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STUDY ON MECHANICAL BEHAVIOR OF REINFORCED CONCRETE SLABS WITH CONCRETE OVERLAY

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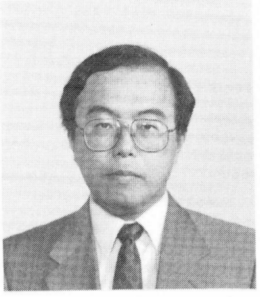
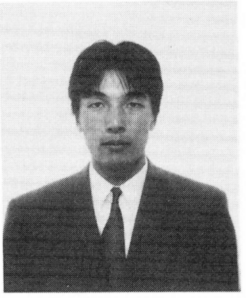
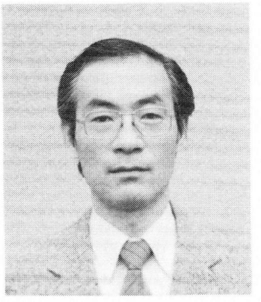

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SYNOPSIS

Concrete overlaying is one of the repair methods used for slabs in steel girder bridges. However, overlaid concrete may separate from the old slab because of the shear stresses resulting from heavy loads such as trucks or trailers. Therefore, experimental research has been conducted to clarify the mechanical behavior of slabs with a concrete overlay. An analytical technique using a non-linear finite element method is also developed and compared with the experimental data. Furthermore, this analysis is applied to the models of actual bridge slabs to estimate the shear stresses at the boundary between overlay and slab, and it is shown that overlaid concrete will not separate from the slab under traffic loading.

Keywords: reinforced concrete slabs, concrete overlay, shear stress, non-linear finite element method

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1. INTRODUCTION

Beginning about 20 years ago, damages such as heavy cracks and local subsidences have been noted in the reinforced concrete slabs of bridges along the expressways. To prevent failures, these slabs need to be repaired at an early stage. One of the means of repairing and reinforcing bridges in this condition entails increasing the thickness of slabs by placing new concrete directly over the existing concrete. This is known as the concrete ovelaying method. However, when this method is applied, the new concrete may possibly exfoliate from the original slab due to the shear force caused by moving vehicles. Thus, it has become necessary to investigate the shear stresses acting at the boundary between the old and new concrete layers and to examine the possibility of exfoliation along the boundary.

In this study, the authors carried out loading tests of the slab with a concrete overlay by choosing the floor slab section of the expressway as the object of testing. An analysis was also implemented by expanding the laminated element method [1~7], which is capable of tracing the cracks in the direction of thickness in the slab so as to be applicable to the slabs with increased thickness, by first dividing the floor slab into quadrilateral elements and further dividing each element into strata. Then, by comparing the results of this analysis with the experimental results, the authors establish a method of analysis for the slab with the concrete overlay and simultaneously obtain the shear stress acting along the boundary between old and new concrete analytically by estimating the behavior of the slab with the concrete overlay in the actual bridge with application of this analysis, in order to investigate the effectiveness of the overlaying method.

Incidentally, it has been generally thought that reinforced concrete slabs are susceptible to fatigue since they directly support wheel loads of the vehicles and that the development of cracks is mainly caused by the transition and repetition of loading which is unique to automobile loads [8,9]. However, it is not the purpose of the present study to analyze the development of damages due to fatigue, but to analyze the shear stress acting at the boundary between old and new concrete due to wheel loads when a concrete overlay is applied to the top surface of the concrete slab where cracks have occurred and to investigate the possibility of exfoliation. Therefore, leaving such problems as the development of cracks and loss of the adhesive strength at the boundary between old and new concrete due to fatigue to the future studies, the authors have chosen to study static loading as the subject of this study.

2. BENDING TEST OF THE REINFORCED CONCRETE SLAB WITH CONCRETE OVERLAY

2.1 Experimental Method

The eight types of specimen on which the experiments are conducted and their material properties are shown in Table 1. The shape of these specimens is shown in Fig.1.

In this experiment, the tests are conducted with the main focus being the influence of the condition of thickness increase and conditions of support. The aim is to investigate the behavior of the slab with a concrete overlay, the conditions of cracks and so forth. In order to compare the influence of the conditions of thickness increase, specimens without thickness increase and those to which the concrete overlay is applied after cracks have occurred are provided and further in order to compare the conditions of support, specimens with two ends simply supported and those with four ends simply supported are

Table 1 Test specimens of reinforced concrete slab

Specimen	Support condition	Span length (cm)	Thickness (cm)	Thickness increase (cm)	p (%)	Loading pad (cm)	d − s (mm-cm)	f_y (kgf/cm²)	f'_c (kgf/cm²)
No.1	①	110x 110	12.0		u-0.377 l-0.754	30x30x6	u D13-28 l D13-14	3503	375
No.2	①	110x 110	12.0	3.0	u-0.377 l-0.754	30x30x6	u D13-28 l D13-14	3503	u-426 l-334
No.3	①	110x 110	15.0		u-0.302 l-0.603	30x30x6	u D13-28 l D13-14	3503	233
No.4	②	110x 110	12.0		u-0.377 l-0.754	30x30x6	u D13-28 l D13-14	3503	277
No.5	②	110x 110	12.0	3.0	u-0.377 l-0.754	30x30x6	u D13-28 l D13-14	3503	u-410 l-300
No.6	②	110x 110	15.0		u-0.302 l-0.603	30x30x6	u D13-28 l D13-14	3503	245
No.7	①	108x 108	15.0		u-0.176 l-0.176	30x30x6	D10-22	3738	409
No.8	①	108x 108	15.0		u-0.176 l-0.176	*(15x15 x6)x16	D10-22	3738	341

① four ends simply supported
② two ends simply supported
* distributed load

p : reinforcement ratio
d : diameter of reinforcing bar
s : space of bars

u : upper bars
l : lower bars

provided for testing. The loading conditions are assumed to be the wheel load on the road bridge, namely concentrated loads. Accordingly, in the cases of specimens with four ends simply supported, the concentrated loading tests for the specimen with its original thickness and no concrete overlay (No.1), the specimen whose thickness is increased after cracks have occurred (No.2) and the specimen that has the thickness equal to that with a concrete overlay from the beginning (No.3) are conducted. Likewise, in the cases of specimens with two ends simply supported, the specimen with the original thickness and no concrete overlay (No.4), the specimen whose thickness is increased after cracks have occurred (No.5) and the specimen that has the thickness equal to that with a concrete overlay from the beginning (No.6) are tested with concentrated loading.

While the above six specimens all have the same cross section, the specimens with different cross sections are tested for the purpose of investigating the adequacy of the program for

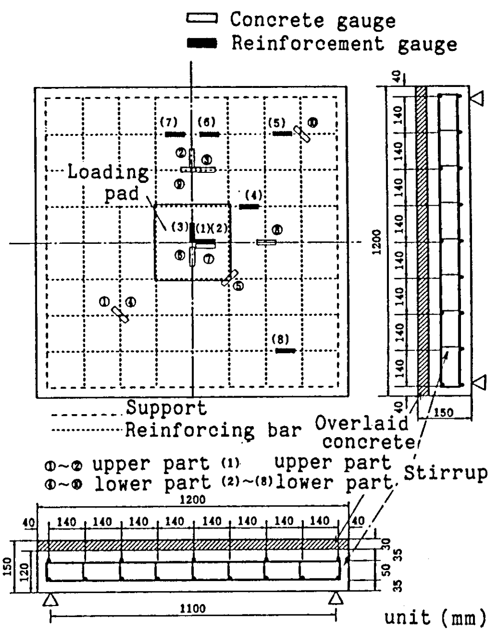

Fig.1 Dimensions of test specimens

analysis. In these cases, in order to compare the influence of different conditions of loading, the tests are conducted in two ways, namely the concentrated loading (No.7) and the distributed loading (No.8) with four ends simply supported in both cases. The specimens are square in shape, 120cm x 120cm, with thickness of 12cm or 15cm.

High-early-strength portland cement is used and the specimens without a concrete overlay are tested two weeks after concrete was placed (f'_{ck} =300kgf/cm^2). On the other hand, the specimens to which a concrete overlay is applied are loaded two weeks after concrete was placed and after cracks have occurred, the concrete overlay is placed. Then, one week thereafter, they are tested (f'_{ck} =400kgf/cm^2). Incidentally, f'_{ck} of the concrete overlay is made greater than that of the slab in order to raise the adhesive strength of the concrete overlay.

The concrete overlay is placed when cracks are judged to have reached through about half of the thickness as seen from the side by the naked eye. The load applied at that time is 20tf for the slab No.2 and 13tf for No.5 respectively. Since the increased thickness in the actual cases is often taken at around 28%, 3cm which is equivalent to 25% of the original thickness is chosen (the maximum size of coarse aggregate is 15mm). Prior to placing the concrete overlay, the surface of the old concrete is processed with a wire brush to ensure good adhesion between the slab and the concrete overlay and kept in wet condition until the new concrete is placed by covering the surface with a damp cloth. The reinforcing bars are orthogonally arranged and a considerable number of stirrups (D10) is arranged so as to prevent the occurrence of punching shear before bending fracture takes place.

The load is applied to the specimens of the slab with the testing machine of 100tf capacity. The size of the loading pad is 15cm x 15cm, and it is made of hard rubber with 6cm thickness. This may appear a little too large as compared with the span, but this large size is intentionally chosen to prevent possible fracture by punching shear. The support is made by way of round steel bars with 5cm diameter and lifting of the corners is made free.

Measurements taken during the loading tests are the displacement at the center of the slab, the strain on the reinforcing bars, the strain at the surface of concrete and the state of cracks generated, as shown in Fig.1. With regard to the state of cracks, since it is not possible to observe them while being loaded, they are recorded after fracturing has occurred.

2.2 Experimental Results

In these experiments, the maximum load, the relation between load and displacement at the center, the relation between load and strain on the bottom reinforcing bars, the influences of thickness increase and support on the displacement and strain of reinforcing bars, and the state of cracks generated are investigated.

(1) Maximum Load

The maximum loads of the specimens are presented in Table 2. When a comparision is made among slabs No.1 to No.6, the slab with four ends simply supported having the thickness equal to the increased one without a concrete overlay (No.3) is the strongest which broke down at 41.1tf. The weakest is the slab of the original thickness without a overlay with two ends simply supported (No.4) which broke down at 23.5tf.

Table 2 Maximum load

Specimen	Experiment P_{test} (tf)	A (%)
No.1	29.8	100
No.2	35.2	118
No.3	41.1	138
No.4	23.5	100
No.5	27.5	117
No.6	32.5	138
No.7	20.7	100
No.8	84.2	406

A : Comparison with the slab of original thickness without an overlay

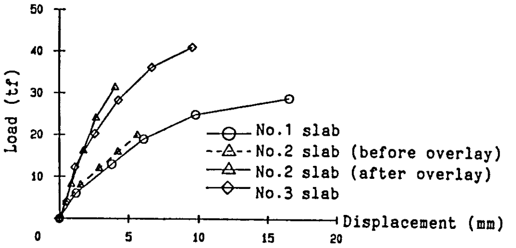

Fig.2 Relationship between load and displacement (four ends simply supported)

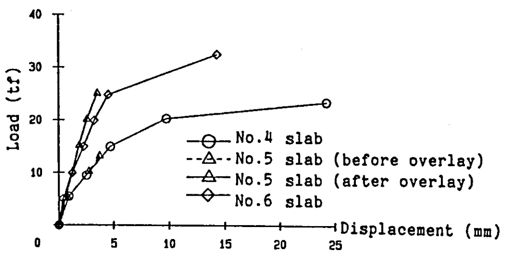

Fig.3 Relationship between load and displacement (two ends simply supported)

As compared with the slab of original thickness without an overlay, in the slabs whose thickness is increased after cracks have occurred, there is a gain of 5.4tf in strength for the slab with four ends simply supported (No.2) and a gain of 4.0tf for the slab with two ends simply supported (No.5). Likewise in the slabs having the thickness equal to the slab with the concrete overlay from the beginning, there is a gain of 11.3tf in strength for the slab with four ends simply supported (No.3) and a gain of 9.0tf in strength for the slab with two ends simply supported (No.6), respectively. If there are represented in terms of the ratio of strength of each slab to that of the slab of the original thickness, the slabs with increased thickness after cracks have occurred gains the strength increase by about 17% for both cases of four ends simply supported and two ends simply supported, and the slab made to the thickness equal to the slab with the concrete overlay from the beginning gains the strength increase by 38%.

If a comparison is made between the case of the concentrated load (No.7) and that of the uniformly distributed load (No.8), the failure load under concentrated loading is 20.7tf against that for distributed loading being 84.2tf. It is known that in the case of a uniformly distributed load the specimen can bear the load about four times as great.

(2) Displacement

The load-deflection curves at the center for the slabs with four ends simply supported (No.1, No.2, and No.3) are shown in Fig.2 and those for slabs with two ends simply supported (No.4, No.5, and No.6) in Fig.3. In the slabs whose thickness is not increased, bending cracks occur at the load of 20~30% of the breaking load, though there are some differences in accordance with the support

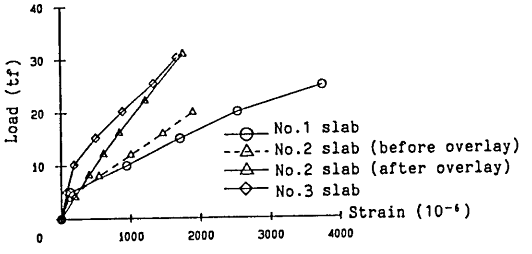

Fig.4 Relationship between load and strain on reinforcing bars (four ends simply supported)

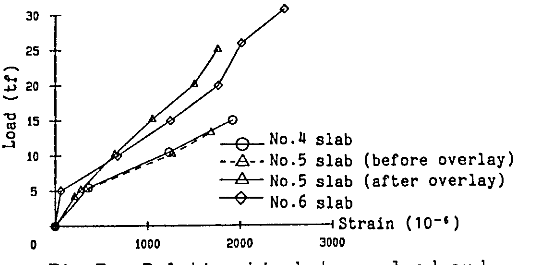

Fig.5 Relationship between load and strain on reinforcing bars (two ends simply supported)

or loading conditions, and the increment of displacement grows bigger. Thereafter, at 50~60% of the breaking load the central reinforcing bars on the bottom face yield causing further growth of increment of the displacement and finally the bending fracture takes place.

The load-displacement curves of the slabs whose thickness is increased after cracks have occurred (No.2 and No.5) almost coincide with those of the slabs of the original thickness without an overlay (No.1 and No.4) when tested before the thickness is increased and when tested after the thickness has been increased, they almost coincide with the load-displacement curves of the slabs that have the thickness equal to the slab with a concrete overlay from the beginning (No.3 and No.6). This indicates that the cracks generated before the application of a concrete overlay have little influence on the displacement after the thickness has been increased and that the concrete overlay applied to increase the thickness fully adheres to the slab. Moreover, in both specimens, No.2 and No.5, the displacement at the center is reduced to about half at the same load after the thickness has been increased as compared with the value when tested before the thickness is added. However, since the concrete in the overlaid section exfoliated when the central reinforcing bars at the bottom yielded, the load-displacement curve beyond that point could not be obtained. Incidentally, exfoliation occured suddenly and no slips between the concrete overlay and the slab had been observed until it started.

(3) Strain on Reinforcing Bars

The load-strain curves for the central reinforcing bar on the bottom face of the slabs with four ends simply supported (No.1, No.2, and No.3) are shown in Fig.4, and those for the central reinforcing bars on the bottom face of the slabs with two ends simply supported (No.4, No.5, and No.6) in Fig.5. Compared with the strains on the reinforcing bars of the slabs having the original thickness with no concrete overlay (No.1 and No.4), those of the slabs whose thickness is increased after cracks have occurred (No.2 and No.5) and those of the slabs having the thickness equal to the slab with a concrete overlay from the beginning (No.3 and No.6) are generally smaller for the same load. Especially, in the case of the slab with four ends simply supported, the strain value is less than half.

In the cases of the slabs whose thickness is increased after cracks have occurred (No.2 and No.5), the load-strain curves almost coincide with those of the slabs that have the original thickness without a concrete overlay before their thickness has been increased, as are the cases of the load-displacement

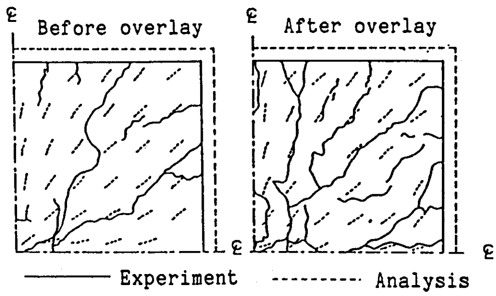

Fig.6 State of cracks (Slab No.2)

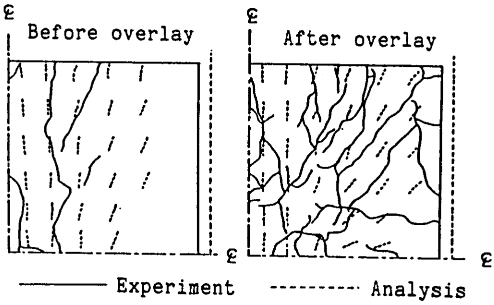

Fig.7 State of cracks (Slab No.5)

curves. However, after their thickness is increased, since cracks have already occurred, they do not present the trend that the inclination of the curve changes when cracks occur as the load-strain curves of the slabs that have the increased thickness without an overlay (No.3 and No.6) present, but their strains tend to linearly increase with the load. In contract to this, their strains when the loads get close to the maximum indicate nearly the same values. As seen from these facts, the load at which cracks occur may be deemed to be the load where the inclination of the load-strain curve changes, and it is estimated from Fig.4 and Fig.5 that it occurs at the load of around 5tf in all slabs.

(4) State of Cracks

The state of cracks generated in the specimens No.2 and No.5 just before the concrete overlay is applied and the state of cracks at the moment of the maximum load after the concrete overlay has been applied are shown in Fig.6 and Fig.7. The state of cracks in the slab with four ends simply supported whose thickness is not increased is similar to that indicated in Fig.6 and the cracks developed radially. In the slab with two ends simply supported, the state of cracks is similar to that shown in Fig.7. They are generated at the center of the span parallel to the supports and radially in the area close to the support. Thus, little difference can be seen in the states of cracks at the maximum load due to the conditions of thickness increase.

In the case of the concentrated loading (No.7) and in the case of the uniformly distributed loading as well, the state of carcks shows a radial configuration nearly the same as those of other slabs with four ends simply supported. However, compared with the slabs No.1 to No.6, far fewer fine cracks are observed.

3. ELASTO-PLASTIC ANALYSIS OF THE SLABS WITH A CONCRETE OVERLAY BY THE LAMINATED ELEMENT METHOD

In this analysis, the laminated element method developed by expanding the finite element method in which the elements are divided into laminates so as to enable to trace the cracks in the direction of thickness was used. Many studies have investigated laminated element methods, but here in this study the authors applied the program developed by Sato et al [7]. This program is developed by applying a constitutive model of concrete after cracking as proposed by Okamura et al [10] , and Maekawa [11]. This takes into consideration not only tensile stiffness but also compressive and shearing stiffness and its adequacy has already been verified through comarison with test results. To the slabs whose thickness is not increased, this program is applied as it is, but the authors expand the laminated element method to make it applicable to the slabs whose thickness is increased after cracks have developed.

3.1 Method of Analysis for The Slab with Concrete Overlay

In analysis procedure, the slab of the original thickness is considered first. The analysis proceeds until the cracks starting at the bottom surface reach the specified divided layer, as shown in Fig.8. Then, assuming that a repair is carried out by adding a concrete overlay to this cracked condition and the stiffness of the reinforcing bars and concrete is preserved, the stiffness after the thickness has been increased is gained by adding the stiffness of the new layer. In experiments, the thickness is increased in the unloaded condition after cracks have occurred, but since just before unloading the reinforcing bars have not yielded yet, they are assumed to remain elastic. With regard to the concrete, while its stiffness falls to zero on the tension side if cracks occur, the stress on the compression side is supposed to be not so large even if it is once unloaded and then reloaded, its stiffness will not vary much from the value when it was loaded first. Therefore, disregarding the change of stiffness due to unloading, the stiffness of the slab after its thickness has been increased is calculated first and then returning the displacement and the load to zero under the assumption that the residual strain is zero, the behavior of the slab after its thickness has been increased is analyzed. In this analysis, the thickness of the slab is assumed to change as follows. The original thickness is denoted by H_1+H_2. After the overlay is placed, the portion of H_2 is removed and concrete of the thickness $H_2 + H_3$ is added. Since it is thought from the experimental results that perfect adhesion of the concrete overlay is maintained until the slab breaks down, perfect adhesion is assumed in the analysis.

3.2 Model for Analysis

An example of the model of the slab for analysis is given in Fig.9. This is

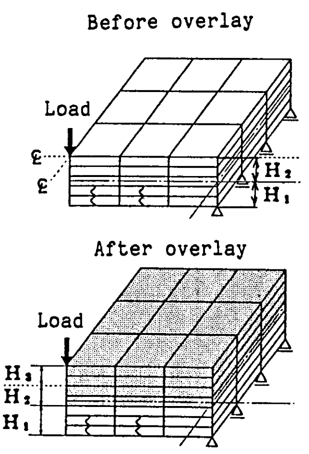

Fig.8 Analytical model of overlaid concrete slab

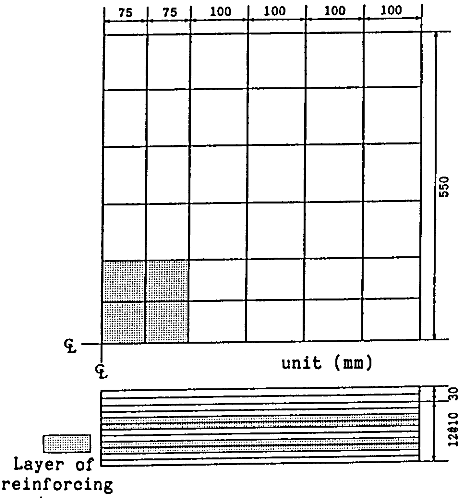

Fig.9 Analytical model of slab

made by modeling 1/4 of the slab used in the experiment. By applying the increment of displacement to the node at the bottom left of the drawing, the increment of load working at the node of the element in the hatched part of the drawing in accordance with the shape, properties of material, support conditions and method of loading is calculated and development of the strain and cracks are analyzed.

4. COMPARISON OF EXPERIMENTAL AND ANALYTICAL RESULTS

In order to investigate the adequacy of the program of analysis for the slabs with a concrete overlay, comparison between the experimental values and the values obtained by the analysis is made with respect to maximum load, displacement, strain on reinforcing bars and conditions of cracks for eight specimens.

4.1 Maximum Load

With regard to the maximum load of the slab, the experimental values, analytical values, and the ratios of the analytical values devided by the experimental values are shown in Table 3. In this analysis, the instant when the load begins to fall against the increment of displacement is deemed to be the point at which the bending fracture occurs and the maximum load is reached. As shown in Table 3, the analytical value of the maximum load presents nearly the same value as the experimental one as a whole. However, the slab No.2 with four ends simply supported whose thickness is increased after cracks have occurred showed the higher analytical value than the experimental one unlike the cases of other slabs. As mentioned before, this indicates that because the concrete overlay exfoliated during the experiment, bending fracture did not occur. Qualitatively speaking, a similar case may be made with regard to the slab No.5 with two ends simply supported, but judging from the fact that the analytical value is just 1.05 times the experimental value, it is presumed that exfoliation of the concrete overlay may have happened in a condition which is very close to bending fracture.

Table 3 Comparison of experiment and analysis

Specimen	Experiment	Analysis	
	P_{test} (tf)	P_{cal} (tf)	$\frac{P_{cal}}{P_{test}}$
No.1	29.8	30.0	1.00
No.2	35.2	40.0	1.14
No.3	41.1	44.5	1.08
No.4	23.5	24.0	1.02
No.5	27.5	28.9	1.05
No.6	32.5	32.0	0.98
No.7	20.7	20.0	0.97
No.8	84.2	81.0	0.96

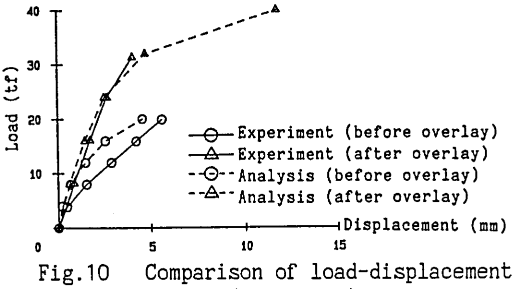

Fig.10 Comparison of load-displacement curves (Slab No.2)

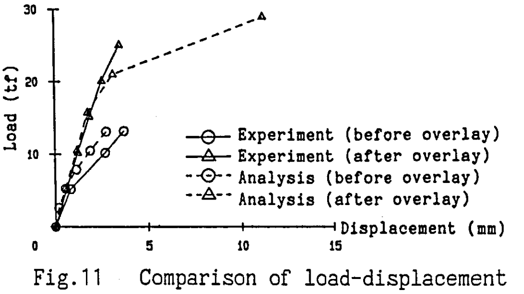

Fig.11 Comparison of load-displacement curves (Slab No.5)

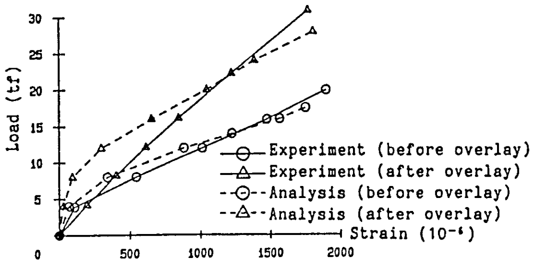

Fig.12 Comparison of strain on reinforcing bars (Slab No.2)

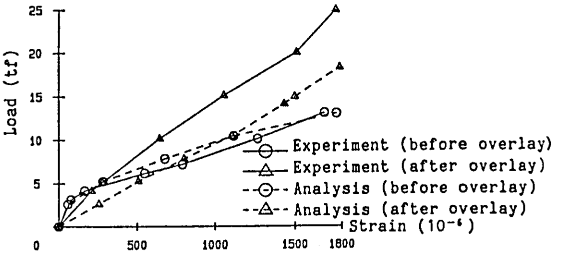

Fig.13 Comparison of strain on reinforcing bars (Slab No.5)

4.2 Displacement

Comparison of the experimental and analytical load-displacement curves for the center of slabs No.2 and No.5 whose thickness is increased after cracks have occurred is shown in Fig.10 and Fig.11, respectively. In each case, before the thickness is increased, the analyzed value of the displacement is smaller than the experimental value in the early stage of loading. This behavior is similar to that of other slabs. This is supposed to be that since the slabs and their supports are not always in full contact, a certain displacement takes place while the slab comes to close contact to the support when the load is applied. However, since the slab whose thickness is increased has been loaded once in order to generate cracks, the experimental values conform better with the analyzed ones even during the early stage of loading as compared with the other slabs.

4.3 Strain on Reinforcing Bars

Comparison of the experimental and analytical strain for the central reinforcing bars on the bottom face of the slabs No.2 and No.5 (the reinforcing bars of gauge (2) as shown in Fig.1) is shown in Fig.12 and Fig.13. In almost all cases of the slabs the experimental values and the analytical ones conform very well. However, considerable differences are seen in the cases of the slabs No.2 and No.5, especially after their thickness has been increased, between the experimental and analytical values. As mentioned previously on the method of analyzing the slab whose thickness has been increased, this is because in the analysis it is assumed that the slab retains the stiffness it had just before being unloaded to which the stiffness of the overlaid concrete is added and the sum of the two is taken as the stiffness of the slab when it is reloaded after the thickness has been increased. However, in every case, though there are certain differences between the experimental and analytical values, the analysis is thought to represent the overall trend of the experimental values quite well.

4.4 State of Cracks

Comparison of the experimental and analytical state of cracks on the bottom surfaces of the slabs No.2 and No.5 at the time of the maximum load is shown in Fig.6 and Fig.7, respectively. Since it is assumed in the analysis that when the principal stress of each element exceeds its tensile strength, cracks occurs in the direction perpendicular to the principal stress, the directions of cracks obtained are shown in the diagrams. The state of cracks in the slabs No.1 and No.3 with four ends simply supported at the time of the maximum load indicates, similar results to the state of cracks after concrete overlay is applied as shown in Fig.6. These analytical results precisely represent the radial cracks, and catch the trend of the experimental results exactly both with regard to the distribution of the cracked elements and the directions of cracks. In the case of the slab No.2 before the concrete overlay is applied, though the analyzed direction of cracks coincide well with the experimental results, the distribution of cracks is greater in the analysis. It is presumed that there is a possibility of some cracks being missed in the experiment.

As regards the state of cracks in the slabs No.4 and No.6 with two ends simply supported at the time of the maximum load, the results are similar to those shown on the right-hand side of Fig.7 (for the slab after the concrete overlay is applied). The analysis precisely captures the experimental behavior as regards the distribution of the elements in which cracks occur as well as the directions of cracks. In the case of the slab No.5 prior to increasing the thickness, though the directions of cracks coincide, the distribution of cracks is wider in the analysis than in the experiment. Also, for the slab No.7 (concentrated loading) and the slab No.8 (uniformly distributed loading) similar results as shown in Fig.6 are obtained.

4.5 Shear Stress

In the experiments, the slabs No.2 and No.5 did not reach the state of bending fracture because the concrete overlay exfoliated. By calculating the maximum shear stress at the boundary between slab and concrete overlay at the time of exfoliation, it is determined that the peak is $33kgf/cm^2$ at the end of the loading pad in the slab No.2 with four ends simply supported and in the slab No.5 with two ends simply supported, exfoliation likewise occurs at the end of the loading pad at a shear stress of $29kgf/cm^2$. This means that by processing the surface of the slab with wire brushes, the shear strength in the order of $30kgf/cm^2$ is obtained at a compressive strength of $400kgf/cm^2$ and overlaid concrete adheres fully to the slab and is integrated.

As mentioned in the above, this comparison of analytical results with experiments demonstrates that this program enables analysis of the maximum strength, displacement, strain on reinforcing bars and cracks of the slabs with a concrete overlay with adequate accuracy.

5. ANALYSIS OF THE SLAB WITH CONCRETE OVERLAY IN AN ACTUAL STRUCTURE

5.1 Outline of Analysis

For a reinforced concrete slab bridge consisting of three continuous beams with three main girders (designed in accordance with the specifications for the road bridge enforced prior to 1972), the formation of cracks on its bottom surface was reported as shown in Fig.14. The authors attempted to predict the behavior of the slabs after a concrete overlay is applied, assuming that these slabs are repaired by applying the method of a concrete overlay. Especially in applying the method of a concrete overlay, since there is a possibility of exfoliation of the newly placed concrete from the original slab due to the shear force caused by moving vehicles, the shear stress acting at the boundary between old and new concrete is calculated in the analysis. The slab for which this analysis was carried out is shown in Fig.15. The concrete portion is originally

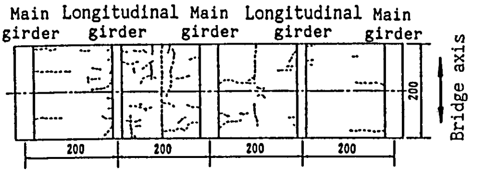

Fig.14 State of cracks

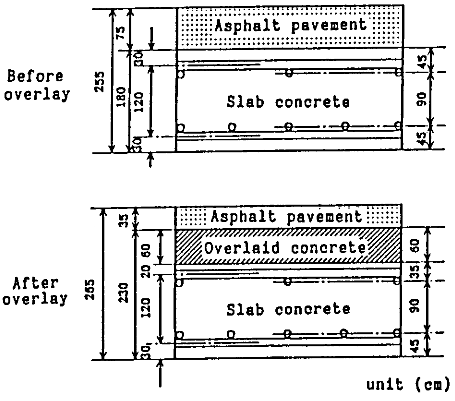

Fig.15 Cross section of slab

18cm thick with an asphalt pavement 7.5cm thick, a total of 25.5cm. Before a concrete overlay is applied, the top surface is cut off by 1cm. Then the concrete 6cm thick is newly placed and an asphalt pavement 3.5cm thick is added, thus the overall thickness of the slab reaches 26.5cm. Taking as parameters the state of cracks in the concrete slab before a concrete overlay is applied and the conditions of loading and support, this program is used to carry out the analysis.

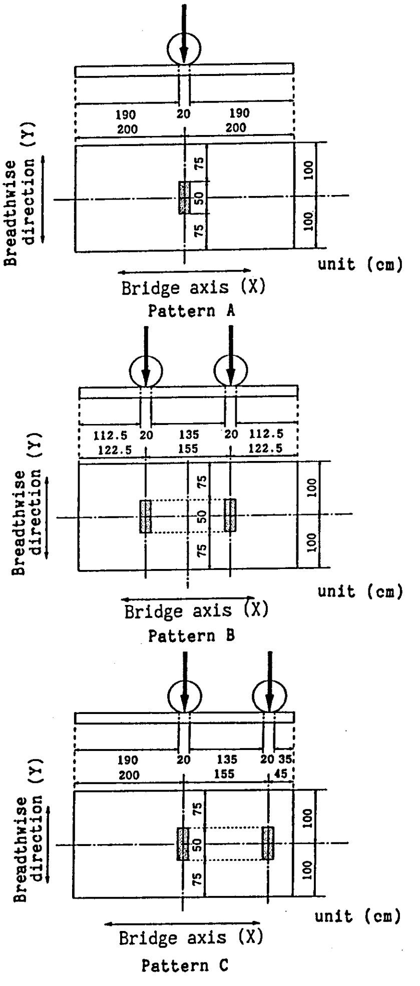

Fig.16 Condition of loading

5.2 Models for Analysis

Since the longitudinal girders are supposed to act as the supports judging from the state of cracks and the transverse bracings are arranged at the intervals of about 4m, the slab 400cm (along the bridge axis) x 200cm (breadthwise) is chosen as the model for analysis.

The loading conditions are divided into three patterns as shown in Fig.16, that is, (A) assuming the rear wheel of a truck acts at the center of the slab, (B) assuming the center of a trailer's two rear wheels acts at the center of the slab and (C) assuming one of a trailer's two rear wheels acts at the center of the slab. Regarding the load applied, since the gross weight above 60tf and the axle weight above 30tf have been observed on the expressway against the rated gross weight 20tf and the rated axle weight 16tf for T-20, in every case of (A), (B) and (C), up to three times of the rated value is loaded. Accordingly, in the case (A) the loading is carried out up to 24tf since the wheel load is 8tf and in the cases (B) and (C), the loading goes up to 18tf since the wheel load per single wheel is 6tf.

With regard to support conditions, two cases are considered: the one in which the influence of the transverse bracing is disregarded and the other in which it is deemed to act as a support. Since the applicability of this program has been verified for the slabs whose ends are simply supported as previously mentioned, simply supported ends are assumed for every slab. Accordingly, if the bridge axis is denoted by X and the breadthwise direction by Y, the cases dealt with are the one in which two ends in the X-direction are supported and the other in which four ends are supported in both X and Y directions. As for cracks, two cases are considered. In the first case, the concrete overlay is placed when cracks have developed to 1/2 of the thickness and in the second case it is placed when cracks have developed to 3/4 of the thickness.

Table 4 Parameters of model

Model	Condition of loading	Condition of support	State of cracks
1	A	two ends along X-direction simply supported	1/2
2			3/4
3		four ends simply supported	1/2
4			3/4
5	B	two ends along X-direction simply supported	1/2
6			3/4
7		four ends simply supported	1/2
8			3/4
9	C	two ends along X-direction simply supported	1/2
10			3/4
11		four ends simply supported	1/2
12			3/4

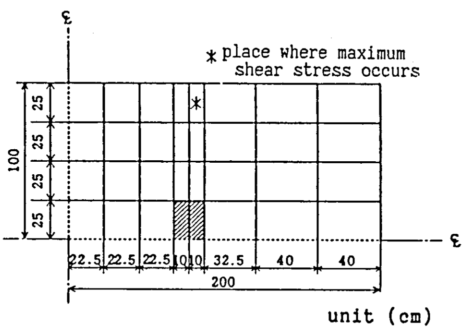

Fig.17 Division into elements (pattern B)

Taking the conditions of loading, support, and the state of cracks in the concrete before the thickness is increased as parameters, the analysis is carried out for 12 models as shown in Table 4. In the analysis, with the patterns A and B, a 1/4 portion of each slab is modeled and with the pattern C, a 1/2 portion of the slab. These models are divided into elements. An example of this division into elements (the pattern B) is shown in Fig.17. With regard to the division into laminar elements in the thickness direction, each slab is divided into 11 layers before its thickness is increased and 14 layers after that. The material properties of the concrete and the reinforcing bars used in the analysis and the arrangement of the reinforcing bars are shown in Table 5

Table 5 Material properties of analytical model

Young's modulus of concrete E_c	old 2.8×10^5 (kgf/cm²) new 2.5×10^5 (kgf/cm²)
Poisson's ratio of concrete ν_c	0.2
Compressive strength of concrete f'_{ck}	old 400 (kgf/cm²) new 240 (kgf/cm²)
Young's modulus of reinforcing bar E_s	2.1×10^6 (kgf/cm²)
Yield strength of reinforcing bar f_y	3000 (kgf/cm²)

Table 6 Arrangement of reinforcing bars

	Upper part	Lower part
Main reinforcement	D16(SD30), @10cm	D16(SD30), @20cm
Distribution reinforcement	D13(SD30), @20cm	D13(SD30), @40cm

Table 7 Maximum shear stress

Load (tf) / Model	Wheel load	3 times wheel load	Load (tf) / Model	Wheel load	3 times wheel load
1	1.0	3.4	7	2.3	6.9
2	1.2	3.7	8	3.2	8.0
3	0.9	3.1	9	4.0	7.7
4	1.1	3.5	10	1.8	6.0
5	1.4	4.6	11	3.1	8.4
6	2.2	5.7	12	3.9	9.6

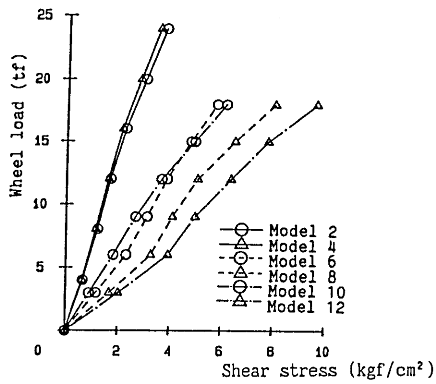

Fig.18 Load-shear stress curve

and Table 6, respectively. Especially, with regard to the new concrete used for the additional thickness, since the bridge should be put into service as soon as possible, it is assumed that the compressive strength is to be 240kgf/cm² and Young's modulus to be 2.5 x 10^5kgf/cm² at the time of opening to the traffic, anticipating the use of ultra-rapid hardening cement. In carrying out the analysis under these conditions, the shear stress arising at the boundary between old and new concrete and the displacement of the center of the slab are obtained.

5.3 Results of Analysis and Discussion

(1) Shear Stress

From the analytical result for each model, it is clear that the shear stress rises in the boundary between old and new concrete in the vicinity of the supports and the loading point. Looking at the case in which the concrete overlay is applied when cracks have developed up to 3/4 of the slab thickness, the relationships between wheel load and shear stress at the position where the maximum shear stress appears at the rated wheel load, namely the end as shown in Fig.17 being element of support, are shown in Fig.18. In every case, the shear stress tends to increase as the load increases.

The maximum shear stresses at the rated value of the wheel load and three times that load are presented in Table 7. Among the maximum shear stresses at the rated wheel loads, that in the case of Model 9 is the largest at 4.0kgf/cm² and in the case of Model 3 is the least at 0.9kgf/cm². If the patterns of loading are compared, in the case of the truck load (pattern A) the shear stress is smaller at about 1kgf/cm², in the case of pattern B it ranges over 1.4~3.2kgf/cm² and in the case of pattern C it ranges over 1.8~4.0kgf/cm² which is about three times as large as the truck load. On the other hand, when the load is three times the rated load, the maximum shear stress is the largest in the case of Model 12 at 9.6kgf/cm² and is the least in the case of Model 3 at 3.1kgf/cm². In terms of the loading patterns, the stress is relatively small in the case of the truck load (pattern A) at below 4kgf/cm² and in the case of the trailer load (patterns B and C) it is larger, ranging over about 5~10kgf/cm². Differences in the state of cracks and the support conditions did not cause significant changes in the maximum shear value.

Considering the shear strength of the boundary between new and old concrete, Minematsu et al [12] have reported on the application of a direct shear testing method to construction joints between the ultra-rapid hardening cement concrete and existing concrete. According to their report, the ratio of the shear strength of the joint of ultra-rapid hardening cement concrete to that of the slab without a joint is 30~40% in case no special processing is carried out at the joint and around 60% if the surface is processed by blasting. On the other hand, the direct shear strength τ_s of concrete is generally believed to be 1/6~1/4 of the compressive strength, and if it is related to the compressive strength of concrete f'_c, the following formula is proposed [13].

$$\tau_s = 0.252\, f'_c - 0.000246\, f'^{\,2}_c \qquad (1)$$

For instance, if f'_c =240kgf/cm² is assumed at the time when the bridge is opened to the traffic, τ_s =46.3kgf/cm² is gained and if the surface of the existing concrete is not processed, the shear strength is about 14kgf/cm². If processed by blasting, it is about 28kgf/cm². The present experiments and analysis, it is known that by processing the surface of the slab with a wire brush, the shear strength of about 30kgf/cm² is obtained when the compressive strength of the overlaid concrete is 400kgf/cm². On the other hand, the analysis of the slab in the actual bridge predicts a maximum shear stress of 4.0kgf/cm² at the rated wheel load and 9.6kgf/cm² when loaded with three times the rated wheel load. This is well below 14kgf/cm² obtained even if the surface of the concrete is not processed.

Generally, the compressive strength of concrete in the actual bridge upon opening to the traffic exceeds 240kgf/cm² and if a concrete overlay is applied, the top surface of concrete is cut off and processed by blasting. Therefore, since the maximum shear force acting on the boundary between old and new concrete is in the order of 1/3 of the shear strength of the concrete when blast processing is used, the chance of exfoliation of the new concrete under the action of wheel load is almost nil. Even if the loss of the shear strength due to fatigue may be 50%, the chance of the shear stress exceeding the shear strength is extremely low. However, as mentioned previously, further investigation will be needed on the influence of fatigue.

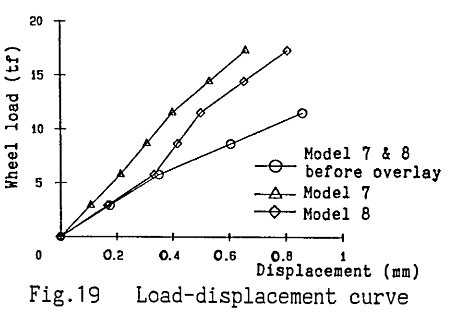

Fig.19 Load-displacement curve

(2) Displacement

For each model, a comparison is made between the displacement at the center of the slab before and after the concrete overlay is applied. Model 7 and Model 8 are shown in Fig.19 as examples. From this figure, it is clear that the displacements after the concrete overlay is applied are reduced to about half as compared with that before concrete overlay is applied, both in case overlaying is made when cracks have reached 1/2 of the thickness (Model 7) and in case it is made when cracks have reached 3/4 of the thickness (Model 8). And if comparison is made between the cases when overlaying made at the crack depth of 1/2 thickness and 3/4 thickness, the former appears to be slightly smaller but the difference almost invisible. Such trend can be seen in the cases of other models, and the displacement at the center of the slab becomes about one half of the value before the concrete overlay is applied, regardless of the state of cracks and the support conditions when the concrete overlay is applied. Thus, the concrete overlaying may be said to be effective enough.

6. CONCLUSIONS

The results of the present study are summarized below.

(1) The bending tests of the slabs whose thickness is increased by 25% from 12cm to 15cm show that the failure strength increases, and furthermore the displacement and the strain on the reinforcing bars are reduced to less than half as compared with the specimens without a concrete overlay.

(2) By comparing the results of analysis with those of experiments, it is confirmed that the breaking load, the behavior of displacement, strain on the reinforcing bars, and the state of cracks can be estimated with good accuracy by application of the program developed in this study so as to be applicable to the overlaid concrete.

(3) Through the analysis of the slabs with a concrete overlay in the actual bridge, it is clarified that the maximum shear stress generated at the boundary between new and old concrete in the slab to which the concrete overlay is applied does not exceed $10kgf/cm^2$ even when the slab is laden with the wheel load three times the rated value, thus there is little possibility of exfoliation of new concrete overlaid in accordance with the conventional process for the construction joint.

(4) In the analysis of the slab with a concrete overlay in the actual bridge, it is clarified that in case the thickness is increased by 28%, the displacement at the center of the slab is reduced to about a half as compared with the case without an overlay regardless of the state of cracks generated in the concrete and the support conditions.

References

[1] F.R. Hand, D.A. Pecknold, and W.C. Schnobrich, "Nonlinear analysis of RC plates and shells", ASCE, pp.1492~1505, 1973
[2] C.S. Lin and A.C. Scordelis, "Finite element study of a reinforced concrete cylindrical shell through elastic cracking and ultimate ranges", Journal of ACI, Vol.72, No.11, 1975
[3] M.K. Wanchoo and G.W. May, "Cracking analysis of reinforced concrete plate", ASCE, ST 1, pp.201~215, 1975
[4] Y.Dobashi, T.Uchiyama, and M.Ueda, "Elasto-plastic analysis of plates by laminate model method — part 1", Proc. of AIJ, No.266, pp.41~49, 1978
[5] Y.Dobashi, T.Uchiyama, and A.Suginome, "Elasto-plastic analysis of plates by

laminate model method — part 2", Proc. of AIJ, No.294, pp.61~73, 1980
[6] M.Ueda and Y.Dobashi, "Nonlinear analysis of reinforced concrete slabs", Proc. of AIJ, No.283, pp.26~36, 1979
[7] M.Sato, T.Uehara, H.Umehara, and H.Yoshida, "Studies on flexural crack behavior of reinforced concrete slab", Proc. of JCI, Vol.12, No.2, pp.603~608, 1990
[8] K.Okada, H.Okamura, K.Sonoda, and I.Shimada, "Cracking and fatigue behavior of bridge deck RC slabs", Proc. of JSCE, No.321, pp.49~61, 1982
[9] K.Sonoda and T.Horikawa, "Low cycle fatigue characteristics of bridge deck RC slabs under the repetition of wheel loads", Proc. of JSCE, No.390 / V-8, pp.97~106, 1988
[10] H.Okamura and K.Maekawa, "Non-linear finite element analysis of reinforced concrete", Proc. of JSCE, No.360 / V-3, pp.1~10, 1985
[11] K.Maekawa, "Constitutive law of concrete based on the elasto-plastic and fracture theory", Proc. of JCI 2nd Colloquium on Shear Analysis of RC Structures, pp.1~8, 1983
[12] T.Minematsu, K.Nomura, and Y.Uchida, "Adhesive properties of construction joint between ultra-rapid hardening cement concrete and existing concrete", Proc. of Cement & Concrete, Vol.40, pp.245~248, 1986
[13] S.Ito, "Strength of concrete under combined stress", Report of Public Works Research Institute, No.100-7, 1958