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Experimental Study on Fatigue Strength of Continuously Reinforced Concrete Pavements with Initial Transverse Cracks

Jong-Sup Park[1*]

초기균열간격에 따른 연속철근콘크리트 포장의 피로강도에 대한 실험적 연구

박종섭[1*]

Abstract A laboratory investigation is conducted to characterize and quantify fatigue life of continuously reinforced concrete pavement with initial cracks. Four specimens scaled were made based on results of finite-element analyses and stress-strain curve comparisons. Static tests were firstly performed to obtain magnitudes of static failure loads and to predict crack patterns before fatigue tests. The fatigue lives measured in the study were compared based on the initial crack spacing. The comparison indicates that the fatigue lives of most specimens increases with increasing the initial crack spacing. The results obtained in the study can be used for maintenance and retrofit of the continuously reinforced concrete pavements.

Key Words : Concrete Pavement, Continuously reinforced concrete pavement, Fatigue, Crack

요 약 공용하중으로 인하여 초기 균열을 가지고 있는 연속철근콘크리트 포장체를 제작하여 피로시험을 실시하였다. 초기 균열의 영향을 검토하고자 4개의 시험체가 제작되었으며 시험체의 길이 및 축소비율을 유한요소해석 및 재료특성을 고려하여 결정하였다. 피로시험에 앞서서 정적시험을 실시하여 정적파괴하중을 확인하고 균열발생 진행상황을 조사하였다. 피로시험 결과로부터 초기발생균열의 간격이 증가할수록 피로수명이 증가하는 것을 확인할 수 있었다. 본 연구의 결과는 국내고속도로에 건설된 연속철근콘크리트 포장의 유지보수에 적극 활용될 수 있을 것이다.

1. Introduction

Continuously reinforced concrete pavement (CRCP) is used extensively on major Korea highway systems over the last decades of the twentieth century because the CRCP provides a durable pavement requiring little maintenance. The CRCP relies on heavy reinforcement, without gaps for joints, to distribute uniformly a large number of fine cracks, which the reinforcement holds closed. To ensure good performance and maintenance of the CRCP, study on the fatigue strength of the pavement need to be investigated.

There have been some of previous investigations for the fatigue strength of concrete pavements (Vesic and Saxena [1], Taute et. al.[2], Majidzadeh and Ilves [3], Suh et. al.[4], and Kang et. al.[5]). Kang et. al. investigated the fatigue strength of CRCP based on laboratory tests of scaled specimens. The research presented that fatigue lives of most specimens were very close to the results from the equation of Vesic and Saxena [1], which is well known for estimating conservative fatigue lives of concrete pavements. The main purpose of this paper is to study fatigue strength of typical CRCP specimens with transverse cracks in the laboratory.

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[1]Department of Civil and Environmental Engineering, Sangmyung University
[*]Corresponding Author: Park, Jong Sup(jonpark@smu.ac.kr)

2. Experiment design and setup

The total length of the CRCP used in Korea highway systems in 1984 is 196 km (Jung et. al. [6]). The experimental models used in this study were developed using a typical CRCP of Jung-Bu highway. The CRCP consists of three layers: concrete slab of 30 cm, cement-treated subbase of 15 cm, and subgrade of 30 cm. Two traffic lanes were constructed in Jung-Bu highway and the width of a traffic lane is 40.25 cm.

2.1 Law of similarity

Ultimate strength model (USM) was used to conduct scaled lab tests with respect to elastic and plastic behavior of CRCP specimens subjected to cyclic loading condition. Table 1 shows similarity ratios of material properties, geometric properties, and loading condition according to the USM method. The stress and strain similarity ratios of the material properties were determined by 1.0. The length ratio of the geometric properties was determined by a quarter (¼) from results of finite-element analyses and considerations of laboratory conditions [5]. Table 2 shows CRCP specimen properties used in the experimental tests. Two-point loading was used to simulate an equivalent axial load of a vehicle. The coefficient of 706 MPa was applied to consider the soil reaction below the concrete slabs.

2.2 Finite element analysis

Finite-element analysis (FEA) was conducted to determine the specimen length based on the results of stresses and deflections of finite-element models.

Table 1. Similarity ratio

Properties		Dimension	Ratio	Scaled model
Material properties	Stress	FL^{-2}	S_E	1
	Modulus of elasticity	FL^{-2}	S_E	1
	Poisson's ratio	-	-	1
	Specific gravity	FL^{-3}	S_E/S_L	4
	Strain	-	-	1
Geometric properties	Length	L	S_L	1/4
	Rotation	-	-	1
	Area	L^2	S_L^2	1/16
	Moment of inertia	L^4	S_L^4	1/256
Load	Concentrated load	F	$S_E S_L^2$	1/16
	Line load	FL^{-1}	$S_E S_L$	1/4
	Pressure	FL^{-2}	S_E	1
	Moment	FL	$S_E S_L^3$	1/64
	Shear force	F	$S_E S_L^2$	1/16

F = force, L = length, S_E = stress ratio, S_L = length ratio

Table 2. Dimensions of Jung-Bu highway and scaled model

Classification			Jung-Bu Highway	1/4 Scaled Model
Concrete Slab	Thickness (mm)		300	75
	Width (mm)		4,025	1,000
	Modulus of elasticity(GPa)		27.6	27.6
	Maximum size of Coarse aggregate (mm)		40	10
Reinforcement	Longitudinal	Diameter(mm)	19	4.5
		Spacing(mm)	50	37.5
	Transverse	Diameter(mm)	13	3
		Spacing(mm)	750	188
	Elastic modulus(GPa)		200	200
Soil reaction coefficient(MPa)			177	706

Commercial FEA program, ALGOR [7], was used for this study. Fig.1 shows a typical finite-element model and an applied loading condition. The concrete slab was modeled as 8-node hexahedral solid elements and the soil was modeled as Winkler spring elements. The spring constant used to spring elements was obtained from soil reaction coefficient. Longitudinal and transverse reinforcements were modeled as orthotropic 4-node shell elements.

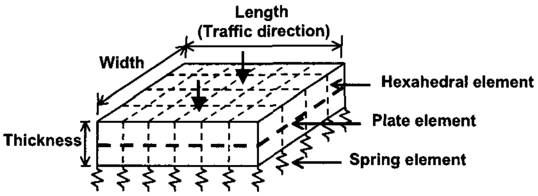


Fig 2. Finite element model

Three typical finite-element models were considered: M1 model with longitudinally infinite length and one traffic lane, M2 model with longitudinally certain length and one traffic lane, and M3 model with longitudinally certain length and two traffic lanes. The ends of the models were fixed to prevent movements of all directions. From the FEA results of the M1 model, the longitudinal length of M2 model was determined with 140 cm because the vertical deflection of M1 was zero at 70 cm from the applied loading point. From the surface stress distributions for each model, it was found that the stress distribution of M1 model was very similar to that of M2 model, and that a traffic lane without directly applied loading at the M3 model was slightly affected, so the magnitudes of the stresses on the lane were very small.

The longitudinal stresses of M2 model are a few larger than those of M1 model. In specialty, the maximum differences of the longitudinal stresses between M1 and M2 are 1% within the distance of 30 cm from the loading point, and 10% between the distance of 20 cm and 50 cm from the loading point. The transverse stresses of M2 model were also a few larger than those of M3 model. The maximum difference of the deflection between M2 and M3 is 2%. FEA results of M2 model is in good agreement with the FEA results of M1 and M3 models. Therefore, the M2 model is used to conduct scaled CRCP fatigue tests.

2.3 Concrete mix design

Three preliminary concrete mix tests and four concrete strength tests were performed to establish the concrete strength and workability of the specimens. Table 3 shows mixing design results and an example of mixing components to make an experimental specimen with the total volume of 1000 liters. The flexural tensile strength of the specimen obtained from flexural tensile strength test was 3.1 MPa. The modulus of elasticity of the concrete specimen obtained from compressive strength test was 24 GPa.

2.4 Pavement base and concrete slab

In order to simulate the cement-treated subbase and the subgrade below the concrete slab, rubber plates were used below the CRCP specimens. Based on modulus of elasticity of the cement-treated subbase, modulus of dynamic elasticity of the subgrade, and similarity ratio of ¼, the reaction coefficient of 706 MN/m^3 was applied to make rubber plates. Several thin metal plates with square rubbers were tested with Universal Test Machine (UTM) to develop the rubber plates having appropriate modulus of elasticity and base reaction coefficient.

Concrete mixing car was used to mix water, cement, and aggregates to make scaled concrete pavement. After the specimens were made in the field, they were covered

Table 3. Mixing components for concrete specimen (Total volume = 1000 liters)

Water (kg)	Cement (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	AE (cc)	Plasticizer (cc)	Flexural tensile design strength (MPa, σ_r)	Flexural tensile strength (MPa, σ_{28})	Modulus of elasticity (GPa)
167	457	333	1281	130	333	5.4	3.1	24

with wet cotton wrap to keep the humidity. Four concrete pavement specimens with adequate reinforce wires and transverse cracks were made: A specimen without initial crack, B specimen with initial crack spacing of 250mm, C specimen with initial crack spacing of 375mm, and D specimen with initial crack spacing of 500mm. Fig. 3 shows the dimensions and components of a typical CRCP specimen made in the study.

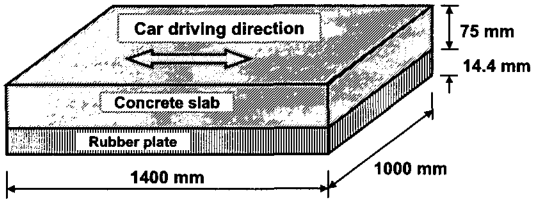


Fig 3. Specimen size

2.5 Instrumentation and loading condition

Instrumentation on the surface of the specimens with strain gages was the first step of the testing process. Gage location relative to the crack path was an important consideration in measuring the stress ranges and crack distribution for use in predicting the fatigue livesof the CRCP specimens. Fig. 4 shows the typical strain gage locations on the surface of the specimens. Lead wires connected the gages to a data acquisition system placed on a side table of a loading frame. Fig. 5 shows the loading frame that consists of dynamic actuator, concrete slab, rubber plate, and basement of laboratory. As shown in Fig. 6, two point edge loadings were subjected to the specimens to simulate the equivalent vehicle loading.

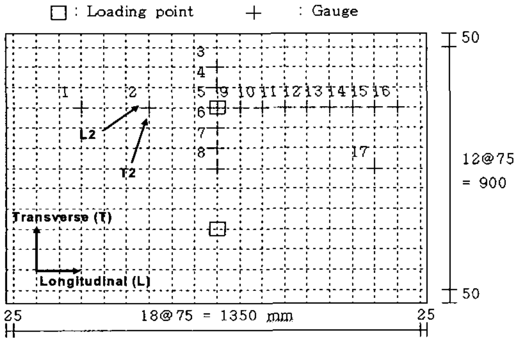


Fig 4. Typical strain gauge locations

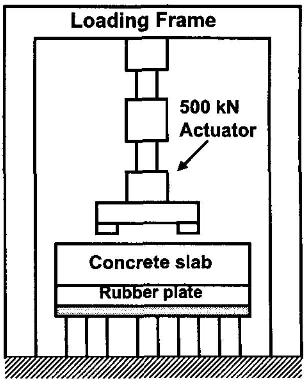
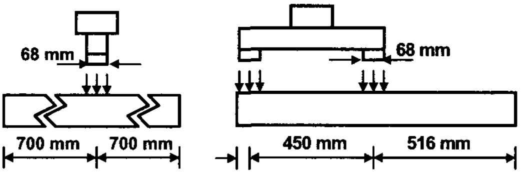


Fig 5. Loading setup



(a) Side view (b) Front view

Fig 6. Loading positions on the specimens

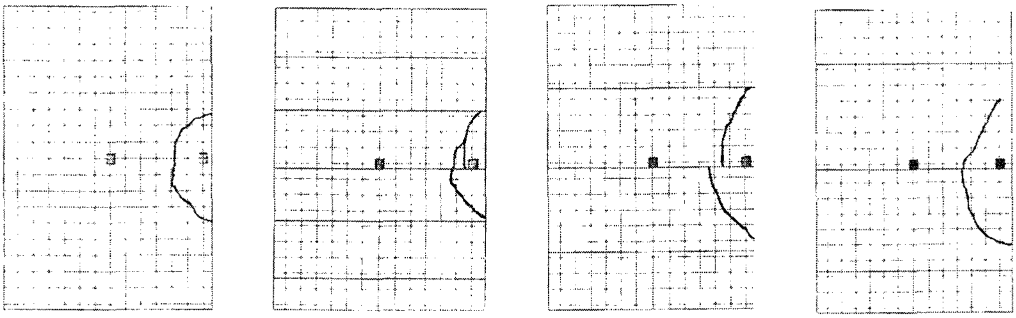
3. Fatigue test

The magnitude of applied fatigue load for each specimen was decided based on the static failure load determined from the previous static failure test. The cyclic load of 4.8 tonf, 80% of static failure load, was applied on the specimens with frequency of 5 Hz (cycles/second), and several strain gages were attached on the surface of the specimens. A DAA-10A dynamic measure machine measured and recorded the strain data per 100,000 cycles. Cracking and crack spacing were investigated using the Demec gage per 500,000 or 1,000,000 cyclic loading. The fatigue tests were finished when a punchout failure occurred or when the crack width or spacing measured were larger values than allowable crack width of 1 mm defined in the American Association of State Highway and Transportations Officials (AASHTO) *Guide for design of pavement structures* [8].

The numbers and durations of the cyclic load applications for each CRCP specimen are presented in table 4. Table 4 also shows the fatigue life and the crack

Table 4. Applied cyclic loading and fatigue life

Specimen	Loaded cycle (Number)	Duration (hour)	Fatigue life (Number)	Crack width (mm)	Life Comparison
A	2,900,000	174	2,100,000	0.27	100%
B	1,100,000	68	1,080,000	0.21	51%
C	1,300,000	78	1,250,000	0.29	60%
D	1,900,000	125	1,650,000	0.26	79%



(a) ASpecimen (b) B Specimen (c) C Specimen (d) D Specimen

Fig 7. Crack propagation during fatigue tests

width of each specimen. The crack propagations on the surface of the specimens are shown in Fig. 7.

For the A specimen, strain data indicate that a transverse crack through loading points occurred at 2.1×10^6 cyclic loads. The visible crack through loading points shown in Fig. 7(a) was also observed at 2.1×10^6 cyclic load on the surface. The magnitude of the measured crack width was 0.27 mm. The value of 0.27 mm was consistent with 1.08 mm at the CRCP prototype. Though the cyclic loading number was applied until 2.9×10^6, a new crack did not occur. The fatigue life of the 9th Specimen was estimated at 2.1×10^6 cyclic load based on the measured crack width.

The B specimen shown in Fig. 7(b) has initial crack spacing of 250mm and the strain data were firstly changed between 1.0×10^6 and1.1×10^6 cyclic loads. A visible transverse crack was observed at 1.1×10^6 cyclic loads. From the strain data of the Data Analyzer, the crack was detected between 1.07×10^6 and1.08×10^6 cyclic load. The number of fatigue life for the B specimen was estimated at 1.08×10^6.

For the C specimen, the strain data was firstly changed at 1.1×10^6 cyclic loads. However, a visible crack was not observed. The repeated load was applied until 1.3×10^6 cyclic load and a crack with width of 0.29mm occurred on the surface of the C specimen as shown Fig.7(c). According to the strain data of the Data Analyzer, the crack was detected between 1.24×10^6 and1.25×10^6 cyclic load. Therefore, the C specimen with initial crack spacing of 375mm has the fatigue life of 1.25×10^6 cyclic load.

Sudden changes of strains for D specimen with initial crack spacing of 500mm were occurred at between 1.6×10^6 and1.9×10^6 cyclic load. A punch-outfailure crack at the edge near the one loading point was found at the same loading cycles. The magnitude of the measured crack width at the scaled D specimen was 0.31 mm. The number of fatigue life for the D specimen was determined with 1.65×10^5 cyclic load.

4. Summary and concluding remarks

Laboratory tests of scaled specimens were made to investigate fatigue lives of continuously reinforced concrete pavements with initial cracks. Static tests were performed to obtain magnitudes of static failure loads and to predict crack patterns before fatigue tests. Some of the important findings of the fatigue test are as follows:

1. Stresses at each point of strain gages increase with increasing applied load. This trend appears linear until a transverse crack firstly occurs. From the static failure tests, the failure loads used to determine fatigue loading ranges were 128 kN for the specimens.
2. The fatigue lives measured in the study were compared based on the initial crack spacing. The comparison indicated that the fatigue lives of most specimens increased with increasing the initial crack spacing. The fatigue lives of B, C, and D specimens with initial crack spacing of 250mm, 375mm, and 500mm, respectively, were 51%, 60%, and 79% of the fatigue life of A specimen without initial crack.
3. The fatigue life of prototype CRCP with crack spacing of 1 2.5m that was presented for the allowable crack spacing in the AASHTO Guide [8] was estimated as 50% 90% of the prototype CRCP without the crack. Therefore, the criteria suggested by AASHTO Guide can be used for maintenance and retrofit of the CRCP in Korea.

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Jong-Sup Park [Regular Member]

- 1994. 2. Korea University (BS)
- 1996. 8. Korea University (MS)
- 2002. 12. Auburn University (PhD)
- 2005. 9. ~ Present : Sangmyung University, Dept. of Civil & Environ. Eng., Assistant Professor.

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