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AN INVESTIGATION AND STUDY ON CRACKING AND CORROSION OF REINFORCED CONCRETE BRIDGES

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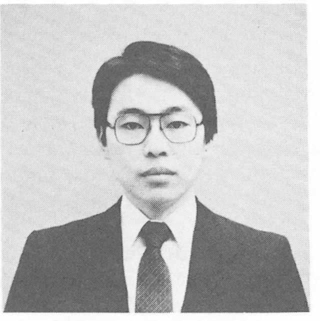

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SYNOPSIS

There are few global consensus on the crack width, concrete cover, and others to prevent the corrosion of reinforcement in the design codes of the world. This paper attempted to evaluate the distribution of cracks, the factors of crack width, and the control of corrosion using the data collected from 75 reinforced concrete railway bridges. The possibility of a more rational design approach to the control of corrosion of reinforcement is discussed.

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1. INTRODUCTION

Design methods for crack in reinforced concrete structures have not been fully established so far. There are various kinds of examination methods for cracks, however, most of the design specifications are adopting the method to limit the crack widths, which are derived from some proposed equations, within permissible crack widths. These proposed equations of crack widths are in general based on experimental equations obtained from model test results. On the other hand, there are only few studies which have examined the relationship between crack widths derived from some proposed equations and crack widths of real structures.

As for the derivation of permissible crack width, the fundamental relationship between the crack width and the corrosion of reinforcing bar is still a matter of argument. The reports of exposure tests (six to eight years) conducted by Kamiyama[1], soaking tests (nine years) by Seki and Maruyama[2], exposure tests (20 years) by Nishida, Sugimoto and Tomiyama[3], and others described that there were certain relationship between the crack width and the corrosion of reinforcing bar. On the other hand, Tremper[4] reported using the results of exposure tests that there was not any clear relationship between them. The break-up-test results of a reinforced concrete bridge conducted by Ohta[5] described that there was not any relationship between the crack width and the corrosion of reinforcing bar in the case that the cover was 20 to 30mm, but was a relationship in the case the cover was 40mm.

Accordingly, there are many uncertainties with the relationship between the crack width and the corrosion of reinforcing bar, such as the relationship between crack widths obtained by proposed equations and crack widths of structures, the relationship between corrosion of reinforcing bars and crack widths, cover, quality of concrete, age of structures, environmental conditions and others.

In this study, the distribution of cracks, corrosion of reinforcing bars, carbonation of concrete and others were investigated with 75 reinforced concrete railway bridges of the age from 10 to 60 years. The relationship between the crack width given by a proposed equation and the crack width of real structure, and the relationship between the crack width and corrosion of reinforcing bar, concrete cover, and others are especially examined.

2. SCOPE OF INVESTIGATION

(1) Investigated bridges

The investigation was conducted with the 75 reinforced concrete bridges as shown in Fig.1, which consist of 54 T-beam simple bridges, 19 box-beam simple bridges, and two rigid-framed viaducts. The age of these bridges are from 10 to 60 years. As for the environmental condition, bridges located in the severe corrosive environment were excluded, and the ones located in the normal environment were mainly investigated. (The bridges located in a cold district but not suffering the frost damages were included.)

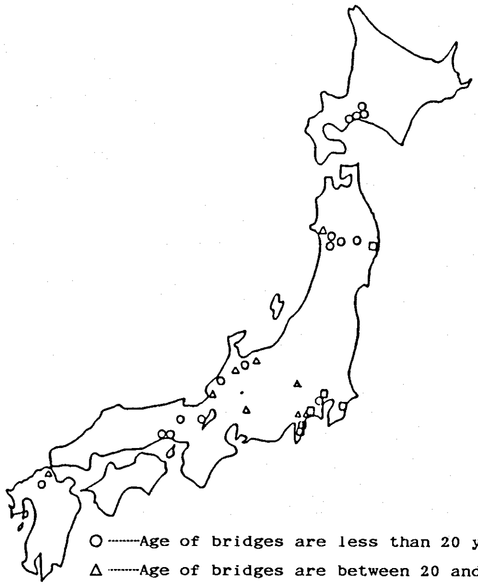


Fig. 1 Places investigated bridges

(2) Items and methods of investigation

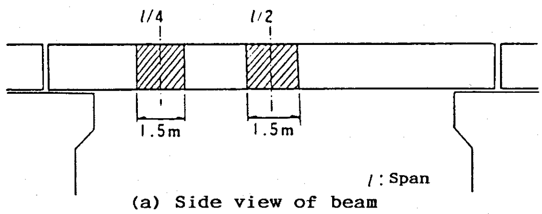
The items shown in Table 1 were investigated. The surveyed positions of crack distribution are the bottom and sides of beam at the center and quarter of span as shown in Fig.2. The crack widths which cross the line drawn parallel to the bridge axis (the line is crossing other lines drawn perpendicular to the bridge axis with approximately 20cm intervals) were measured using a crack scale. Development figures of crack distribution as shown in Fig.3 were made.

In order to measure the carbonated depth of concrete, the place of maximum crack width observed was chipped off approximately 10cmx10cm to the depth where reinforcing bars were located. The carbonated depths of concrete were measured using slide calipers to the depth where the sprayed one percent phenolphthalein alcoholic solution did not turn into red in color. The mean value of four measured depths at one spot were presented in this paper. The measurement of concrete cover and the observation of corrosion of reinforcing bars were made at the same spots of carbonation measurement. The visual evaluation of corrosion of reinforcing bars was classified in accordance with the ranks shown in Table 1.

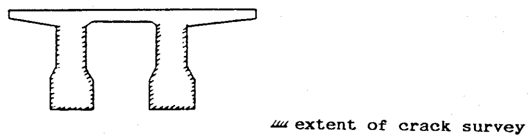
The increments of strain in reinforcing bars and crack widths when the train load was applied were measured in three bridges besides the items shown in Table 1. The strains of reinforcing bars at the location of flexure cracks formed were measured using wire strain gauges (the measurement length was 5mm). The increments of crack widths were measured using displacement gauges (the accuracy of 5/1000mm) across cracks that formed on three different beams from that of the strain of reinforcing bars were measured. (see Fig.4)

Table.1 Items and Methods of Investigation

Item	Surveyed Positions and Methods
Crack distribution Crack length Crack width	Cracks (crack width >0.04mm) of the bottom and sides of beam at the center and quater of span were investgated
Carbonated depth of concrete	The places where the maximum crack width was observed (using one percent phenolphthalein alcoholic solution) were investgated
Concrete cover	Concrete cover for longitudinal reinforcing bar and stirrup at the place where the carbonated depth were measured
Condition of corrosion of reinforcing bar	Conditions of corrosion of reinforcing bars were visually observed at the place where the carbonated depths were measured. They are classi fied in accordance with the following ranks, I～IV I……… not corroded II……… spottily or partially corroded III……… corrosion stretching the full length of reinforcing bar was observed IV……… loss of cross section due to corrosion was observed



(a) Side view of beam



(b) Cross section of beam

Fig. 2 Survey positions of cracks

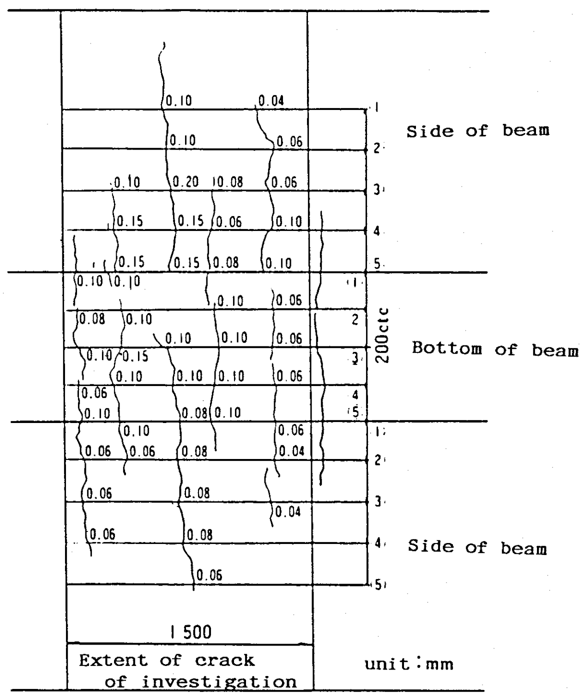
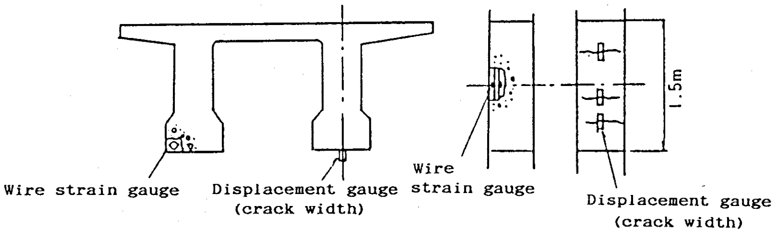


Fig. 3 Example of development figure of crack distribution



(a) Cross section of beam (b) Bottom of beam

Fig.4 Measurement of strains in reinforcing bars and crack widths at the time of train load applied

3.RESULTS OF INVESTIGATION

(1) Concrete cover

Concrete covers of longitudinal reinforcing bars and stirrups at the center of span were measured in every bridges. The ratios of the measured value to the designed value (measurement/design) of concrete cover for longitudinal reinforcing bars at the bottom of beams were shown in Fig.5. The designed values of concrete cover were 40 to 73mm. The mean value of the ratios was 1.32, and the measured values were greater than the designed values in general. However, there were 12 bridges among investigated 53 bridges that had the actual concrete cover smaller than the designed values, and this accounted for 20 percent. There was a bridge that had the concrete cover 17mm less than the designed value.

(2) Carbonation of concrete

The results of tests for the carbonation of concrete using one percent phenolphthalein alcoholic solution are shown in Fig.6. The carbonated depth of concrete tends to increase with the age of structures. However, it had a great scatter. In Fig.6, the carbonated depths of concrete of relatively new bridges, whose ages are less than 20 years, are from 0 to the maximum 50mm. Therefore, the carbonation of concrete may be considered that it is affected by the factors like concrete quality, environmental conditions and others. The quality of concrete of the bridges whose carbonated depths of concrete is 50mm and the age is less than 20 years may be considered no good and many voids were found through the observation.

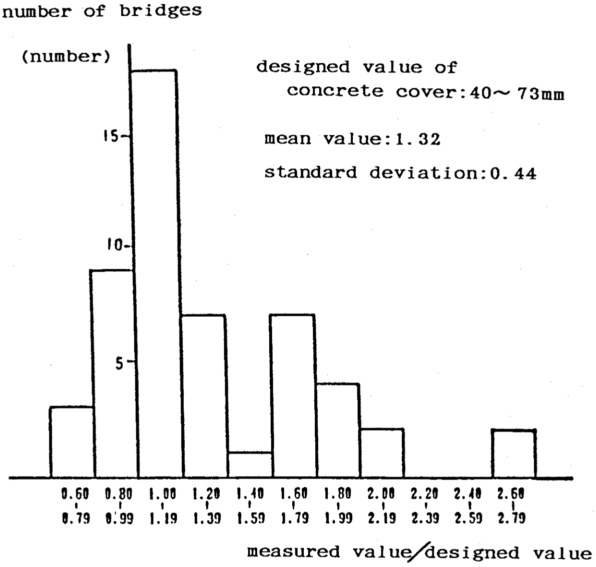


Fig. 5 Construction error of concrete cover for longitudinal reinforcing bars at the bottom of beam

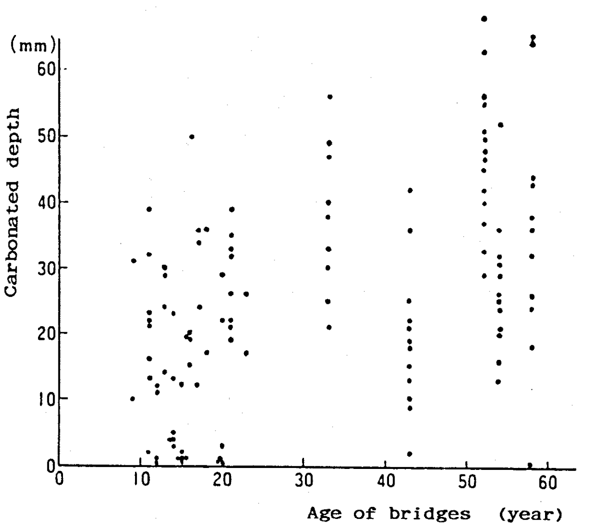


Fig. 6 Age of bridges and carbonated depth of concrete

(3) Crack

This clause examines about cracks which formed on the bottom and sides of beam at the center and quarter of span within the 1.5m band for T-beam simple bridges and box-beam simple bridges.

The following terms for cracks are defined in this study.

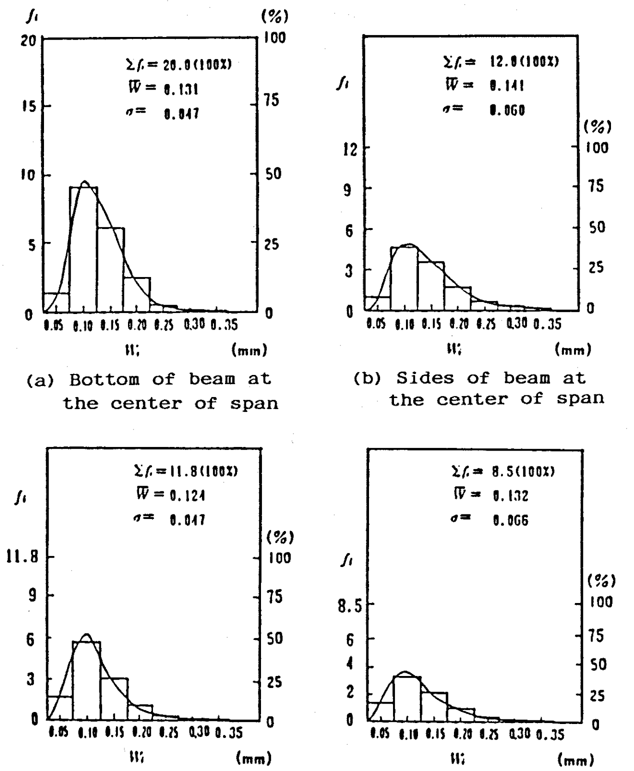
Crack frequency fi: the total number of cracks within the 1.5m band that cross the lines drown parallel to the bridge axis as shown in Fig.3.

Crack width Wi : the crack width of crossing the line (mm)

Mean crack width $\overline{W}$: Σ Wi/fi (mm)

Mean crack distance $\overline{l}$: 1500 n/fi, where, n: the number of lines drawn at 20cm intervals. In the case of Fig.5, n is 5. The length of the line is 1500mm.

Distributions of frequency for crack widths are shown in Figs.7 and 8. Distributions of frequency in Fig.7(a)-(d) show the individual beam,s mean distribution for T-beam simple bridges (42 bridges, 84 beams) whose stresses of longitudinal reinforcing bars at the center of span are calculated as 700 to 1000 kgf/cm^2 (68.6 to98.0 MPa). (This will be named "mean distribution of frequency" from now on.) Fig.7(a)-(d) shows the mean distribution of frequency



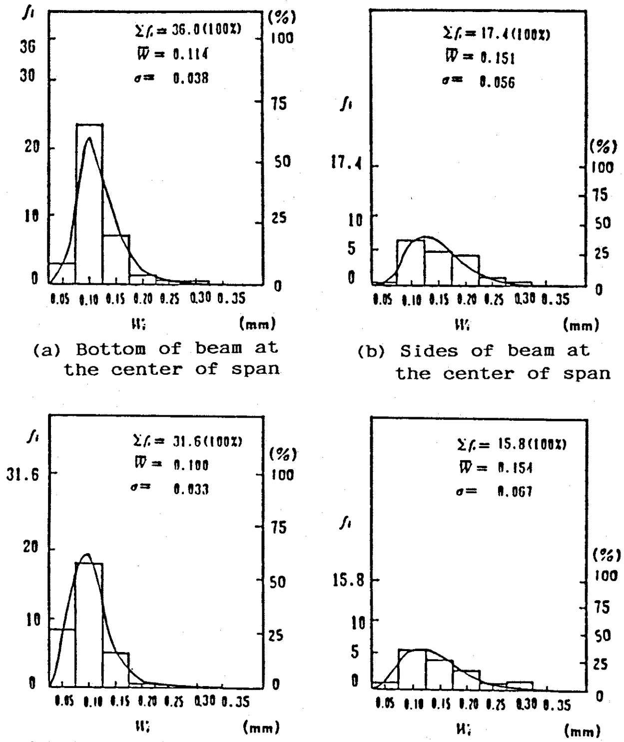
(a) Bottom of beam at the center of span

(b) Sides of beam at the center of span

(c) Bottom of beam at the quarter of span

(d) Sides of beam at the quater of span

Fig.7 Distribution of frequency for crack width (mean of T-beam simple bridges, 84 beams in 42 bridges)



(a) Bottom of beam at the center of span
(b) Sides of beam at the center of span
(c) Bottom of beam at the quater of span
(d) Sides of beam at the quater of span

Fig. 8 Distribution of frequency for crack width (mean of box-beam simple bridges, 4 bridges)

at the respective surveyed position (the bottom and sides of beam at the center and quarter of span). The curves of lognormal distribution derived from the measured mean crack widths and the standard deviation are also shown in this figure. The mean distributions of frequency for crack widths may fit the lognormal distributions in Fig.7.

The distribution of frequency in Fig.8(a)-(d) shows the mean distributions of frequency of crack widths of four bridges which are box-beam simple bridges and whose calculated values of stress in the longitudinal reinforcing bars at the center of span are 760 kgf/cm^2 (74.5 MPa). The mean distributions of frequency for crack widths may also fit the lognormal distributions curve. This result may agree with the study of Ozaka and et al[6].

The following facts may be clarified from the results of Figs.7 and 8 comparing the mean distribution of crack width.

(1) The crack frequency of the bottom of beam was larger than that of sides and the mean crack width of the bottom of the beam was smaller than that of the sides. (see Figs.7, and 8(a)-(d)) The differences were considered that because the spacing of reinforcing bars of the bottom of beam is smaller than that of the sides and cracks were disperted. The shape of distribution of frequency of the bottom of beam is concentrated comparing with the sides of beam, and the standard deviation is small. This is also considered because of the influence due to the arrangement of reinforcing bars.

(2) From the distributions of frequency (see Figs.7,8(a), and (c))of the bottom

of the center and quarter of span, crack frequency and mean crack widths at the center of span are larger than those at the quarter of span. There are no differences in the stress of longitudinal reinforced bars because the reinforcing bars are bent up and decrease in numbers in proportion to the moment. The difference of cracks between the center and quarter of span may be considered as the difference of fiber stresses of concrete.

4.EXAMINATION FOR CRACKS

(1) Maximum crack width and mean crack width

The relationship between the maximum crack width and the mean crack width defined in the section 3(3) is shown in Fig.9. The relation in Fig.9 shows that the bottom of beam at the center span for T-beam simple bridges.

The following linear regression equation was derived from the relation.
$W_{max}=1.67\ \overline{W}$
Here, Wmax is approximately 1.7 times as large as $\overline{W}$. Similarly, the relationships between maximum crack widths and mean crack width of the bottom and sides of beam at the center and quarter of span are shown in Table 2. From Table 2, the maximum crack width may be approximately 1.6 to 1.8 times as large as the mean crack widths regardless of the position of the members.

Probabilistic density distribution and cumulative probabilistic distribution of lognormal distribution of cracks on the bottom of T-beam bridge (see Fig.7(a)) at the center of span are shown in Fig. 10. The relationship between the crack width and the cumulative probabilities may be derived from Fig.10(b). For example, the cumulative probability is approximately 50 percent when the crack width is 0.1mm, and is approximately 95 percent when the crack width was 0.2mm. Supposing that the maximum crack width is 0.22mm (=$1.7\overline{W}$) and the mean crack width $\overline{W}$=0.131mm (see Fig.7(a)), the cumulative probability of the maximum crack was derived as approximately 97 percent.

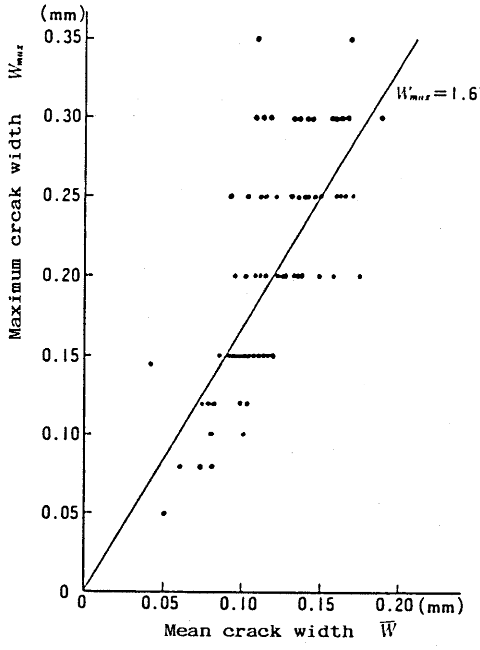


Fig.9 Maximum crack widths and mean crack widths

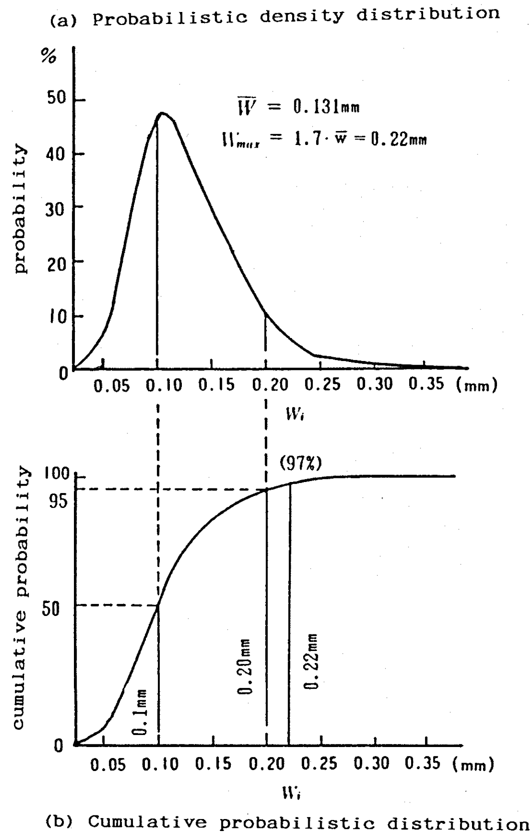


Fig. 10 Probabilistic distribution of crack width

Table. 2 Maximum Crack Widths and Mean Crack Widths

Positions		Regression equation	Variable coefficient
Center of span	Bottom	$W_{max} = 1.67\ \overline{W}$	25.5 %
	Sides	$W_{max} = 1.81\ \overline{W}$	22.8 %
Quarter of span	Bottom	$W_{max} = 1.60\ \overline{W}$	23.8 %
	Sides	$W_{max} = 1.17\ \overline{W}$	23.0 %

(2) Increment of crack width when the train load is applied

The relationship between the measured increment of crack width and calculated crack width derived from the strain of reinforcing bars when the train load was applied wasoobtained from four bridges. This is shown in Fig.11. The crack widths were measured on beams which were different from the beam that the strain of reinforcing bars was measured (see Fig.4). The calculated values of the increment of crack width are derived from Eq.(1).

$Wcal = \varepsilon\, l(h-x)/(d-x)$ (1)

where, Wcal: calculated increment of crack width

- ε : measured increment of the strain in reinforcing bar
- l : measured crack distance
- h : height of beam
- d : effective depth
- x : distance from compression resultant to centroid axis

From Fig.11, the calculated values are approximately as large as the measured values. The increment of crack widths may be derived from the increment of strain in reinforcing bars multiplied by the crack distances.

The measured increment of crack widths when the train loads were applied were obtained by the typical cracks whose distances were 20 to 30cm and the crack widths produced by the dead loads were o.2 to o.35mm at the center of span.

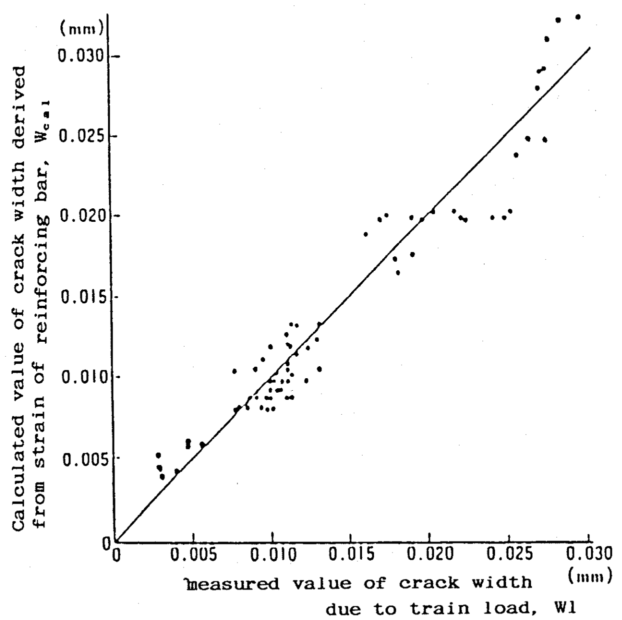


Fig.11 Comparison of the increment of crack widths due to train loads

(3) Measurement and calculation of crack width

As the increment of crack width given by Eq.(1) fits the measured value fairly well, the crack widths produced by the dead loads are calculated as the values shown in Table 3 using Eq.(1) and the measured strains in reinforcing bars. The strain in reinforcing bar was measured by cutting the reinforcing bar attaching a wire strain gauge. From Table 3, the calculated values of crack widths produced by the dead load are approximately 0.3 times as much as the measured values. Therefore, it is considered that the increment of crack widths are affected by the creep and dry shrinkage of concrete rather than the strain in reinforcing bars. It is considered that the increment of crack widths are affected by the condition of the construction and environment of the structures.

Table. 3 Comparison Between Measured Values and Calculated Value of Crack Widths due to Dead Load

Number of bridges	No.	Crack width due to dead load W_d(mm)	Strain of reinforcing bar due to dead load $\varepsilon_d(\mu)$	Crack distance l(cm)	$\frac{h-x}{d-x}$	Calculated value of crack width W_{cal}(mm)	$\frac{W_{cal}}{W_d}$
①	1	0.25	280	21	1.15	0.068	0.27
	2	0.30	280	24	1.15	0.077	0.27
②	1	0.35	345	27	1.07	0.100	0.29
	2	0.35	345	30	1.07	0.078	0.22
	3	0.25	345	23	1.07	0.085	0.34
③	1	0.30	338	22	1.07	0.080	0.27
	2	0.30	338	22	1.07	0.080	0.27
	3	0.30	338	22	1.07	0.080	0.27

(4) Crack distance and crack value

The relationship between the mean crack distances and measured concrete cover of the bottom of beam at the center of span is shown in Fig.12. From Fig.12, the minimum value of the mean crack distances is approximately as much as 3 times of the concrete cover. However there are some bridges which had few cracks, so the maximum values of the mean crack distances were scattered greatly.

The mean crack values according to the difference of the concrete fiber stress of the bottom of beam produced by the dead load are shown in Fig.13. The concrete stress of the bottom of beam is calculated that the gross cross section is effective considering the dead weight and added dead weight (barast, track and others) at the center and quarter of span. In Fig.13, the mean crack values at the bottom of bridges were shown at every 10 kgf/cm^2 by the different concrete stress at the center and quarter of span. From Fig.13, the crack values tend to increase in accordance with the increment of concrete stresses.

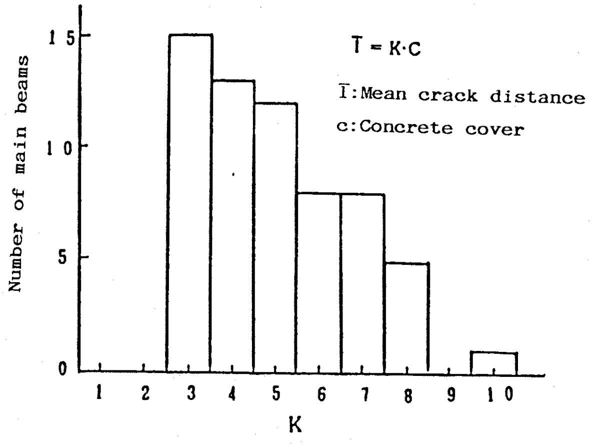
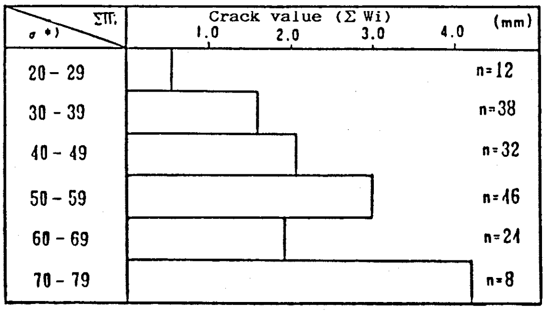


Fig. 12 Mean crack distances and concrete cover



*) σ :Tensile fiber stress in concrete at the bottom of beam which calculated that the gross cross section is effective (kgf/cm^2)

n:Number of data

Fig. 13 Crack values according to the concrete fiber stress at the bottom of beam

5.EXAMINATION FOR CORROSION OF REINFORCING BARS

(1) Method of analysis

The conditions of corrosion of reinforcing bars are classified into four grades (I-IV) as show in Table 1. These four grades shown in Table 1 are classified as two major groups like "not corroded" for grades I and II, and "corroded" for grades III and IV. They are analyzed using discriminant analysis separetely. The parameters used in the analysis were the crack width, W, the concrete cover, C, and the carbonated depth of concrete, Y, chosen among the investigated items shown in Table 1. The analysis was made for three cases which are different in the members (beam, slab) and age as shown in Table 4 using 100 samples respectively. The analysis is separated depending on the beam or slab which have differences in the spacing and the diameter of reinforcing bars. The age of structure are classified in every 20 years. As from the results of analysis of bridges less than 20 years were nearly equal to that of 20 to 40 years,however, they are gathered as the age less than 40 years. The ranges of variables used in the analysis are shown in Table 4. The crack width in Table 4 is the crack width produced by the dead load.

Table. 4 Ranges of the Variables used in the Analysis

Age of members	Number of bridges	Number of data	Crack widths	Concrete cover	Carbonated depth
			mm	mm	mm
beam 10～60 years	70	100	0～0.4	8～110	0～56
beam 10～60 years	5	100	0～2.0	8～63	0～65
slab 40～60 years	5	100	0～0.9	7～102	14～66

(2) Results of analysis and consideration

The results of discriminant analysis for the combinations of the factors related to the corrosion of reinforcing bars are shown in Table 5. The analysis was made for the combinations of four cases with the three factors (such as crack width, concrete cover, carbonated depth of concrete). The discriminant function,Z, is discriminated that: if $Z>0$, the reinforcing bars are "not corroded", and if $Z<0$, the reinforcing bars are "corroded". The F-values shown in Table 5 was calculated for the significance test of the discriminant functions. The F-values of the level of 99-percent-significance for the three-factor-combination and two-factor-combination are shown in Table 6. (If the F-values shown in Table 5 are greater than that in Table 6, the discriminant functions may be said that they are tested as significant at the level of 99 percent.

From the results of analysis, the following items may be considered.
a) For the beams of the age of 10 to 40 years, the F-values of discriminant function for the combination of the crack width, W, and concrete cover, C, indicated that they have a strong relation to the corrosion of reinforcing bars.
b) For the beams and the slabs of the age of 40 to 60 years, the F-values of the discriminant functions for the combination of concrete cover, C, and the

Table. 5 Results of Analysis (Discriminant Functions and F-values)

Variable	Beam 10～40 years		Beam 40～60 years		Slab 40～60 years	
	Discriminant function	F-values	Discriminant function	F-values	Discriminant function	F-values
$W\cdot C\cdot Y$	$Z=-0.12W+0.00073C+0.00026Y-0.016$	23.30	$Z=-0.0021W+0.00052C-0.00051Y-0.012$	5.92	$Z=-0.028W+0.00092C-0.0011Y+0.0022$	7.43
$W\cdot C$	$Z=-0.11W+0.00072C-0.015$ Eq. (2)	33.92	$Z=-0.0038W+0.00051C-0.022$ Eq. (3)	4.77	$Z=-0.044W+0.00038C-0.0084$	5.79
$W\cdot Y$	$Z=-0.069W+0.00023Y+0.0047$	3.63	$Z=-0.0013W-0.00051Y+0.011$	4.48	$Z=-0.043W-0.00016Y+0.013$	3.37
$C\cdot Y$	$Z=0.00063C+0.000010Y-0.022$	25.04	$Z=0.0051C-0.00052Y-0.011$	8.83	$Z=0.00098C-0.0012Y-0.0012$	10.11

carbonated depth, Y, were both large. Therefore, the concrete cover and the carbonated depth may be said that they have a strong relation to the corrosion of reinforcing bars in old structures.
c) For all of the three cases (beams: 10 to 40 years, beams: 40 to 60 years, and slabs: 40 to 60 years), the F-values of the discriminant functions for the combination of crack width, W, and the carbonated depth, Y, are the smallest. Therefore, the concrete cover may be considered that it affects the progress of the corrosion of reinforcing bars greatly.

Table.6 F-test (1%)

3 variables	$F(3.97;\ 0.01)=3.99$
2 variables	$F(2.98;\ 0.01)=4.83$

(3) Relationship between corrosion of reinforcing bars and the factors

a) Influence of concrete cover

It was considered from the results of analysis that the concrete cover affected most to the corrosion of reinforcing bars. Then the necessary concrete cover to avoid the commencement of corrosion of reinforcing bars without cracking of concrete was calculated by Eq.(2). (This is shown in Table 5.)
$Z=-0.11\ W+0.00072\ C-0.15$ (2)
Substituting Z=0 and W=0 into Eq.(2), 0.00072C=0.15 Then, C=20mm
Therefore, if the concrete cover is not less than 20mm at the non-cracked cross section and the age of bridge is less than 40 years, the corrosion of reinforcing bars may seldom occur.

And likewise, the necessary concrete cover is calculated from Eq.(3).
$Z=-0.0038\ W+0.00051\ C-0.022$ (3)
Then, 0.00051C=0.022 C=45mm
Therefore, if the concrete cover is not less than 45mm and the age of bridge is between 40 and 60 years, the corrosion of reinforcing bars may seldom occur. However, as the F-value for Eq.(3) is smaller comparing with that for Eq.(2), the significance of the disxriminant function is low. Then the necessary concrete cover to avoid the corrosion of reinforcing bars depends on the age of structure. For the structures whose design life span is long, the concrete cover shall be taken sufficiently.

b) Influence of crack width

Using Eq.(2) which has the largest F-value among the discriminant functions shown in Table 5, the condition of crack width,W, and the concrete cover,C, for "not corroded" is given as follows.
Substituting Z=0, then $W=0.0065\ C-0.14$ (mm) (4)
From Eq.(4), the corrosion of reinforcing bars will seldom occur in the case that the crack width is less than 0.12 mm, supposing that the age of bridges is less than 40 years, and the concrete cover is 40mm. In the case that the age of bridge is between 40 and 60 years, The F-value of the discriminant function which includes the crack width,W, is small comparing with that of the bridges aged less than 40 years. Therefore, it may be considered for older bridges that the corrosion of reinforcing bars will progress by the influence of the carbonation of concrete and others even if the crack width is small.

6. SUMMARY

The results of the investigation and the analysis are summarized as follows.
(1) The carbonated depth of concrete tends to increase with the age of bridge in general. It has great scatter in each structure. This may be considered as the influence of the concrete quality and others.

(2) The distributions of frequency for crack widths may fit the lognormal distribution from the result of the investigation.

(3) The relation between maximum crack widths, Wmax, and the mean crack width, $\overline{W}$, defined in this report is as follows:

$$W_{max} = 1.6 - 1.8\ \overline{W}$$

(4) From the cumulative probability of the crack widths shown in Fig. 10, the cumulative probability of the maximum crack width is derived as approximately 97 percent supposing that the maximum crack width is $1.7\ \overline{W}$.

(5) The increment of crack widths when the train load are applied may be calculated using the increment of strain in reinforcing bars multiplying the measured crack distance.

(6) The calculated values of crack widths for the dead loads obtained by Eq.(1) using the measured values of strains in reinforcing bars are approximately 0.3 times as much as the measured values of the crack widths. Therefore, it may be considered that the creep and dry shrinkage of concrete have great effect on the crack widths of structures.

(7) As the concrete cover has great effect on the corrosion of reinforcing bars, the minimum concrete cover shall be decided considering the design life span of structure.

(8) As for the corrosion of reinforcing bars, the crack width has a strong relation as much as concrete cover for the bridges ages less than 40 years, and the carbonation of concrete promotes the corrosion of reinforcing bars even if the crack width is small for the bridges aged between 40 to 60 years.

7. ACKNOWLEDGMENT

The investigation and analysis of concrete bridges were made for getting the basic knowledge on the crack design method. The data collected in the investigation had scatter, however, it is considered that the characteristics of cracks and the factors affecting the corrosion of reinforcing bars are clarified.

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