. CONCLUSION

We collated the real condition of cracks in existing reinforced concrete buildings. Although the calculation was performed using the assumption of “more than 0.3mm crack was equal as 0.3mm”, the correlations between the crack and the live load were examined by the perpendicular margin load. The results are following:

(1) Many cracks in girders and beams were 0.3 mm or greater.

(2) A girder or beam very often has a 0.2 mm or greater crack on one end or at the center of the member.

(3) Many girders showed single cracks only, irrespective of the slab pattern (slab with no beam, slab with one beam, or slab with two beams). Many cracks were generated at corners in radial or ring forms by drying shrinkage. Not many cracks were generated by primarily bending stress.

(4) The margin rate of loading exceeded 1 for many of the girders and beams with a 0.2 mm or greater crack. For girders with a 0.3 mm crack, the margin rate of loading was from 0 to 3, but mainly 1 or lower. For beams, the margin rate of loading was 1 or lower.

(5) For slabs cracked on the end or at the center parallel to the short side, the margin rate of loading was about 1.7 to 3.7. For slabs cracked on the long-side end or at the center parallel to the long side, however, the reinforcement stress at the crack location was over 200 $N/mm^2$ and no more load seemed allowable.

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