FATIGUE-BASED STRUCTURAL BEHAVIOR OF RC BRIDGE SLABS WITH DIFFERENT LOADING HISTORIES

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ABSTRACT

This paper discusses the path dependency of high cycle fatigue behaviours of RC bridge slabs under various loading histories in use of laboratory experiments and numerical behavioural simulation.

A prototype standard RC slab and another two specimens, which were initially loaded statically in advance, were prepared for the subsequent wheel-type loading. All three of them were tested under a moving load of 160kN. Observed is the independency of the progressive mid-span deflection on the loading histories. Furthermore, the same trend is rather observed at a level of 220kN as well with another set of specimens of exactly the same shape and dimension.

The observed phenomenon in the experiments was successfully simulated by direct path-integral 3D nonlinear FE analysis considering the varying boundary conditions from the preliminary loading state to the main one to introduce the high cycle fatigue damages.

Keywords: RC bridge slab, fatigue, wheel moving load test, life prediction

1. INTRODUCTION

An accurate prediction of the remaining life of reinforced concrete (RC) bridge slabs may lead tofurther rationalization of the bridge maintenance. The deck slab damage criteria specified by the Japan Society of Civil Engineers (JSCE) and the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) are presented based on on-site visual observation. Although this measure is practically useful for rough judgment of damage level of RC members in service, they are not directly related to the structural performance assessment quantitatively, and do not enable us to determine the loading history of the targeted bridge or identify the cause of damage. Fatigue of RC members in shear was investigated by Ueda *et al.* (1981), who conducted beam tests focusing on stirrup strain in progress and elucidated the relationship between loading history and fatigue

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damage. Here, it remains unknown whether the damage modes are applicable to three-dimensional out-of-plane shear failure in slabs.

In this study, a series of tests on bridge RC slabs subjected to high cycle repetition of the moving wheel-type loads was conducted by parameterizing the magnitudes of load and loading history. Primary engineering interest is addressed to the progressive deflection of RC slabs under varying loading histories and boundary conditions.

2. TEST METHOD

The slab specimens used in this study are haunched RC slabs having a span of 2500 mm and measuring 3500 mm in the bridge axis direction, 2800 mm in the transverse direction and 160 mm in thickness, designed in accordance with the 1964 Specification for Steel Road Bridges. Figure 1 shows the shape of the RC slab and the reinforcement pattern. In view of the availability, D19 reinforcing bars made of SD295 steel (JIS), and D13 and D16 bars of SD345 steel were used. The cement used is high-early-strength Portland cement. For the drying shrinkage measurement, plain concrete specimens of 100×100×400 mm were fabricated, and the measurement was conducted while the specimens were cured under the same conditions as those for the RC slabs. The specimens were cured for about two days after concrete placement until the concrete became stiff enough for the form removal. After the form stripping, the specimens were cured in air, covered with plastic sheeting.

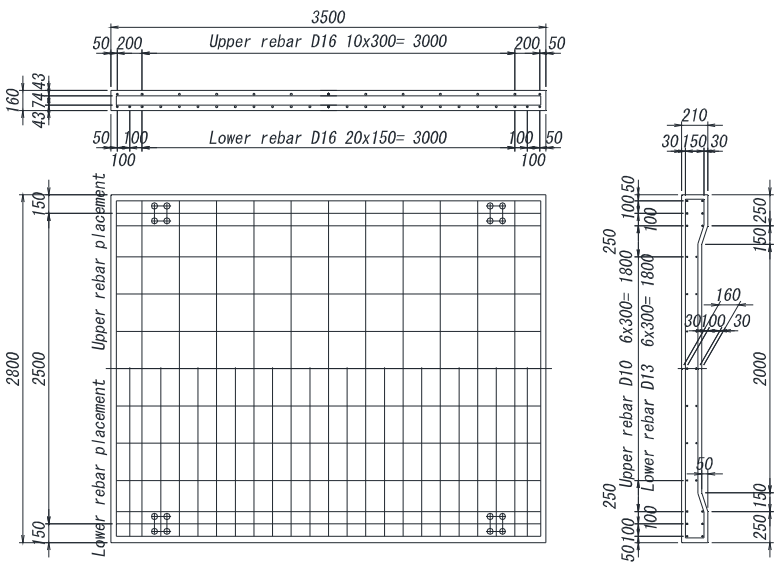

Figure 1: The shape of the RC slab and reinforcement pattern

As typical cases of loading histories, both static load tests and fixed point fatigue ones were conducted to produce mechanical damages to the specimens. **Table 1** shows the cases analyzed. A 500 kN fixed point fatigue testing machine was used for the preliminary loading, and a self-propelled 250 kN fatigue testing machine equipped with aircraft rubber tires was used in the

moving load tests. The slab was supported at a span of 2500 mm in the transverse direction, and round steel bars were placed on top of the supporting girders. The slab underside areas to come into contact with the supporting girders were protected with a 9-mm-thick steel plate bonded to the slab with an epoxy resin. In the bridge axis direction, the slab was elastically supported at a span of 3300 mm. Four corners of the specimen were bolted down to prevent a uplift, but rotation was permitted.

Table 1: Cases examined

Series	Case	Preliminary loading	Moving load
16 Series	16-S	Static 288kN + Moving load 160kN (1000 times)	220kN
	16-F	Pulsating load 220kN (30,000 times) + Moving loads 160kN (1000 times)	220kN
	16-M	Moving loads 160kN (1000 times)	220kN
22 Series	22-S	Static 230kN	160kN
	22-F	Pulsating load 160kN (100,000 times)	160kN
	22-M	-	160kN

3. FATIGUE LIFE AND DEFLECTION

3.1. Material properties of concrete

Shrinkage strain in concrete was measured by using a contact gauge. **Figure 2** shows the measurement. The measured shrinkage strains can be largely classified into two categories: the shrinkage strains around 1200 μ and approximately 600 μ. This is thought to be due to differences in the moisture absorption and the self-shrinkage characteristics of aggregate. The strain values of plain concrete specimen are converted equivalently to the slab-based shrinkage by taking the volume-to-surface area ratio into account, that is to say, about 800 μ and 400 μ. The compressive strength of concrete, which were measured before and after the test, ranged from 24 to 32 N/mm^2 for all specimens.

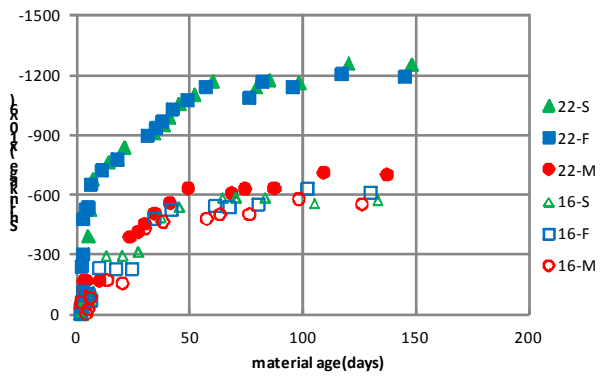

Figure 2: Drying shrinkage strain

3.2. Fatigue damage under higher level of loads

Figure 3 shows the relation of the deflection and the number of load cycles in the case of 220 kN moving load. A solid line represents the total deflection, and a broken one the residual deflection

under no external load. The mid-span deflections of specimens for 22-F, 22-M and 22-S cases increase sharply after 622, 1173 and 1427 cycles, respectively. In this study, the term "fatigue life" is here defined as the number of cycles corresponding to the sharp increase in slab deflection. The inflection points of deflection where a rapid progress starts are similar despite of different loading histories, and the rates of deformation in each cycle seems similar for all specimens as well.

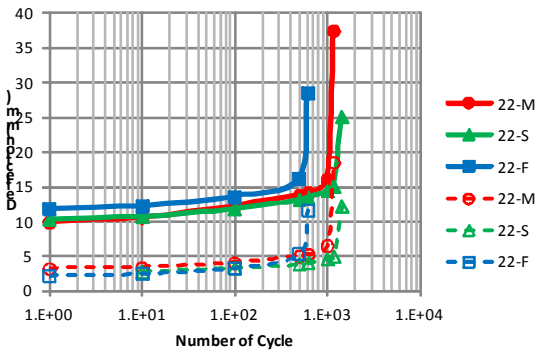

Figure 3: Total deflection and residual deflection during moving load test (220 kN)

3.3. Fatigue damage under middle level of service loads

Figure 4 shows the relations of the mid-span deflection and the number of cycles for the 160 kN moving load. Total deflection is shown with solid lines, and residual deflection with broken ones. In the RC slab damage process, microcracks occur and gradually grow and, at the final stage, large cracks occur and slab displacement increases sharply. Mid-span deflection is thought to be a possible indicator for the degree of slab damage under the influence of overall progress of slab cracking. It is practically hard to exactly interpret the loading histories of slabs. It is thought that if the current damage level can be roughly estimated from the mid-span deflection, future damage including the remaining fatigue life of slabs can be estimated. Therefore, by linearly interpolating the measurements for 16-M (the reference specimen), the peak deflection on the initial loading cycle is associated with the number of loading cycles. Those corresponding to the initial deflection obtained were 1231 for 16-F and 112 for 16-S. **Figure 5** shows the relationship between the shifted deflection and the number of cycles.

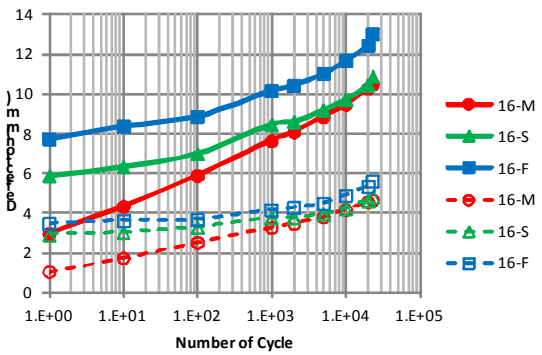

Figure 4: Total deflection and residual deflection during moving load test (160 kN)

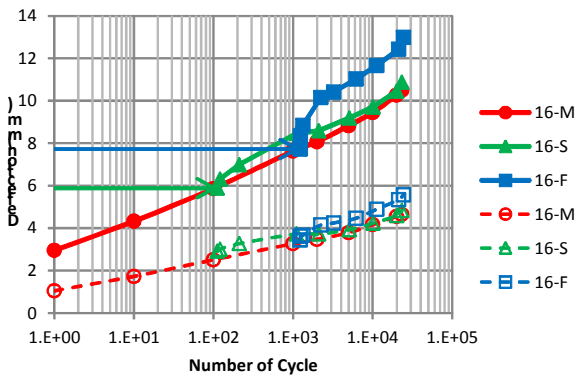

Figure 5: Total deflection and shifted residual deflection (160 kN)

In this study, three 16-Series specimens mentioned previously were not loaded to complete failure. It was decided to roughly judge their fatigue life from the rate of increasing deflection in rapid progress. Since these three specimens show similar trend of deflection, it is judged that failure almost occurs at similar points in time in consideration of reproductability of fatigue structural experiments. Then, the test was terminated upon completion of the 23,000th cycle.

4. NUMERICAL ANALYSIS

4.1. Overview

In this study, the slabs under various loading histories were simulated by numerical analysis in use of the elasto-plastic and failure constitutive model proposed by Maekawa *et al.* and COM3D, a smeared crack-based nonlinear finite element analysis model.

In the analysis, a high-frequency path-dependent constitutive model capable of simulating reinforced concrete fatigue damage due to cyclic loading was used. Consisting of three constitutive laws expressing the tension and compression of reinforced concrete and shear transfer along cracks, the model expresses space-averaged behaviors of RC elements with multi-directional cracking. It is said that fatigue damage caused by cyclic loads can be explained by increases in time-dependent plastic deformation and decreases in stiffness defied as “fracturing”.

It has been confirmed experimentally that the time–deformation history of a structure determined by direct path integral scheme using the abovementioned constitutive laws reproduces the fatigue damage process of the structure under highly repeated loads with a reasonable accuracy.

4.2. Numerical analysis model

Figure 6 shows the model used for the analysis. The finite elements used are solid iso-parametric elements. To allow for the effect of changes in boundary conditions due to the change of the testing machine, the slab was modeled with solid elements, and the main girders and cross beams with plate elements. The same compressive and tensile strength of concrete were assumed for the whole domain of analysis. **Table 2** summarizes the conditions used in the analysis.

Loads were assumed to act directly at nodes, and a total of 16 nodes (450 mm in the bridge axis direction, 300 mm in the transverse direction) were considered. The loading rate was 1 Hz in the fixed point fatigue test. It is equivalent to 4 km/hr for the moving load test.

The amount of drying shrinkage was determined by converting the amount of shrinkage measured by using the reference specimen to the shrinkage of the slab by taking the volume-to-surface area ratio into account. For 22-S and 22-F, 800 μ was assumed, and for 22-M and 16 Series specimens, 400 μ was assumed. The shrinkage period, which varies from specimen to specimen, was assumed to be 30 days until the first day of preliminary loading.

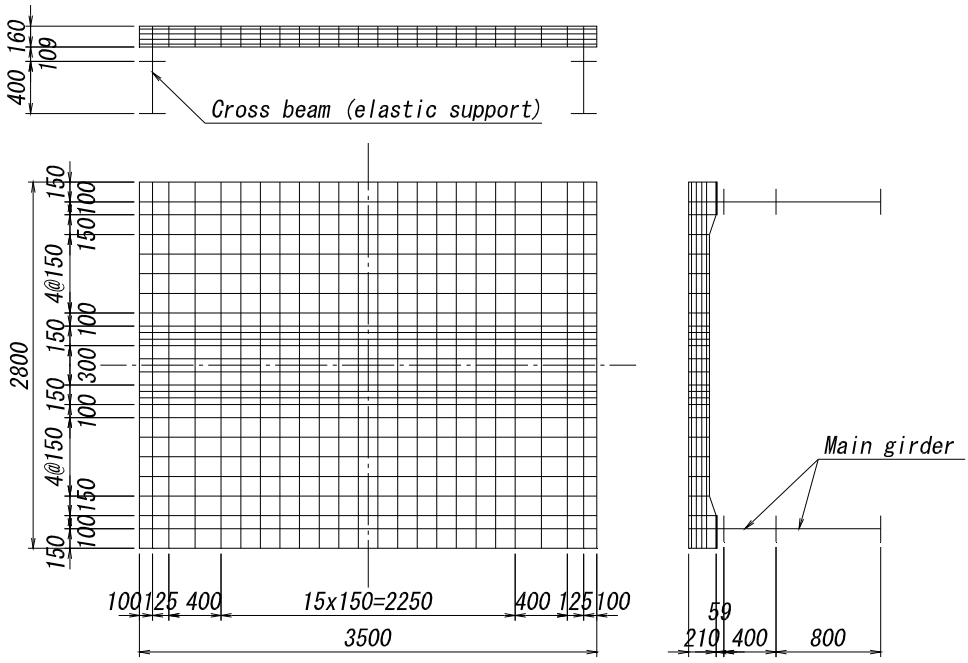

Figure 6: Analysis model

Table 2: Material properties used in the analysis

Material	Modulus of elasticity(N/mm^2)	Characteristic value
Concrete	2.1*10^6	Compressive strength: 25.5N/mm^2 Tensile strength: 1.8N/mm^2
Reinforcement	2.1*10^5	Yield point: 355N/mm^2
Steel plate	2.1*10^5	Yield point: 245N/mm^2

4.3. Analytical results

The targeted deflection of the analysis was obtained by first applying a coupling of mechanical loads and ambient conditions. After suspending the pulsating loads, static loads were applied at the center of the slab to examine the remaining residual capacity.

Figure 7 shows a comparison of the results of 22 Series and 16 Series specimens, respectively. If the criterion value for punching shear failure is assumed to be 25 mm (L/100) in the analysis, the fatigue lives of 22-F and 22-S show relatively good agreement. In contrast, the fatigue lives of

22-M and the 16 Series specimens are somewhat overestimated. This is thought to be due to the differences in boundary conditions, and further study will be made on it.

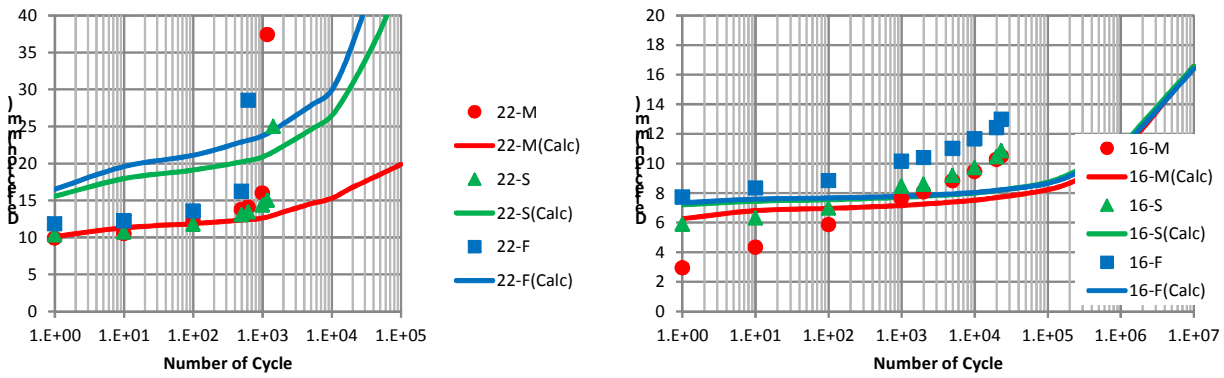

Figure 7: Number of loading cycles and deflection

As with the test results, let us consider shifting the results by using the calculated initial deflection values in order to estimate future fatigue life from the current damage level of slabs without relying on loading histories. **Figure** 8 shows the results obtained. As shown, in the 22 Series results, the results for 22-F and 22-S are completely different, while the 16 Series results show good agreement. This is consistent with the result reported by Fujiyama *et al*. concerning slab strains to the effect that the remaining fatigue life of slabs with minor damage can be estimated, but if slabs are severely damaged, the damage level cannot be expressed with good accuracy because of the differences in estimated stiffness. The analytical results indicate, however, that at least as long as the loads concerned are more or less standard and the damage level is not extremely high, service life can be predicted, independent of the loading history, if the current damage level can be estimated from the initial deflection.

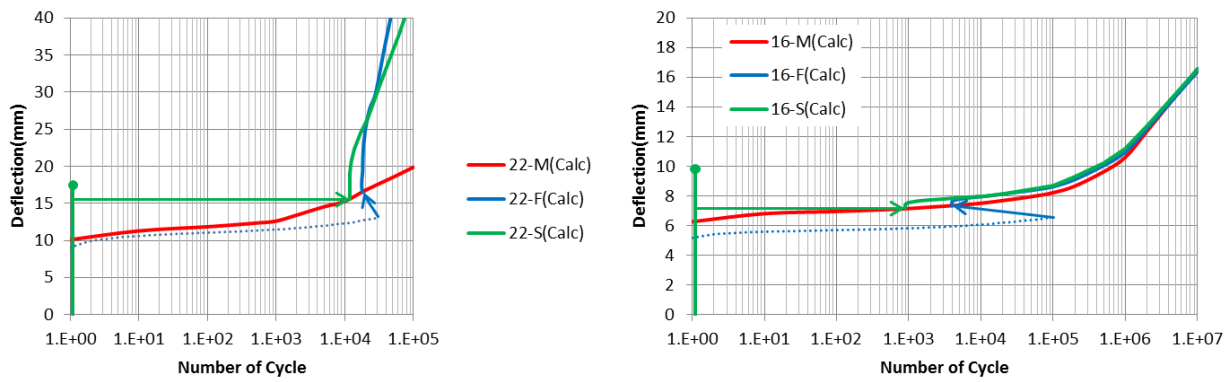

Figure 8: Shifted total deflection

5. CONCLUSION

By conducting moving load tests on reinforced concrete slabs with different loading histories, this study has shown that it is possible to estimate the remaining fatigue life of reinforced concrete slabs

if the current damage level is estimated from mid-span deflection. Numerical simulation has also shown that just as the test results indicate, the fatigue life can be estimated from the initial deflection if the load level is low even if loading histories vary.

As the next step, we intend to identify boundary conditions for fatigue testing and continue the study on application to numerical analysis.

6. ACKNOWLEDGMENTS

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