Dissertation Abstract

STUDY ON EVALUATION METHOD FOR DETERIORATED BRIDGE SLABS BY SELF-PROPELLED IMPACT VIBRATION EQUIPMENT

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Abstract

It is well known that almost highway bridges in Japan were built in period 1965-1980 when the Japanese economy grew up rapidly. Currently, there are a significant number of bridges nearly 50 years of age, and their aging has become a massive challenge for maintenance. Fatigue damages of reinforced concrete slabs have been seen not only in Japan but also in developing countries, such as Vietnam, which might be serious problems in future. As of 2008, the mandatory maintenance of bridge deck slabs has taken place every 5 years. After confirming and evaluating the situation through a visual inspection, repair plans and detailed investigations have been carried out. However, material deterioration such as salt damage, frost damage, an alkali silica reaction, and other types of damage have conspicuously appeared, and hence, it is difficult to evaluate the degree of deterioration when focusing solely on cracks. It is necessary to provide reasonable judgment and economic repair methods for highway bridges, which make up a valuable infrastructure in rural areas.

Therefore, in this study, an experiment was conducted on the impact force using self-propelled impact vibration equipment (SIVE), which was developed for highway bridge deck slabs and pavement. The measured values and analysis results using the finite element method (FEM) were then compared, leading to an establishment of a method for evaluating the degree of deterioration.

Also, we propose a method of inserting rods of carbon fibers impregnated with resin in grooves on the lower surface of the concrete slab and confirming the reinforcing effect by the wheel load running experiment.

Chapter 1: Introduction

After the end of The World War II, in period 1965-1980 Japanese economy grew up rapidly, not only home appliances, but also social infrastructure such as water supply, electricity, roads speedily penetrated society and people. Japan's economic development has been influenced by the achievement of these period.

Regarding this time, almost all highway bridges were built, currently, the are a significant number of bridges nearly 50 years of age and more. These bridges function as a part of a transportation network that is very important such as the Shinkansen and expressway, long-distance flows of people and things, people like the city roads and farm roads, etc. Also, even though there are large and small, each is still being used as a substitute, as an indispensable thing. However, it is about 50 years since the start of service, and after had been used for a long time so far, many bridges where degradation phenomenon was found.

Owing to all these advantages and disadvantages of all soundness method, we will introduce Self-propelled Impact Vibration Equipment (SIVE) as a loading machine and conduct experiments. SIVE is a loading machine that gives impact force by dropping a weight loaded with FWD, but the difference from the conventional in-vehicle FWD is that loading is impossible in the past because the loading machine is moved by a small crane. It also possible to load at the end of the road surface and make fine adjustments to fit the loading board to the loading point, as it also benefited from small turning, making the choice of loading points wider. In addition, in order to save labor in installing the displacement measuring device, we decided to adopt a system that uses a placement type accelerometer for the displacement measurement and calculates the second order integral value of the measured acceleration as the measurement displacement. Furthermore, the accelerometer was arranged at regular intervals in the direction of the girder, and displacement was measured in the form of displacement distribution. Actual tests were mainly carried out on the RC slab of the actual bridge. SIVE (Self -propelled impact vibration equipment) was developed to evaluate the deterioration of slab simply and rationally. This equipment can change the mass of falling weight, a height and a rubber condition used as cushion system. When SIVE is used at the site, generally, proper impact force, momentum and duration of impact force are required depending on the scale of objective structure. In this study, impact tests for series of rubber buffer were performed, characteristics of impact force were shown and summarized.

Also, in order to ascertain what degree of deterioration of the experimental value is, we compared it with calculated value and analysis value.

After determined the degradation of those bridges, it is considered necessary to give a reasonable judgment method to select two ways, which specifically is the way ensuring the required performance by repair and reinforcement and the way prolonging the life until the next countermeasure.

Therefore, in this research, in order to provide the reinforcement method to improve load bearing performance and the method that can be expected to prolong life even if improvement of load bearing performance cannot be anticipated, experimental research had been done.

Chapter 2: Development of Self- propelled Impact Vibration Equipment.

Generally, a certain equipment which has a feature of mobility and enough power to carry out a field test on an entire bridge or a part of bridge, such as a slab deck, is required. Therefore, an equipment(SIVE) was developed to fulfill such requirements.

The overview of SIVE is shown in Figure 1. It is easier to set SIVE at any point by a simple operation compared with FWD car systems. This equipment consists of two large parts which are a forklift truck and an impact occurrence equipment. Electric truck works by the battery DC 24 volt and supplies necessary power to the impact occurrence equipment, the measuring equipment and personal computer. The occurrence equipment consists of the hoist lifting a weight, steel weight, rubber buffer, load cell and loading plate. The equipment can change the mass of a falling weight, a falling height and a rubber cushion used in cushion system. The maximum falling height is 0.3 m and the maximum mass of weight is 220 kg. The capacities of energy and momentum are 0.65 kJ, 0.44 kNs respectively.

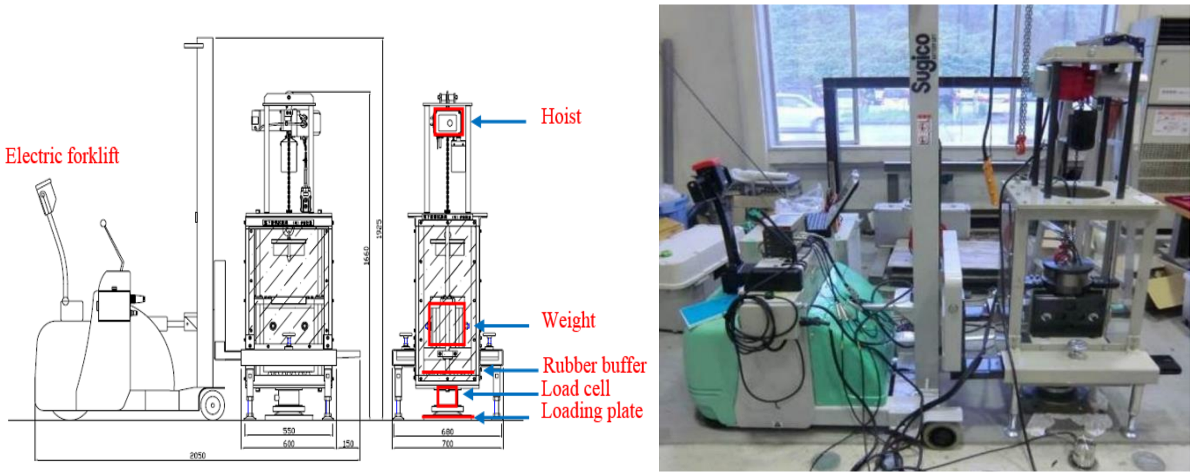


Figure 1: Overview of SIVE

The figure 2 shows the arrangement of 5 types of rubber cushion for choosing the suitable rubber to control the maximum forces and duration of impact

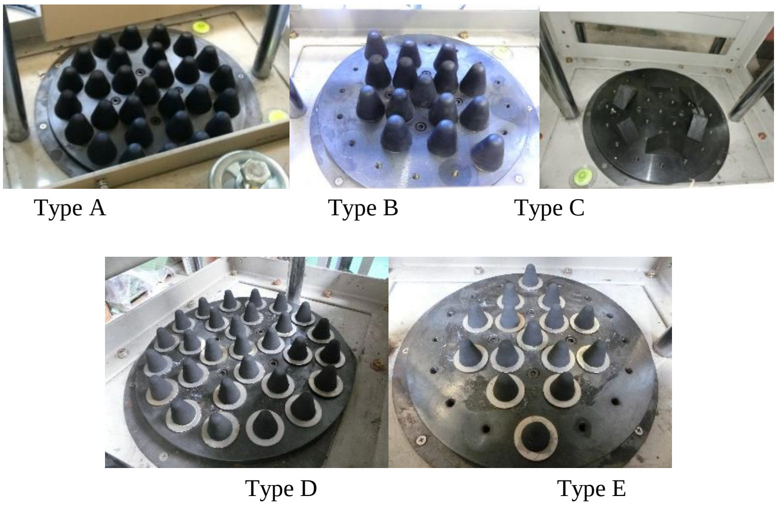


Figure 2: Rubber cushion

Table 1: List of experiment by SIVE

Cushion Type	Mass of weight	Falling height	Collision energy	Momentum
	M_w (kg)	H_f (m)	E_{ini} (kJ)	M_{ini} (kNs)
A	220	0.05 to 0.30	0.11 to 0.66	0.22 to 0.53
B	220	0.05 to 0.30	0.11 to 0.66	0.22 to 0.53
C	220	0.05 to 0.30	0.11 to 0.66	0.22 to 0.53
D	220	0.05 to 0.30	0.11 to 0.66	0.22 to 0.53
E	220	0.05 to 0.30	0.11 to 0.66	0.22 to 0.53

Type A and B There were 29 and 15 of rubber cones were arranged in Type A and B respectively. This type of rubber cone (rubber buffer KFDF-51, Tokyo sokki kenkyujo co. ltd) is normal rubber, 48 mm of height, 40 mm of diameter . Type D and E are low rebound rubber (Hanenaite, Naigai rubber industry co. ltd.) with the height is 32 mm and the diameter is 26.09 mm. In addition, type C arranged by 6 low rebound triangle rubbers.

Experiments were conducted with a plate that has detail of dimensions (Figure 3). The plate was setup in two support, loading plate was set in the center of plate. Displacement of the center point of the plate was measured by a displacement meter (CDP5, Tokyo sokki kenkyujo co. ltd.).

In the same conditions and five types of rubber, data were collected from equipment built-in load cell. Velocities and displacements were got by using numerical integrations.

Figure 3 shows the time course impact force from 0.3 m height in case of type D rubber and the acceleration data. The first impact is the most important for the dynamic behavior of structure. Thus the first impact should be focused. In this type of cushion, the impact force reached the peak at about 80 kN in only 0.02 s. With rebound rubber, the rebound of falling weight seems to be reduced. The displacements measured by the displacement meters and calculated based on acceleration were shown. It became clear that the displacement calculated from acceleration at the center point is in good agreement with the value by displacement meter. The ratio between them was approximately 1.0.

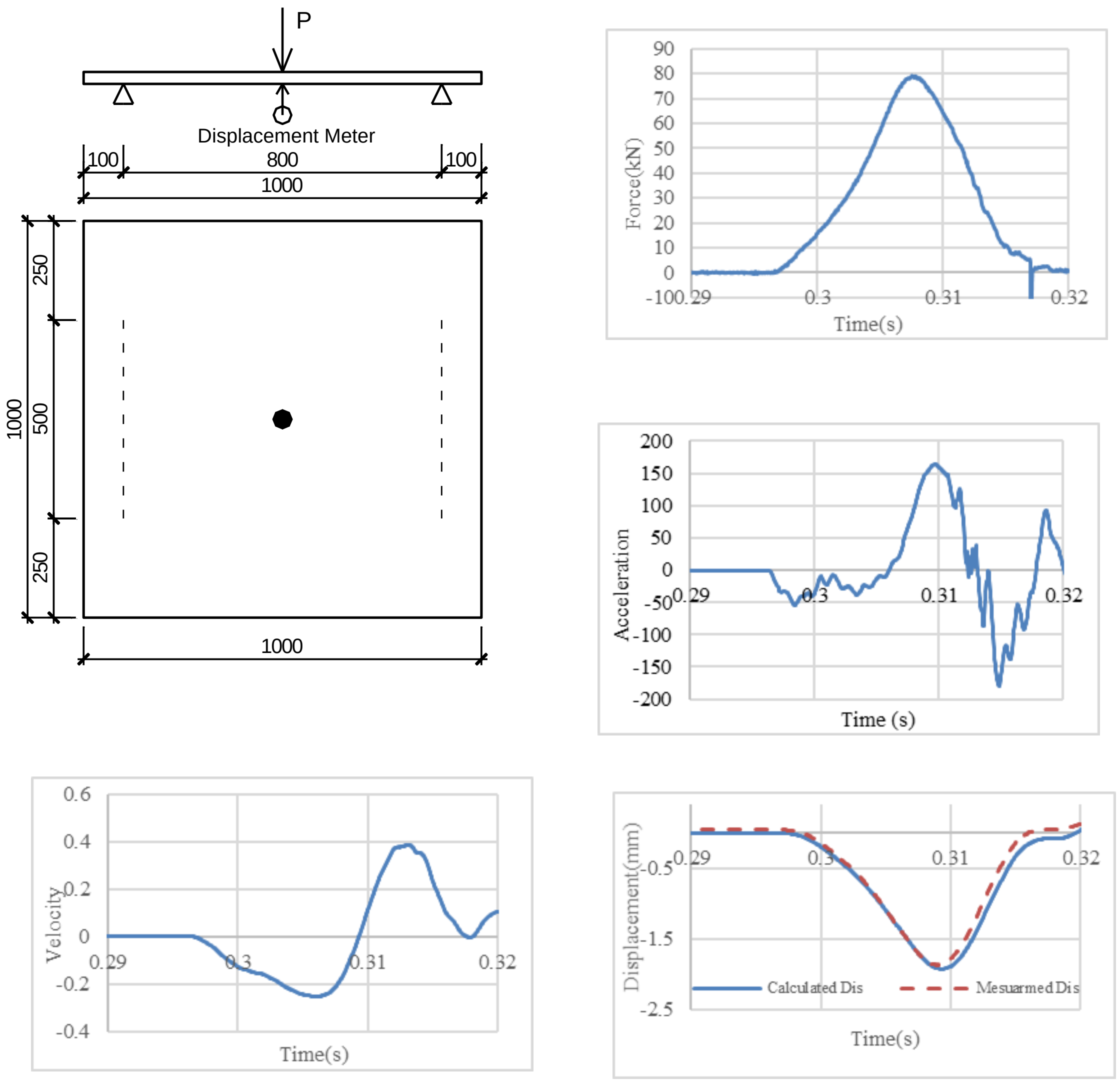


Figure 3: Experiment outline and Experiment results example of Impact force, acceleration, Velocity and Displacement.

Table 2 provides the overall view of displacement. The difference between the calculated displacements and the true value is small in all case except the one with a low falling height 0.05 m. Displacements experienced the same trend of increase in all case with the rise of falling heights

Table 2: Relationship between calculated displacements and measured displacements

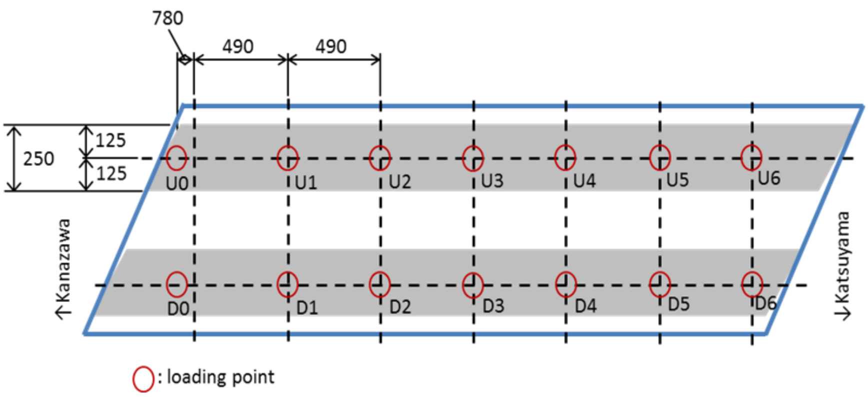
Height (m)		Type A	Type B	Type C	Type D	Type E
0.05	D^{C}_{max} (mm)	-0.579	-0.483	-0.399	-0.396	-0.285
	D^{m}_{max} (mm)	-0.552	-0.425	-0.345	-0.358	-0.305
	D^{C}_{max}/ D^{m}_{max}	**1.049**	**1.136**	**1.158**	**-1.106**	**0.934**
0.1	D^{C}_{max} (mm)	-0.815	-0.812	-0.926	-0.648	-0.068
	D^{m}_{max} (mm)	-0.888	-0.743	-0.771	-0.620	-0.068
	D^{C}_{max}/ D^{m}_{max}	**0.918**	**1.093**	**1.201**	**1.045**	**1.004**
0.15	D^{C}_{max} (mm)	-1.092	-1.115	-1.252	-0.868	-1.033
	D^{m}_{max} (mm)	-1.115	.068	-1.154	-0.803	-1.035
	D^{C}_{max}/ D^{m}_{max}	**0.980**	**1.044**	**1.084**	**1.081**	**0.998**
0.2	D^{C}_{max} (mm)	-1.311	-1.487	-1.616	-1.160	-1.705
	D^{m}_{max} (mm)	-1.305	-1.460	-1.553	-1.147	-1.721
	D^{C}_{max}/ D^{m}_{max}	**1.005**	**1.019**	**1.041**	**1.012**	**0.990**
0.25	D^{C}_{max} (mm)	-1.620	-1.870	-2.001	-1.576	-1.985
	D^{m}_{max} (mm)	-1.603	-1.869	-1.856	-1.567	-1.986
	D^{C}_{max}/ D^{m}_{max}	**1.011**	**1.000**	**1.078**	**1.006**	**1.000**
0.3	D^{C}_{max} (mm)	-1.947	-2.241	-2.358	-1.927	-2.569
	D^{m}_{max} (mm)	-1.840	-2.268	-2.276	-1.869	-2.462
	D^{C}_{max}/ D^{m}_{max}	**1.058**	**0.988**	**1.036**	**1.031**	**1.044**

It is generally suggested that it was so important to control the maximum force, duration of force and less rebound of falling weight for better pursuit of experiment at site. It is possible to calculate the accurate displacement by the acceleration measured in SIVE. With the accuracy we will us SIVE for the measurement of displacements at actual site in the future.

Chapter 3: STUDY ON INSPECTING REAL BRIDGE DECK BY SEVERAL FALLING WEIGHT DEFLECTOMETER SYSTEMS

3.1. Hinoki bridge

In this study, SIVE (Self -propelled impact vibration equipment) was developed to evaluate the deterioration of slab simply and rationally. This equipment can change the mass of falling weight, a height and a rubber condition used as cushion system. When SIVE is used at the site, generally, proper impact force, momentum and duration of impact force are required depending on the scale of objective structure. Hinoki bridge is constructed in Ishikawa Prefecture in 1973 is a bridge passing through Shiramine, which is a mountainous area of Hakusan City, and is a composite plate girder bridge with one RC on which four RC slabs are placed on the main girder. The cross-sectional view and the plan view of the bridge are shown in Figures 3.1 and 3.2. The bridge length is L = 35,800 mm, and the total width is B = 9200 mm. The width of roadway is 7000 mm



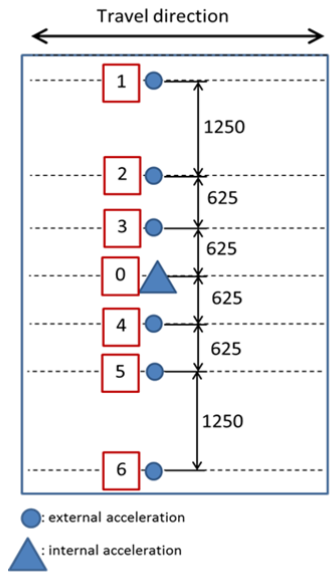


Figure 4: Experiment outline

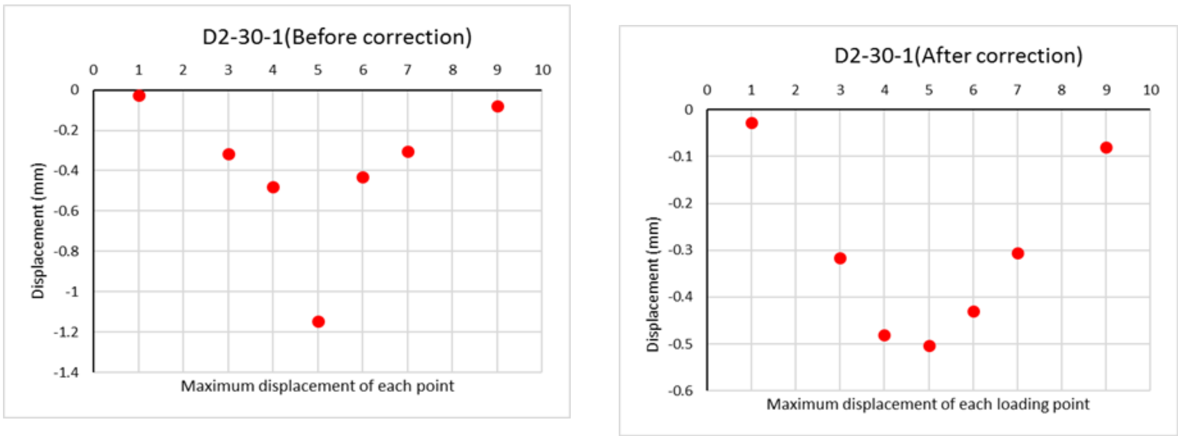


Figure 5: Maximum displacement of loading point D2 before and after Newton Interpolation

Maximum value of displacement in each point of external and inner acceleration. However, the results seem to have the phenomenal differences between the value of loading point and external point. Looking at these plots, we can see that the calculation displacement at the loading point is large. What is considered as a cause is that the asphalt pavement has been damaged due to the damage condition. Therefore, based on the calculated displacement obtained from the external accelerometer, the displacement of the actual bridge deck slab is considered by using the shape function. Using interpolation method for approximating between values of a given function and handling it as a continuous function.

Other systems were used to have references results such as FWD light and Doppler system. After all the experiments, results have been collected. In brief, in this experiment on Hinoki bridge the result between SIVE and FWD light are quite comparable each other. Displacements which are collected by Doppler measure, the average values are lower than the one from SIVE. In U0 loading point we can see the large difference between the values, in addition to loading point 1 and 4 with the displacement gauges were the smallest value on U side. Whereas on D side these values seem to be in proportionate to others result such as Doppler average displacement value.

In the future experiments, it is important to clarify the cause of the large displacement at the loading point, and it seems to lead to a smoother deterioration evaluation. After a series of experiments on Hinoki bridge we have some conclusion. Rubber type E which is low rebound rubber is the ideal one to control the maximum impact forces. The result of displacement which is calculated by the acceleration in SIVE are quite equivalent with the result of FWD light. Some differences were found in the results, detailed inspection and further experiments by this method are now scheduled to get more accurate results. They give concrete information on repair.

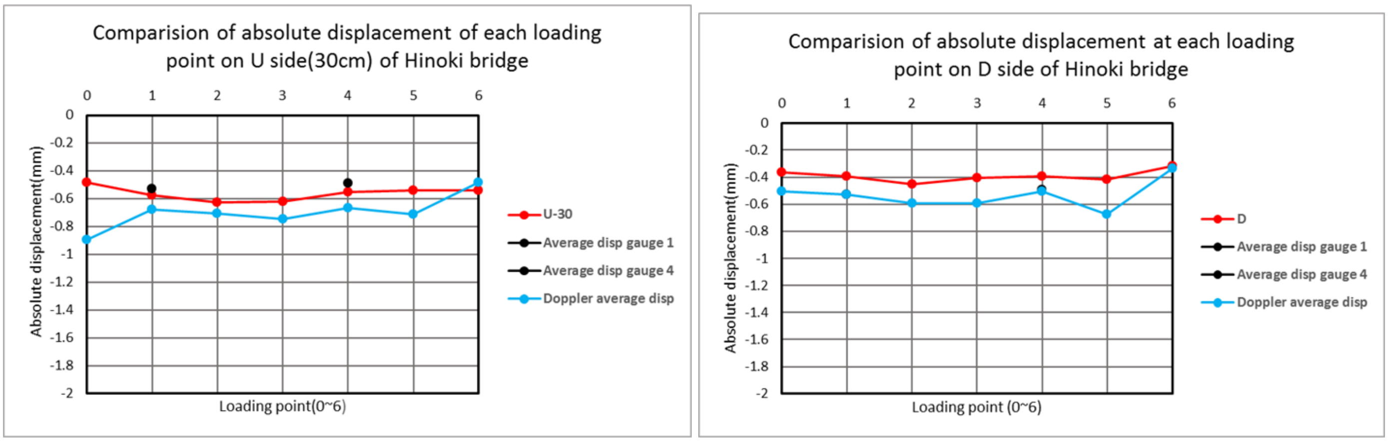


Figure 6: Comparison of absolute displacement of each loading point.

We would like to accumulate displacement data of many bridge slabs by this SIVE and build reliable and accurate checking method. We will also conduct research on analytical reproduction.

3.2. Yatsuo bridge

Yatsuo Bridge, as the target of this research, is a synthetic plate girder bridge with three spans and is located on a city road in Toyama Prefecture. The bridge has five main girders, and reinforced concrete is used for the deck slab (hereinafter referred to as RC). The length of the objective span is 29.20 m, and the total width is 14.80 m. At the time of the testing, a number of places showed discoloration from water exposure on the lower surface of the slabs during a visual inspection.

The falling weight was 250 kg and the falling height was 150 mm. The load positions were set to 11 points per row, as shown in Figure 7. At the yellow loading point in the figure, a sensitive displacement gauge (CDP-25, Tokyo Instruments Research Institute) was installed on the back of the deck slab, and the actual displacement was measured. The loading at each position was applied twice. After the experiment we have the results, It is clearly that, the displacement of the loading point was influenced by the pavement,

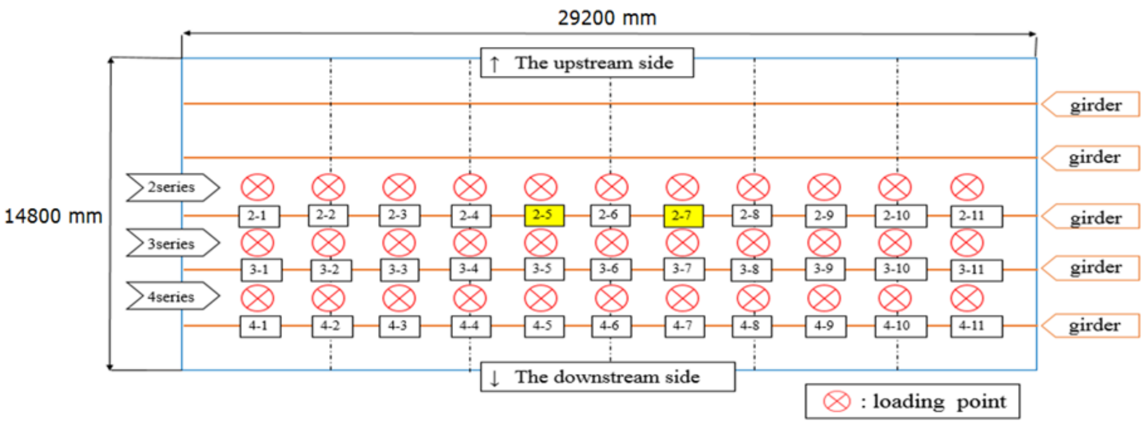


Figure 7: Plan view and loading point

after use interpolation, the results quite equivalent with the displacement meter.

Other points of SIVE loading test experienced the same trend with Doppler system and displacement gauges which were installed on lower surface.

Chapter 4: Analysis using Finite Element Method

In the impact loading test described above, occurrence displacement of the floor slab by impact loading was measured. In this study, we estimate the degree of deterioration of the deck from these measured values also estimate the degradation degree by comparison with the analysis displacement by the impact analysis model reproducing the actual experiment situation. In this chapter, we will describe the method and results of the analysis. Also, from the actual test results described above, the measurement displacement by the accelerometer with respect to the load point shows a tendency to be larger than the measurement displacement by the gauge and the Doppler system, the displacement distribution showed a sharp shape, we also analyze the purpose of clarifying the cause of this. With Hinoki and Yatsuo bridge, two types of model is solid partial model and shell full model have been used.

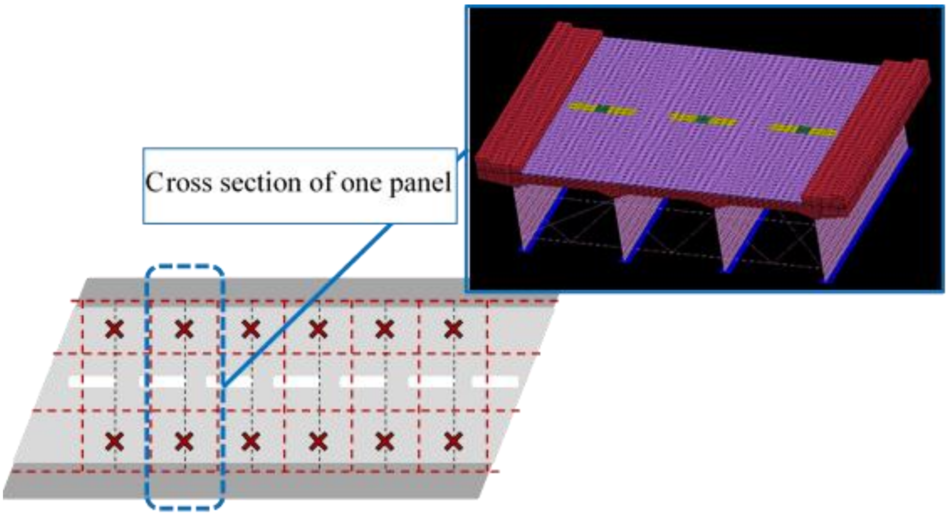


Figure 8: Solid partial model

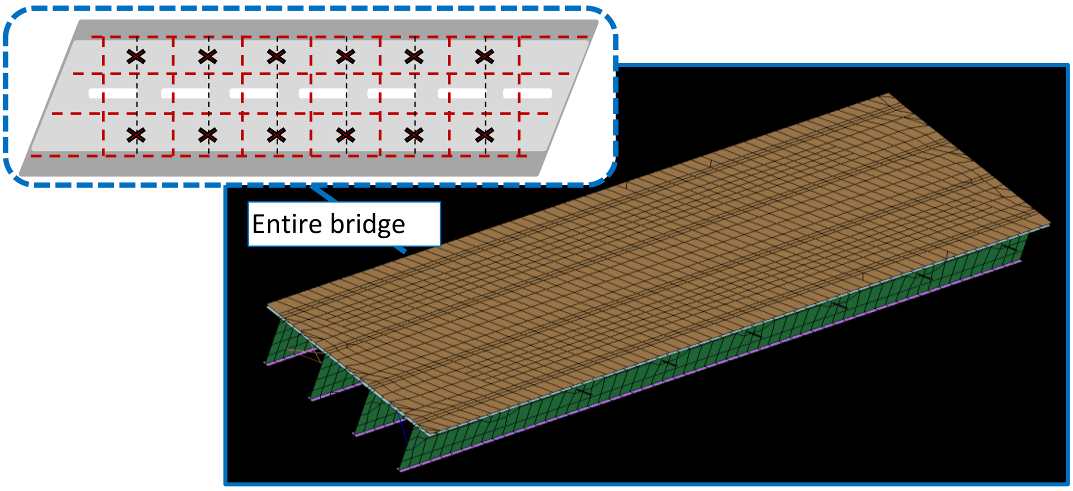


Figure 9: Shell model of full bridge

Properties of each member used for analysis show table 3. All the properties were elastic and MAT_elastic was applied

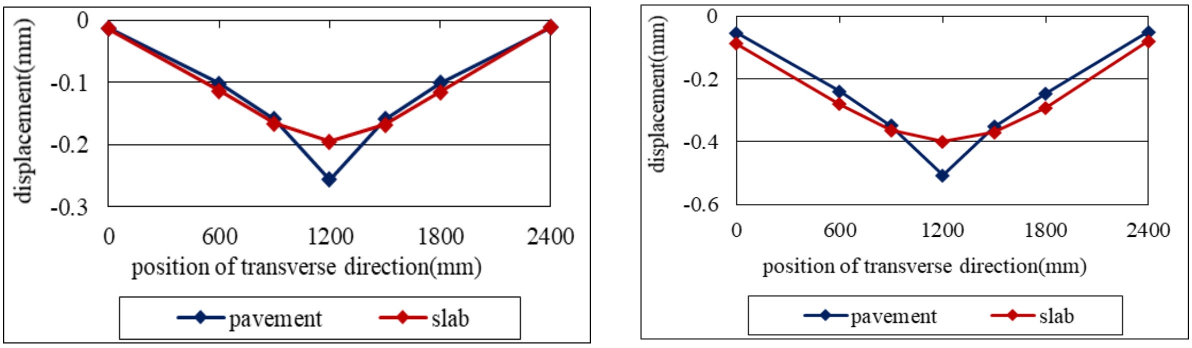


Figure 10: Displacement distribution of solidmodel and shell model

Table 3: Properties of model element

Model element name		Elastic coefficient (kN/mm²)	Poission's ratio	Remarks
Slab	Healthy condition	21.5	0.2	By the core test result of healthy part of bridge
	Some deterioration	13.3	0.2	At the time a relatively minor deterioration phenomenon confirmation
	Serve deterioration	6.67	0.2	When comparatively severe degradation phenomenon is confirmed
Pavement	5°C	10	0.35	Using reference
	15°C	7	0.35	Using reference
	40°C	0.938	0.35	Using reference
Steel main girder		200	0.3	Using general value
Steel cross girder		200	0.3	Using general value
Truss		200	0.3	Using general value

Here we compare the distributions of pavement and slab displacement in the case of E_c = 21.5 kN /mm^{2}and E_p = 7 kN /mm^2 for both Hinoki Bridge shell model and Solid model.

For the displacement of each bridge on the lower surface of the deck, the analysis value is compared with the experiment value calculated by interpolation. Figures 11 shows the comparison of Hinoki bridge and each series.

In Hinoki Bridge, leakage occurred in any measurement panel in the actual slab, clearly indicating that relatively severe degradation occurred. From this and the comparison of the above analysis value and experiment value, it is considered that the degree of deterioration can be inferred. However, from the appearance observation, it was impossible to determine whether there was a clear difference between the degree of deterioration of the panels and the degree of deterioration of other panels. The girder end panel located immediately adjacent to the spar side as viewed from the panel clearly has more severe deterioration as compared with other panels, such as leaking water covering the entire surface thereof and exudation of white precipitates occurred. There is a possibility that the influence of the deterioration may be exerted on the panel near the corresponding girder end, which seems to have appeared in the magnitude of the displacement experiment value.

As a result of Yatsuo bridge in series 2, the interpolated value of the experimental displacement was close to the usage limit state obtained from the analysis of the slab. In series 3, it was found that the interpolation value of the experimental displacement exceeded the displacement of the usage limit state obtained from the analysis of the slab, but did not exceed the ultimate limit state. In addition, at a point where deterioration, such as a leakage, occurred, a large displacement was obtained, as compared to the other loading point.

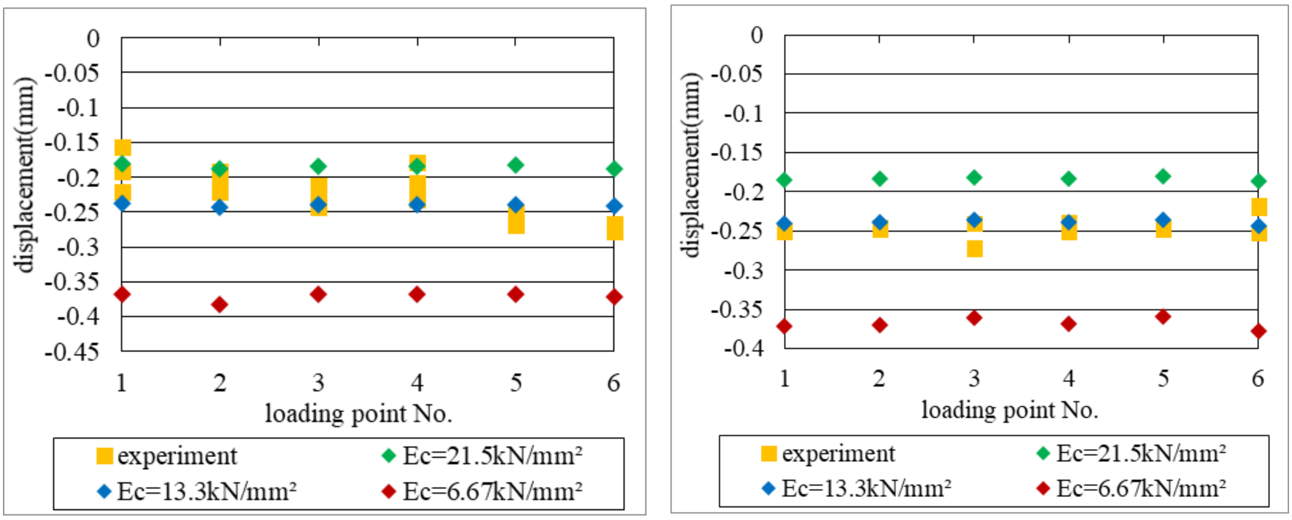


Figure 11: Comparison of experiment value and analysis value series 1 and 2.

For the estimation of deterioration degree from the pavement top surface displacement, it was inferred that severe deterioration occurred from the comparison between the analysis value and the experiment value at the place where severe deterioration was observed in observation from the lower surface of the deck. In addition, it was inferred that degradation phenomenon of cracking degree or severe degradation phenomenon occurred in the part where only damage such as cracks was found. In the analysis, when the displacement of the loading point reaches the maximum values, the displacements of the other points are clearly in agreement when comparing the pavement and deck slab. From the above, it was shown that the deterioration degree of the deck can be estimated from the displacement of the pavement upper surface. When the damage progression is confirmed during the next bridge inspection, it is considered that an implementation of a similar load test at this time will be effective from the viewpoint of determining the degree of damage.

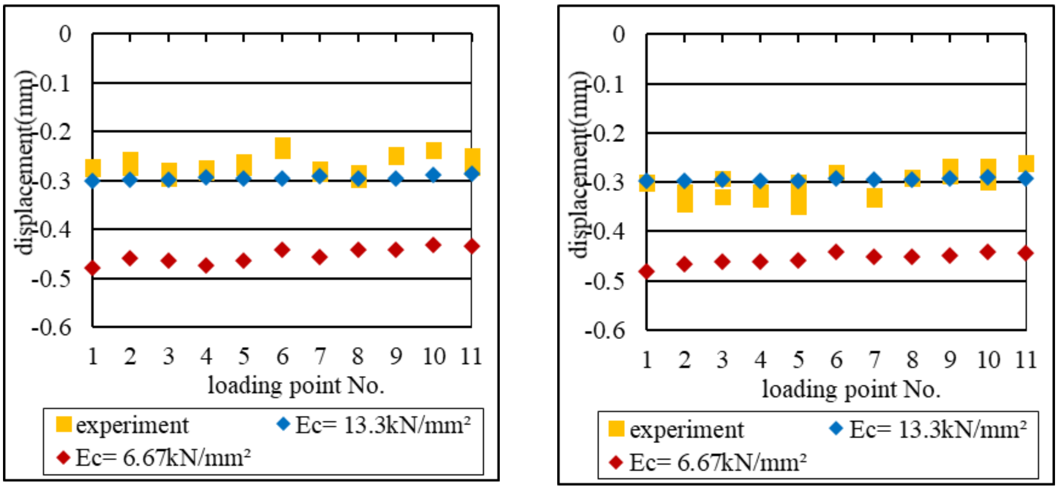


Figure 12: Comparison of experiment value and analysis value of Yatsuo bridge series 2 and 3

Chapter 5: Reinforcement effect by carbon fiber for Fatigue-damaged concrete slabs

The number of aging bridges increases certainly in Japan, maintenance and management of them become an unavoidable social issue. Therefore, the planning of effective countermeasures for damaged bridge is one of urgent important issues. In the present situation, the bridge inspection legislated in 2014 has been proceeding in Japan. The grasp of damage degree and implementation of repair countermeasures corresponding the results of bridge damage have been executed mainly on the national highway. Therefore, in this research, in order to provide the reinforcement method to improve load bearing performance and the method that can be expected to prolong life even if improvement of load bearing performance cannot be anticipated, experimental research had been done.

The specimens were full size, specimen A was conformed to the specification of road bridge in 1964 (Showa 39 era). The amount of reinforcing bar and thickness of the deck slab were specified as B specimen which is compliant with 1972 (Showa 47 era) specification road bridge.

By inserting it into the groove cutting (15mm*15mm*2400mm), deterioration progression after reinforcement can be confirmed, and even when water leakage due to a defect of the waterproof layer occurs, it does not stay inside the slab. One strand consisted from 48 bundles of carbon fibers is roughly equivalent to two layers of a general 300 g basis weight and regular length of the strand sheet is 50 m. Therefore, it is possible to construct without a joint until the length 50 m. Additional work does not occur at a construction site of a real bridge which takes time and effort concerning a joint problem. After an experiment on simple beam with reinforcement of carbon fiber with the quantity 48 and 72 respectively, we decided to use 48 bundles of carbon fiber for this experiment due to the effectiveness of strength and cost.

After reinforcement with CFRP rods, the loading carried out by crank type running test machine (Figure 13), in this test, the slab was simply supported with round bar.

Evaluation the fatigue durabilities by CFRP

It is considered that the reinforcement effect can be grasped using the SN curve obtained from the results based on the previous road experiments by the same wheel load- running machine used in the past. The equivalence number of runs by the same load of 160 kN is calculated by following equation [5].

$$\mathrm{Log}(P/P_{sx}) = -0.09121\mathrm{Log}N_{eq} + \mathrm{Log}1.52 \qquad (1)$$

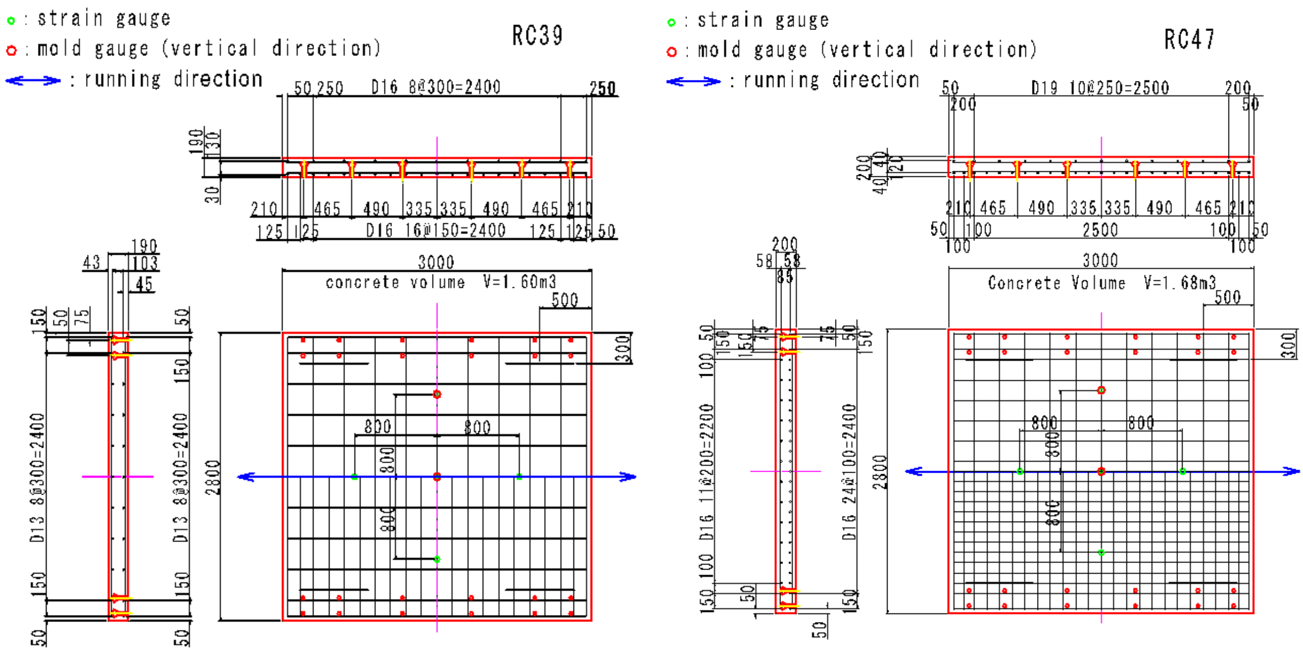


Figure 13: Crank type running test machine

Here, P is wheel load (kN), P_{sx} is punching shear strength and N_{eq} is equivalent load running number. The calculation formula is based on P_{sx} in consideration of the formation of beams from a concrete slab by Matsui. The reinforcing layer with carbon fiber are not considered in this equation. Calculation results are as shown in Table 4, and a reinforcement effect of 10.14 times against that of non-reinforcement is obtained. Therefore, it can be expected that sufficient reinforcing effect can be expected, and it is considered to have a life prolonging effect.

Table 4: Calculation results concerning Fatigue durability

<table>
<tr><th>Items</th><th colspan="2">S39-2
(No reinforcement)</th><th colspan="2">S39-2
(A specimen)</th><th colspan="2">S47-2
(No reinforcement)</th><th colspan="2">S47-2
(B specimen)</th></tr>
<tr><td>Compression strength
f'_c (N/mm^2)</td><td colspan="4">49.6</td><td colspan="4">25.2</td></tr>
<tr><td>Young's modulus
E_c (kN/mm^2)</td><td colspan="4">34.3</td><td colspan="4">8.0</td></tr>
<tr><td>P_{sx} (kN)</td><td colspan="4">326.9</td><td colspan="4">381.3</td></tr>
<tr><td rowspan="2">Loading program</td><td>P_i</td><td>ΔN_i</td><td>P_i</td><td>ΔN_i</td><td>P_i</td><td>ΔN_i</td><td>P_i</td><td>ΔN_i</td></tr>
<tr><td colspan="2">160</td><td>160</td><td>100,000</td><td colspan="2">160</td><td>160</td><td>100,000</td></tr>
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		190	315,000		230	250,000
P/P_{sx}	0.49	0.49		0.42	0.42	
Equivalent number N_{eq} (P=160kN)	214,187	2,171,548		15,440,759	13,445,108	
Reinforcement effect	1.00	10.14		1.00	0.87	

Chapter 6: Conclusion

The results of SIVE and analysis achieved in this study are summarized follow

(1) In the impact test, no difference in the feature of the displacement distribution in the bridge axis due to the load action time was observed. From the displacement distribution in the direction of the girder, it was found that the displacement of the loading point shows an abnormally large value, and it was suggested that the cause is due to the influence of the pavement. As a result of applying Newton’s interpolation for the loading point displacement measured from the pavement, rough agreement was found with the actual displacement measured from a high-precision displacement meter from the lower surface of the deck slab.

(2) Since it was suggested that the pavement displacement during the test did not show much change due to temperature and the displacement of the pavement other than the loading point was almost the same as the displacement of the bridge slab. From the viewpoint of the pavement upper surface and the lower surface of the deck, as a result, it was shown that the deterioration situation of the deck can be estimated from the comparison of the experimental value of the displacement on the pavement upper surface and the analysis value in this study.

(3) When the damage progression is confirmed during the next bridge inspection, it is considered that an implementation of a similar load test at this time will be effective from the viewpoint of determining the degree of damage.

By using Carbon Fiber Reinforced Polymer (CFRP) on the lower surface of the slab and confirming the reinforcing effect by the wheel load running experiment. The obtained results are shown

(1) Reinforced by CFRP is an effective method. The life of specimen was postponed by carbon fiber reinforcement in only the direction of the bridge axis. Reinforcing effect of 10.14 times as an equivalent to the number of running times was obtained. It is undenied that reinforcing by CFRP is sufficient not only in reinforcement but in economy problems as well.

(2) It has become clear that the reinforcing effect can be obtained only by reinforcement in the range where the load acts, because the strain of the carbon fiber of the specimen is large just under the wheel load and strain in the vicinity of the support is quarter.

(3) In the specimen with a small Young's modulus, the effect of reducing deflection by carbon fiber reinforcement in two directions was confirmed and it is considered that an improvement in fatigue durability could be expected. However, in the confirmation of the quantitative effect, further examination is required.

In the future, we are going to conduct a confirmation experiments on fatigue durability by wheel load running experiment for deteriorated bridge slab by ASR, and we are planning to examine whether carbon fiber reinforcement shown in this study can be effective for material deterioration.