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Long Term Behavior of a Composite Prestressed Concrete Railway Bridge: Part I—Experiment

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Synopsis: In modern computerized structural analysis, realistic material laws should be used. This research will present a constitutive law and a numerical procedure based on the finite element method for the analysis of a prestressed concrete structure including the time-dependent effects due to the load history, creep, shrinkage, aging of concrete, and relaxation of prestress. A 32.1 meter (105 ft) long U-shape railway bridge, composed of two precast post-tensioned concrete girders and a in situ cast prestressed young concrete slab, was instrumented to observe its long-term structural behavior and used for the comparisons with numerical analysis. In order to evaluate and predict the structural behavior of this concrete structure, the related experiments were designed and performed both in the field and laboratory. Some material properties needed for the analysis were obtained through the extensive program carried out in the laboratory with controlled environments. This paper will describe the details of structure, test program and experimental results. Derivations of constitutive laws and verifications by test results with numerical analysis will be shown in the Part II which follows.

Keywords: Creep properties; humidity; prestressed concrete; railroad bridges; shrinkage; strains; structural analysis.

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INTRODUCTION

In a long-term analysis of concrete structure, it is necessary to take into account the time-dependent deformations and cracking [1,2,3]. As prestressed concrete structure exposed to the drying environment, shrinkage due to the gradual loss of moisture and creep due the sustained load can cause significant influence on its structural performance. As is well known, creep and shrinkage produce or relax stresses which cause cracking, and cracking in turn changes the stress state which causes creep.

The Da-Chia railway bridge is a simply supported prestressed concrete bridge located in Taichung county of central Taiwan. This bridge was built in 1987 with a total length of 1252 meters (4107.6 ft) and in 39 spans. As shown in Fig. 1, the cross section of bridge is composed of two precast post-tensioned prestressed girders and an in situ cast prestressed concrete slab. This type of bridge is widely adopted in Taiwan to replace some existing old steel bridges. The great advantages of using this type of bridge are manyfold, such as the increase of bottom clearance of bridge providing more outlet for the flood, noise reduction due to the shielding effect of both girders, higher stiffness, lower maintenance and construction cost etc. Due to the new adoption of this composite prestressed design concept [4], the great concerns raised regarding its load resistance of composite design section and long-term behaviors including the stress redistribution between composite members and the prestress loss due to creep and shrinkage effects. A field load test was performed to validate the load carrying capacity and check the composite effect basing on the comparison of the designed position of neutral axis with that obtained by field load test [5]. This research aims only to report the portion of research which investigates the long-term behavior of this structure. In order to evaluate and predict the time-dependent structural behavior of this concrete, the assessments including two parts which are (i) the development of constitutive laws and numerical analysis to compare with test data, and (ii) the designed tests to obtain basic material data and field tests with some instrumentations on bridge. The result of first part will be presented in the second part of this paper [6]; this paper provides the results of experiments planned to obtain the basic informations to assist the analysis. A flow chart which describe how the problem was approached is given in Fig. 2.

The experiments were designed to be performed both in the field and in the laboratory. The instrumentation in the field includes demoutable Demec gauges for surface strain in various locations of bridge, and accompanied reinforced or plain concrete blocks designed for the the measurements of shrinkage strain of bridge concrete. The extensive materials program performed in the laboratory was carried out with controlled environment. The specimens were cast simultaneously on site with the bridge and delivered to the laboratory for the material tests. The program includes shrinkage test, measurement of humidity versus time history in concrete blocks, tests for compressive strength and elastic modulus, and creep tests performed at fog or drying conditions and controlled temperature. The details about the bridge and the results of test program will be presented in the followings.

RESEARCH SIGNIFICANCE

This research proposed a method to predict the time-dependent behavior of prestressed concrete structure; the prediction was verified with the measured field data. The satisfactory results achieved in this study indicated that the proposed method can help to predict the long-term structural response with the well planned material tests, a constitutive law which can reflect the realistic behavior, and a numerical procedure based on the formulation of finite element method.

DESCRIPTION AND CONSTRUCTION OF TA-CHIA BRIDGE

Description of the Test Structure

The test span of Da-Chia railway bridge is 31.3 meter long and was made by two precast girders and an in situ cast slab. The girders and slab were composited together by tranverse prestress force applied at proper intervals along the bridge. Fig. 1 shows the central cross-section and location of prestressed tendons of bridge. Some reinforcements were added to the slab and girders as shown in Fig. 3. The dimensions of both ends of girders and slab were slightly thickened to increase the shear force resistance capacity. The cross-section shown in Fig. 1 is a typical section for the structure. The design criterion for live load was done according to Japan KS-18 for railway loading. Fig. 4 shows the elevation of a girder with the locations of prestressed strands and the location of strands for slab as well. Some non-prestressing steel and prestressing bars were used as temperature reinforcement and to increase shear resistance capacity of girder respectively.

Construction of the Bridge

A chronology of the construction of bridge is indicated in the abscissa in Fig. 11. The beginning time of the origin in this figure starts since the casting of girder A. Two girders were manufactured at the site. The girders were cast in steel mold and were demolded after twelue days of moist curing. First phase of prestressing forces including five strands (C1 - C5), shown in Fig.4 , were tensioned immediately after demolding. The prestressing force were applied from both ends of girders. Hydraulic ram and pressure gauge, which were previously calibrated by the materials testing laboratory of National Taiwan University, were used to control the pretensioning at both ends of girder. Friction test of tendons was also performed in the same time. After approximately two months since the casting of girders, the girder was lifted to be placed between two piers. The slab was then cast soon after the arrangements of formwork, reinforcement, and strands which go through the ducts. The formwork was all wood and was supported entirely from the girders by means of steel frames; steel rods tied to steel frames was arranged to go through the drainage holes of slab at proper intervals. One thirds of tranverse prestressing force to tie up the girders and slab were applied prior to the application of second phase prestressing forces, which include two strands (D1, D2) of each girder and longitudinal strands (D3 - D6) as shown in the cross-section view in Fig. 1. Two thirds of transverse prestressing forces were applied finally. The transverse prestressing tendons used to tie up the components was spaced at 300 *mm* (12 *in*) intervals along the girder. After the application of prestressing forces at each stage, the prestressing ducts was grouted with nonshrink mortar.

Materials Used in Bridge

Concrete

The concrete used to cast the bridge were made with the mix shown in Table 1. ASTM Type I portland cement and crushed gravel from Ta-Chia river were used for the mix. Sieve analyses for coarse and fine aggregate are listed in Table 2. The average modulus of elasticity and compressive strength are listed in Table 3. Samples of concrete specimens used in strength, and also for creep and shrinkage tests were taken during the casting of concrete.

Reinforcement

The prestressing reinforcement is 7 *mm* diameter 12-wire high tension strand. For prestressing tendons C1 - C5 are 11 strands wired together in the same duct (denoted as 11T12-7 $mm\ \phi$); while tendons D1 - D6 are 12 strands in each duct (12T12-7 $mm\ \phi$). Transverse prestressed tendons are four strands in the duct (4T12-7 $mm\ \phi$). The specified minimum breaking strength of strand is $270 ksi$ ($19,000\ kg/cm^2$); the average value of breaking stress and yield stress from test samples are 273.9 *ksi* and 248.7 *ksi* respectively. Young's modulus is 28.4×10^6 *psi* .

Tests of non-prestressing reinforcement show that #5 bar (5/8 *in*) has an average yield strength 45 *ksi* and ultimate tensile strength 65 *ksi* using three samples; #4 bar (1/2 *in*) shows higher test values which are 58.3 *ksi* and 86.7 *ksi* respectively.

TEST PROGRAM

The test program was composed of two parts including tests done in the field and in the laboratory. The details of the planned test are described herein.

Shrinkage Test

The shrinkage tests conducted at drying room which was automatically controlled to maintain constant temperature ($23 \pm 0.5°C$) and constant humidity ($50 \pm 2\%RH$). Specimens with $4 \times 4 \times 14$ *in* and $3 \times 3 \times 12$ *in* prisms were used for the tests. The other test variable is the age when concrete specimens were exposed to drying environment. Each test set included four specimens, two were specimens for drying test and two other specimens remained in fog room and acted as control specimens. The test was carried out according to ASTM C341-84; ELE Demec strain gauge was used to measure the strain of specimens at proper time intervals. The gauge length of each pair of mechanical gauges is 8 *in* (200 *mm*). The effective drying shrinkage for all specimens was counted as the difference between the amount of shrinkage measured in dry room and that of respective companion specimen.

Creep Test

Creep tests were performed at moist or drying condition at the laboratory. All specimens were 6×12 *in* cylinders and were unsealed. Basic creep test was conducted in the moist room (fog room) at controlled 23 $°C$ temperature; the other test series was performed in the drying room at 50% relative humidity and 23 $°C$ temperature. Specimens were placed in the curing room until the age when the load was applied. The loading age of concrete has great effect on the development of creep of concrete [7,8]. The loading ages of concrete specimens were designed to be 7, 29 and 94 days. Test series performed at fog room, called as basic creep, was used to find the basic informations regarding the viscoelastic aging behavior of bridge concrete.

During the test, the creep test specimens were mounted on the creep loading frames which were composed of a 44.8 k jack, a load cell and a system of coil springs held in compression by a system of rods and plates between which the specimen was clamped. The desired load, which is roughly calculated as one fifth of the strength measured from companion strength cylinders, was applied by a hydraulic jack [Table 4]. After loading in the frame, the nuts on the tension rods of the load-sustaining apparatus were brought up against the end plates. The actual sustained load, which is listed in Table 4, was monitored by the PC control data acquisition system with the signals passing from load cell. The details of testing procedures of using these creep apparatus is given in Ref. 9. There were control specimens stored with no load in the moist room as dummy specimens and strength cylinders used to provide the information such as modulus of elasticity and compressive strength.

Internal Humidity of Concrete

Six concrete blocks were cast to investigate the behaviors of concrete including the intenal humidity, temperature history due to hydration, shrinkage, and the effect of reinforcement to restrain shrinakge. This paper only presents the result of humidity measurement , other test results were described in Ref. 10.

These concrete blocks, with dimension 16 × 16 × 14 *in*, were cast in field using bridge concrete. Specimens were sealed from five sides with insulating polystyrene foam to prevent the heat exchange and plastic sheets to avoid the moisture exchange with the ambient. The purpose for allowing only one exposure surface was aimed to simulate the real exposure condition of bridge slab, which has only one exposure surface after the completion of the waterproofing work on the top of bridge slab. Two specimens were drilled to different depth to allow the installation of sleeves for the measurement of humidity in concrete [Fig. 5]. The newly developed sleeves can hold tightly to the concrete surface and guarantee the correct measurement at specific depth of concrete using the double seals design [Fig. 5]. The specific depths for the humidity measurement are 2.3, 4.5, 9.5, 13, and 20 cm from the exposure surface of concrete block. During the time of measurement, one simply pulls the peg out of the hole and insert the Vaisala HMP 32 UT measuring probe. The accuracy of measurement for humidity is ± 2 % RH at 20 °*C*.

Surface Strain of Field Bridge

Several mechanical gauge points similar to that used in Ref. 11 were installed on the bridge girders and slab soon after the demolding of form work. Gauge point lines were embedded at locations near the ends, quarter and center span of bridge. For each gauge point line, gauge points were located at top, head, web, and bottom of the girder cross-section [Fig. 11]. The strains were measured by Demec strain gauge.

EXPERIMENTAL RESULTS AND DISCUSSIONS

The test results of all series conducted in this study are given and discussed as follows.

Shrinkage test

The results of shrinkage test are given as the average of two shrinkage specimens dried together. For each shrinkage specimen, the shrinakge strain was obtained by the averaging of measured strains on two opposite surfaces. Fig. 6 shows the test results for shrinkage specimens with two sizes; the faster drying which occurs in the smaller specimens results in higher shrinkage strain. Fig. 7 gives the shrinkage strain for specimens starti tests at various ages; it shows that specimens with a earlier exposure time yields a higher shrinkage strain. This fact can be explained through the following two reasons: firstly, the aging effect on the coefficient of diffusion resulted in slower moisture diffusion and less shrinkage in the well cured old concrete as explained in Ref. 13; secondly, the increase of stiffness due to the aging effect resists the shrinkage of concrete more effectively.

Creep Test

The main variables in the creep series were the loading age and the testing environments. The results are given as the average of two creep specimens sujected to the same sustained load. For each creep cylinder, the creep strain was the averaging strain of three mechanical gauge point sets located on the surface of specimen. Creep strain obtained in this test was counted as the difference between measured strain of creep specimen and its companion specimen. Fig. 8, giving the results of tests, shows the effect of age of concrete at time of loading on creep deformations. Three ages at loading were chosen, namely, 7 days, 29 days and 94 days. It can be seen that creep is greater for specimens loaded at younger age. This phenomenon is valid for the creep test performed either at drying room or at fog room. After eight months of loading at moist condition; the creep for the cylinders loaded at age 7 days was about 2.5 times higher than for the cylinders loaded at age 94 days. If we consider the same case except that the specimens were loaded at drying room, the creep ratio is approximate 1.7 [Fig. 8].

For the concretes loaded at the age of 7 days and 29 days, the combination of creep and shrinkage is five times the instantaneous deformations; for specimens loaded at 94 days this value is 4.3 [Fig. 8]. $J(t,t')$, the ordinate of Fig. 8, is called as creep function , which represents the strain at time t caused by a unit sustained stress acting since time t'.

Fig. 9 gives the results of drying creep strain per unit stress versus various ages of loading. It can be seen that the drying creep for concrete loaded at younger age is much higher than that for the specimens loaded at older ages. After eight months of loading at dry environment, the drying creep for the cylinders loaded at age 7 days was about 2.5 times higher than that for the cylinders loaded at age 94 days. Drying creep, a well known phenomenon called as Pickett effect [12], was recently explained by a mechanism developed by Bažant and Chern [9]. From the microstructural viewpoint, their model rests on one simple hypothesis, namely, that there exists some mechanism causing the viscosity coefficients which characterize the creep rate to depend on the magnitude of the flux of the local microdiffusion of the water between the macropores (capillary pores) and the adjacient micropores in the cement gel (gel pores etc.). The fast moisture change results in the bond rupture of the gel structure and induces additional deformation. Therefore, a coefficient $\bar{r}$ treated as a material constant , was introduced mainly to describe this phenomenon. It was further proposed by Ref. 9 that the coefficient $\bar{r}$ can be a function of loading age t'. Chern et al. [9] presumed that the strength of bond of gel structure which can resist the stress due to moisture flux should develop with age. It means that the Pickett effect for concrete loaded and dried at a younger age should be more obvious than that for concrete loaded at older age. Due to the weaker bond strength and higher chemical reactive potential in the early age, active debonding and rebonding process is the cause of higher drying creep of concrete. This argument can be seen from the test result shown in Fig. 9.

Internal Humidity of Concrete

The measurement of internal humidity of concrete can provide the basic information regarding the process of moisture loss of bridge concrete to the drying environment. The shrinkage behavior of concrete was found to be depending on the internal humidity of concrete [8,14]. The test result presented in Fig. 10, showing the distribution of internal humidity at various times, can be used to find the coefficient of diffusion and then for the analysis of shrinkage strain of concrete.

Surface Strain of Field Bridge

The mechanical gauge points located on bridge were measured using Demec gauge at proper time intervals. Strains are plotted versus time in Figs. 11 and 12, which are measured at gauge lines of the quarter and center span of girder A. Time in horizontal axis is counted since the casting of girder A. Notations AP, BP, and PP represent the respective time to apply the prestressing force on girder A, girder B, and slab. Notations A-girder, B-girder, and Plate shown in the figures show the date of the casting of respective components of bridge. Time indicated by arrow sign and notation 'STONE' is the date when sub ballast was placed to the structure. The readings plotted in Figs. 11 and 12, are all corrected back to the temperature at the time of initial reading as what was done in Ref. 11. The coefficient of thermal expansion obtained from the test and used for calibration is $13.5 \times 10^{-6}/°C$ [10]. This value is quite similar to that was found by Neville [15] using same gravel aggregate concrete.

CONCLUSIONS

This paper describes the material used for construction and the details of bridge structure; it also shows the test results which were obtained from both the field and indoor tests. The usage of these test results to analyze the long-term structural behavior of this bridge is relegated to a subsequent companion paper. Some observations found by the tests are summarized as follows:

1. The older the specimen at time of drying, the less the shrinkage; the larger the size of the specimen, the less the rate of development of shrinkage.
2. The age on loading has significant effect on the magnitude of both drying creep and basic creep. The older the specimen at time of loading, the less the basic creep and drying creep.
3. The fact of larger drying creep due to earlier loading age can well correlate to the microstructural view of the creep mechanism. The weak early bond strength and more active debonding and rebonding potential of solid particles or molecules of calcium silicate hydrate are attributed to the causes of higher drying creep for concrete loaded and dried at earlier age.

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TABLE 1 -- CONCRETE MIX INFORMATION

Slump	W/C	S/A	air	unit weight kg/m^3			
cm	%	%	%	water	cement	fine aggr.	coarse aggr.
8	42.5	39.1	1.5	190	447	669	1042

* $1\ kg/m^3 = 1.71 lb/yd^3$, $1\ cm = 0.394\ in.$

TABLE 2 -- SIEVE ANALYSES FOR COARSE AGGREGATE AND FINE AGGREGATE

Sieve size	$1\frac{1}{2}''$	$1''$	$\frac{3}{4}''$	$\frac{1}{2}''$	$\frac{3}{8}''$	#4	#8
Cummulative percentage passing (%)	100	95	86	60	18	1.4	0
Sieve size	#4	#8	#16	#30	#50	#100	F.M.
Cummulative percentage passing (%)	100	89	72	53	31	9.6	2.45
ASTM C33	95-100	80-100	50-85	25-60	10-30	2-10	2.5-3.1