International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:7, No:5, 2013

An Experimental Study on Behavior of Transverse Connection Appropriate for Modular Girder Bridge

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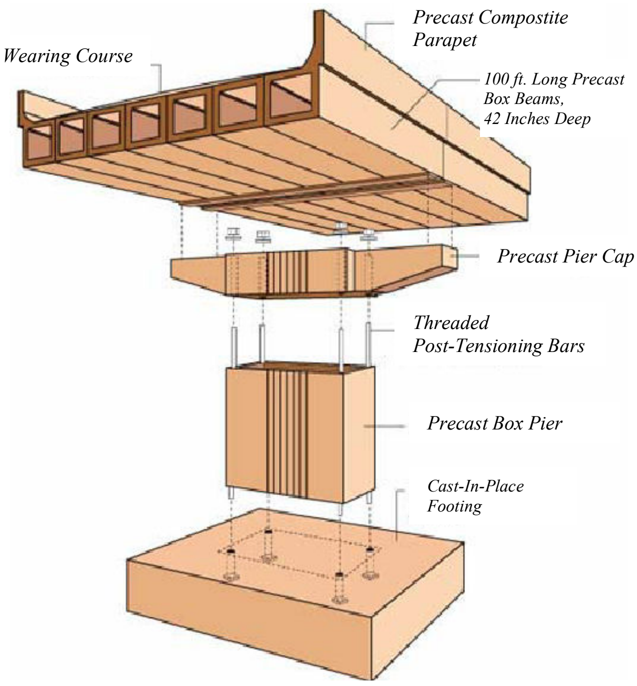
***Abstract*—**This study is to evaluate the behavior of integral and segmental specimens through static and cyclic tests. Integral specimens were made with the same size to be compared with segmental specimens that were made by connected precast members. To evaluate its bending performance and serviceability, 1 integral and 3 segmental specimens were tested under static load. And 1 integral and 2 segmental specimens were tested under cyclic load, respectively. Different load ranges were considered in the cyclic tests to evaluate the safety and serviceability. The test results showed that under static loading, segmental specimens had about 94% of the integral specimen's maximum moment, averagely. Under cyclic loading, the segmental specimens showed that had enough safety in the range of higher than service load and enough serviceability. In conclusion, the maximum crack width (0.16mm) satisfied the allowable crack width (0.30mm) in the range of service load.

***Keywords*—**Modular bridge, Transverse connection, Precast concrete, Static and cyclic test.

I. Introduction

BECAUSE of rapid industrialization and economic growth, many bridges were constructed around the world. In recent years, the need to rehabilitate our aging infrastructure has been recognized. As time goes on, maintenance or replacement should be required due to accident, disaster and deterioration. When the bridges was doing reinforcement and repaired, it was required to minimize the impact on the surrounding environment and traffic congestion due to economical efficiency. The study of prefabricated bridge could respond to these needs. It was conducted in developed countries before. Recently, prefabricated bridge and precast decks has been actively studied in South Korea.

The prefabricated bridge means that it can install using prefabricated structural elements such as bottom plates, girders, piers and abutments as shown in Fig. 1 (a). And it is divided into superstructure, substructure and etc as shown in Fig. 1 (b) [1]. Existing bridges made by using cast-in-place method go through the construction process of labor-intensive production according to the scene of a series of elements of each. On the other hand, prefabricated bridges go through the construction process; production of each element - carrying the elements - assembling the elements – working on construction site. So prefabricated bridges could minimize traffic congestion and shorten the construction period because it makes the exiting road maintain the traffic. Also the elements of prefabricated bridge were produced in the casting beds, the entire bridge could improve and control the quality. In addition, prefabricated bridge has a reduction of construction costs and improvement of the workability according to minimize of the working on site. In recent years, prefabricated bridge can apply both the existing bridge and new bridge, so it has been increasing interest.



(a) Structural elements of prefabricated bridge

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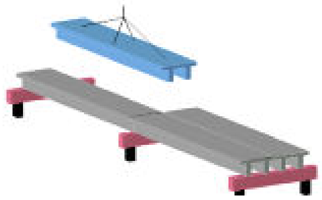


(b) Super•substructure of prefabricated bridge

Fig. 1 Prefabricated bridge details

In the United States since 1996, the study of prefabricated bridge has been developed and used by agencies such as AASHTO, FHWA. They had interested in the prefabricated bridge's elements such as precast decks, segment piers and channel concrete girders for the purposes of shortening construction period and minimizing of traffic controls.

In Japan, the research and construction practices were increasing at the first private companies. Precast decks, steel-concrete composite decks, FRP plates, and integral method of foundation piers and abutments have been applied representatively.

In Europe, prefabricated bridge elements such as girders, precast decks, VFT with large equipment have been attempted with utilizing prefabricated bridge construction method [2].

In South Korea, starting with the pre-cast concrete slab, the study was conducted of a variety of prefabricated slabs. And precast girder technology such as Pressure Prestressed Concrete (PPC) and Spliced Prestressed Concrete (SPC) method has been researched and applied. Also the study of pre-cast piers was conducted in earnest [3].

According to the research results of the Institute of Road Traffic in South Korea, it has reported that construction costs and construction period are reduced to 30% by using precast members but it varies of depending on the construction format and method. In case of construction of new bridge (four-lane overpass, 10km) using precast members, the construction period and costs could be reduced more than 60% and about 45 % compared to the bridge using cast-in-place concrete method. Also in case of reconstructed bridge using precast members, the construction cost could be reduced from 7.2 billion to 2.0 billion won and the construction period could be reduced from 50 days to 0.6 day, approximately. Thus the advantages of using prefabricated bridge are a reduction of the construction period and costs, minimization of environmental impacts and traffic congestion [4].

TABLE I
COMPARISON OF MODULAR BRIDGES AND PREFABRICATED BRIDGE

Division	Prefabricated bridge	Modular bridges
Design	Design in accordance with the each site	Design by using standard module
Purchase	Purchase the material for each site	Purchase the pre-made standard module
Production	Production in accordance with the each site	Production standard modules by using production line
Construction	On-site work	Minimize on-site work

Modular segmental girder which is part of the researches of modular bridge can be constructed by connecting a number of standard modules in a span of bridge using prestressed concrete method different from the prefabricated bridge as shown in Table I. Because of a reduction of area of construction site and easy to carrying the precast members, it will be able to reduce the construction costs. Especially, modular bridge can be useful in mountainous regions and narrow streets in city. Therefore, it is expected to be able to strengthen their global competitiveness not to stop the track of existing technologies in the field of construction of bridges through the foundational study of the modular bridge [5].

In general, modular technology is defined as follows: module technologies is divided into Lego system that is making up the whole system using a combination of typical pre-made production and Plug-in system which is upgrading performance in the standard modules and granting additional functions as shown in Fig. 2. If the bridge combined this module technology, it is possible to increase the large positive effect; a reduction of construction costs and project period, stable quality, ease of maintenance. Modular bridge means that made by assembling the standard precast modules. It can be used permanently and meet the request life by combining of standard modules which is replaceable. Also it can reflect the scene various on-site conditions different from the existing prefabricated bridge. The purpose of the research was carried out to make the next generation of bridge not to concept of expansion and improve the existing prefabricated bridge. In order to respond to a variety of on-site conditions, the pre-made standard modules are free to section and length. And modular bridge can be designed by using a database and simulation programs, also it can minimize assembling the modules on construction site [6].

(a) Lego system (b) Plug-in system

Fig. 2 Modular system

However, despite the benefits better than the existing prefabricated bridge, the practical research of modular bridge is insufficient. So, in order to understand the structural properties of transverse connection, an experimental study has been performed depending on the proposed variables recently.

The girder-type modular bridge inevitably has the transverse connections because it was constructed by connecting precast girders as shown in Fig. 3 [6]. It maybe has structural problems of the connections that should be considered. Therefore, to evaluate the safety and serviceability of transverse connection, integral and segmental specimens were tested under static and cyclic load.

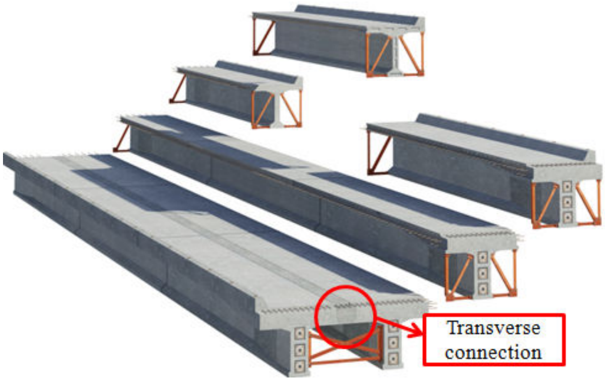
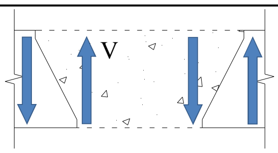
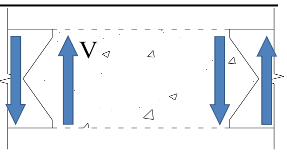


Fig. 3 Girder-type modular bridge systems

Feature	▪ Cross section of concrete cannot resist the shear force along the direction of shear force	▪ Cross section of concrete can resist the shear force along the both directions

TABLE II
COMPARISON OF THE TRANSVERSE CONNECTION SHAPES

Division	Trapezoidal Shape	Diamond Shape
Shape details		

II. Static Test Program

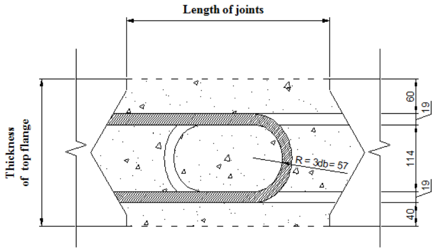
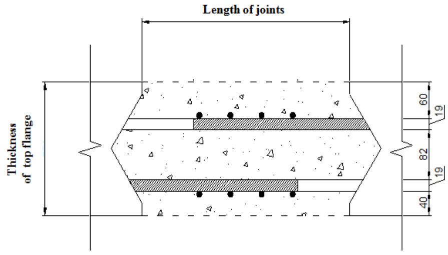
A. Transverse Connection Details

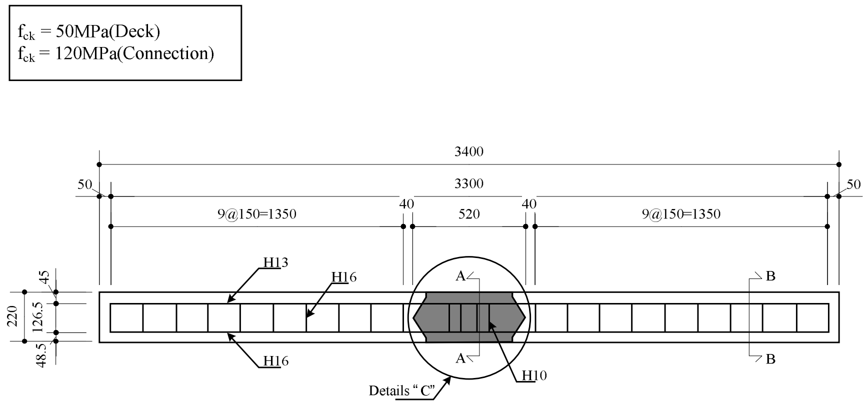
The transverse connection of girder-type modular bridge was chosen between the trapezoidal shape and diamond shape that are easy to construction and most widely used. While trapezoidal shape had the problem of resistance to cyclic and unexpected loading, the diamond shape was possible to resist shear forces in both directions. Therefore, diamond shape was selected as the transverse connection's shape.

The reinforcement detail of transverse connection was chosen by evaluating the loop joint and lapped splice**,** based on the diamond shape.

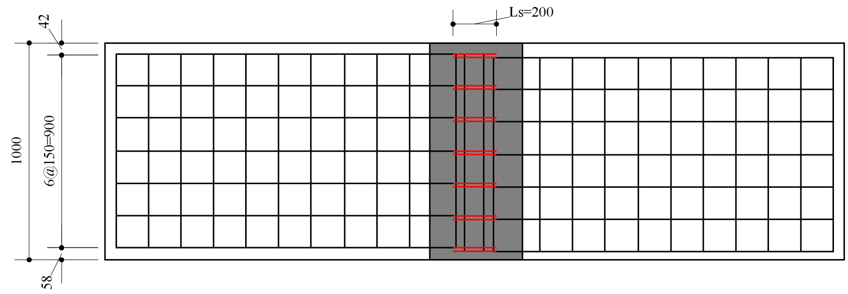
The loop joint exhibited that was lead to gain weight of modules so it reduced the efficiency of the cross-section. In case of using the loop joint, the thickness of top flanges became larger than determined section of transverse connection [7]. Therefore, the lapped splice was selected because it was easy to placing reinforcement and did not affect the thickness of top flange. The length of lapped joints could be reduced by placing high-strength concrete in connection [8].

TABLE III
COMPARISON OF THE TRANSVERSE CONNECTION REINFORCEMENT SHAPES

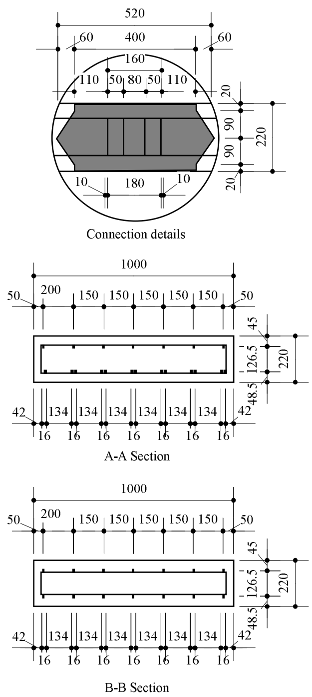
Division	Loop Joint	Lapped Splice
Shape details		
Strength	▪ Short length of joints ▪ Less width of connections	▪ No restriction on the thickness of top flange ▪ Placing reinforcement is simple.
Weakness	▪ Restriction on the thickness of top flange - Radius bending rebar = $3d_b$ ▪ Placing reinforcement is difficult.	▪ Need to reduced length of lap joints → Using a high-strength concrete in connection
the minimum thickness of top flange	▪ The minimum thickness = 252mm > 220mm ※ D16, The minimum thickness = 228mm	▪ The minimum thickness = Below 220mm
Result	▪ Impossible - Increase self-weight → Uneconomical	▪ Possible - Place high-strength concrete(120MPa) in connection ※ The thickness of top flange = 220mm



(a) Side view



(b) Plane view



(c) Cross-sectional view

Fig. 4 Segmental specimen details

B. Bending Test

The bending test included an integral specimen (RC Beam) and 3 segmental specimens (Connected PC Beams). The details of specimens were shown in Table IV.

TABLE IV
BENDING TEST SPECIMENS

Specimen name	Type	Structure	Strength of concrete (MPa)	Loading method
STS-1	Integral specimen	Reinforced concrete(RC)	50	4-point loading (Until the failure)
STJ-1	Segmental specimens	Precast concrete(PC) (connection details: Diamond shapes& lapped splice)	RC & PC: 50 Connection concrete: 120	
STJ-2				
STJ-3				

The segmental specimen's configuration in this study is shown in Fig. 4. In order to evaluate and compare the bending performance, the Integral specimen was same size as the segmental specimens.

The specimens had a total length of 3,400mm. The dimensions of the cross section were 1,000mm wide by 220mm deep.

All specimens were loaded under four-point bending as shown in Fig. 5. A loading span of 3,000mm and a shear span of 1,000mm were used. All specimens were loaded to failure under static load and measured the maximum load and the maximum moment.

Fig. 5 Bending test setup

III. CYCLIC TEST PROGRAM

The cyclic test included an integral specimen (RC Beam) and 2 segmental specimens (Connected PC Beams). The details of specimens were shown in Table V. The segmental specimen's configuration in this study is shown in Fig. 4. In order to evaluate and compare the performance under cyclic load, the Integral specimen was same size as the segmental specimens.

All specimens were loaded under four-point bending as shown in Fig. 6.

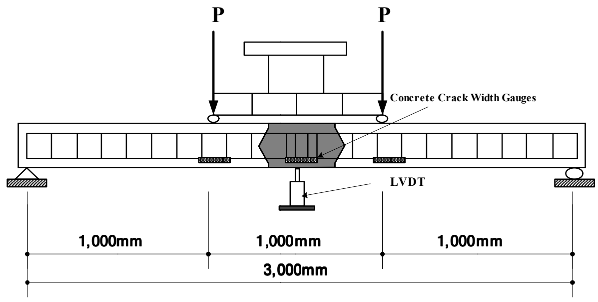


Fig. 6 Cyclic test setup

All specimens were instrumented with several concrete crack width gauges mounted at mid span section on the tension face of the concrete cracks after the initial loading. And LVDT mounted at mid span section under the specimens for measuring the deflection. To look at the detailed behavior and deflection at each repetition number, specimens were loaded under proposed static load in powers of 10 units.

TABLE V
CYCLIC TEST SPECIMENS

Specimen name	Type	Structure	Strength of concrete (MPa)	Loading method
CTS-1	Integral specimen	Reinforced concrete(RC)	50	4-point loading
CTJ-1	Segmental specimens	Precast concrete(PC) (connection details: Diamond shapes& lapped splice)	RC & PC: 50 Connection concrete: 120	
CTJ-2				

All specimens were tested under load-control at a frequency of 4~6 Hz. The cyclic load was applied in the form of sine-wave and load ratio (P_{max} / P_{min}= R) = 0.1 as shown in Table VI.

CTS-1 and CTJ-1 were compared by testing under same cyclic load until failure and applied in cyclic load ranging between 10% and 60% maximum static load which was obtained through a bending test of STS-1.

In order to evaluate the serviceability under cyclic load, CTJ-2 was applied in cyclic load ranging between 10% and 100% service load with 2 million cycles [9].

TABLE VI
CYCLIC LOAD DETAILS

Specimen name	Type	P_{max} calculated basis	P_{max} (kN)	P_{min} (kN)	Number of Cycles
CTS-1	Integral specimen	60% of STS-1's maximum static load	79.1	7.91	Until the failure
CTJ-1	Segmental specimens	60% of STS-1's maximum static load	79.1	7.91	Until the failure
CTJ-2		100% of service load	30.5	3.05	2 million

(a) Precast members (b) Setup the mold (c) Placing concrete

(d) Curing

(e) Test

Fig. 7 Process of producing Segmental specimens

IV. Test Results

A. Bending Test Results

Four specimens were tested under static loading, as reference beams: STS-1 without connection, STJ-1, STJ-2, and STJ-3 had connection. Maximum moments of STJ-1, STJ-2 and STJ-2 were more than 122kN-m as shown in Table VII. STJ-1, STJ-2, and STJ-3 exhibited decreases of 7.3%, 4.7% and 5.7% in the maximum moment compared to STS-1, respectively.

TABLE VII
Results of Bending Tests

Specimen name	Maximum Load (kN)	Maximum Moment (kN-m)	Comparison to the maximum moment of STS-1 (%)
STS-1	131.9	131.9	-
STJ-1	122.3	122.3	92.7
STJ-2	125.8	125.8	95.3
STJ-3	124.4	124.4	94.3

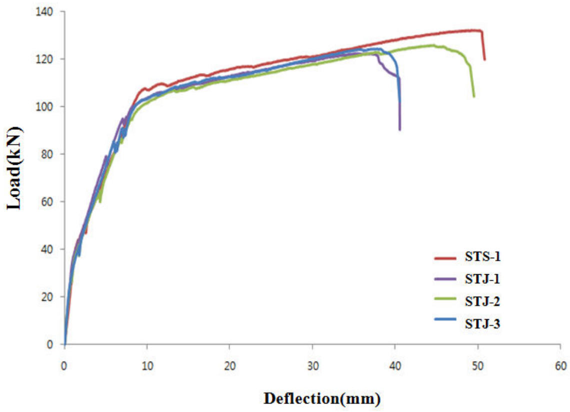
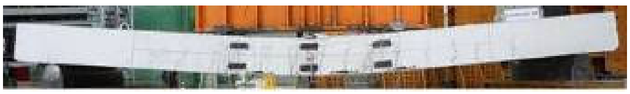


Fig. 8 Load-deflection of bending test



(a) STS-1

(b) STJ-1

Fig. 9 Surface after failure

Fig. 9 shows the failure surface of the STS-1 and STJ-1. The failure surface of STJ-1 was similar with the STS-1.

B. Cyclic Test Results

1. CTS-1, CTJ-1

Fig. 10 and Fig. 11 plot the deflection versus load with number of cycles for CTS-1 and CTJ-1 until failure, respectively. The increase in the maximum and residual deflection with number of cycles is evident. The load-deflection graphs of CTS-1 and CTJ-1 showed a similar pattern.

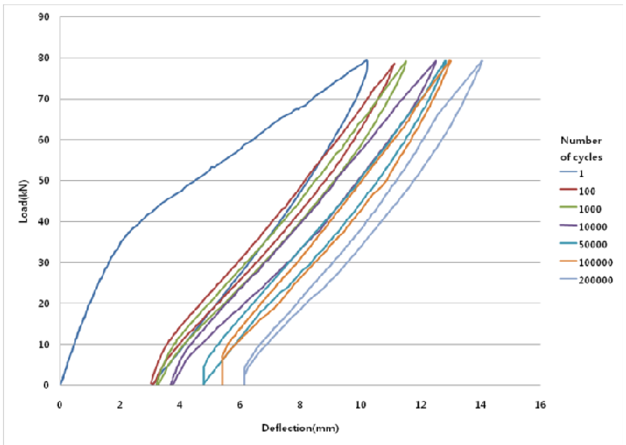


Fig. 10 CTS-1 load-deflection

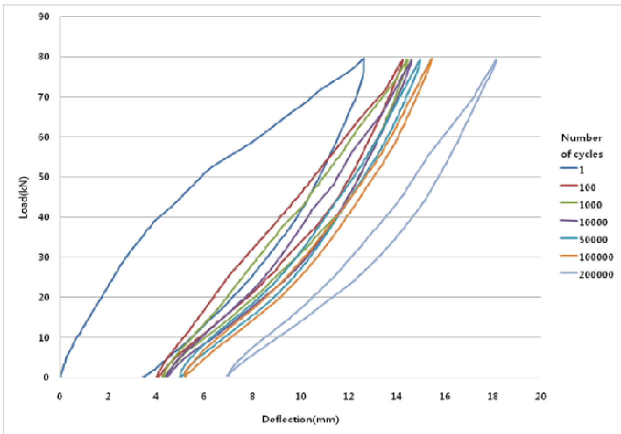


Fig. 11 CTJ-1 load-deflection

However, CTJ-1 exhibited different behavior with increases in the deflection compared to CTS-1. The maximum and residual deflection of CTJ-1 were higher than CTS-1's, possibly due to structural differences.

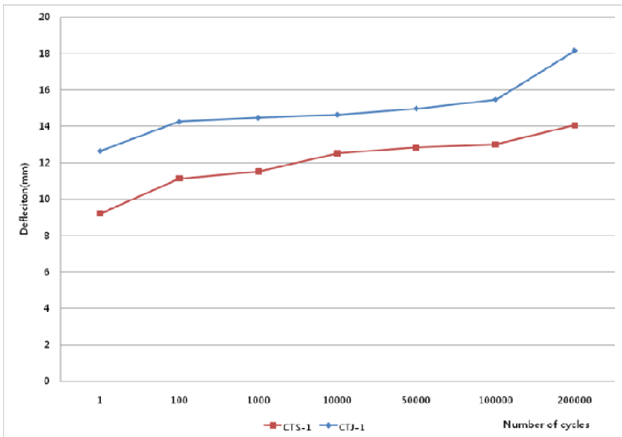


Fig. 12 Maximum deflection

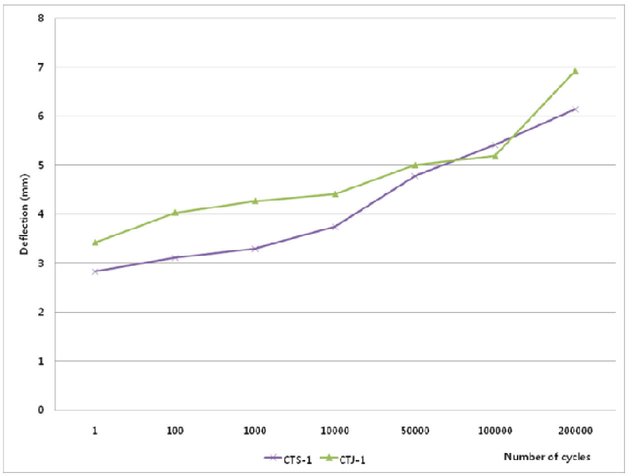


Fig. 13 Residual deflection

Fig. 12 plots the maximum deflection versus number of cycles for CTS-1 and CTJ-1. Fig. 13 plots the residual deflection versus number of cycles for the CTS-1 and CTJ-1. CTJ-1 exhibited increases of about 2.11~4.08mm in maximum deflection over CTS-1. And CTJ-1 exhibited increases of about 0.22~0.78mm in residual deflection over CTS-1.

2. CTJ-2

Fig. 14 plots the deflection versus load with number of 2 million cycles for CTJ-2. The most increment of residual deflection was measured after the initial static loading and CTJ-2 exhibited increases of the deflection proportionally.

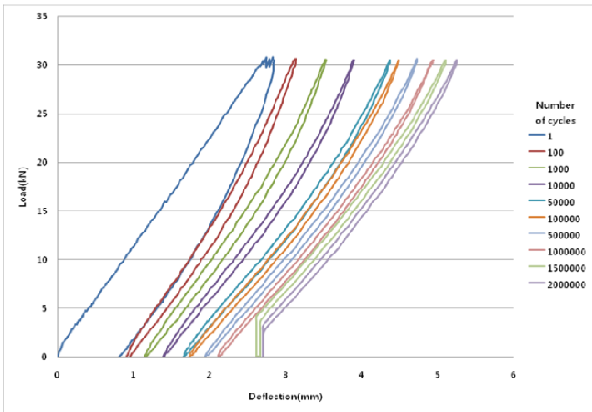


Fig. 14 CTJ-2 load-deflection

According to increasing number of cycles, the increment of residual deflection gradually decreased. The average difference between the maximum and residual deflection was approximately 2.5mm as shown in Fig. 15.

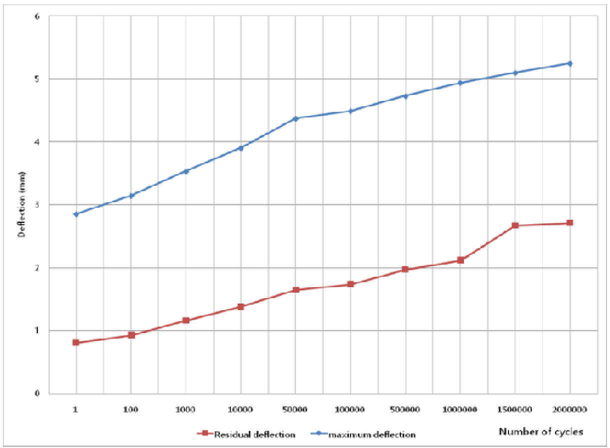


Fig. 15 CTJ-2 deflection

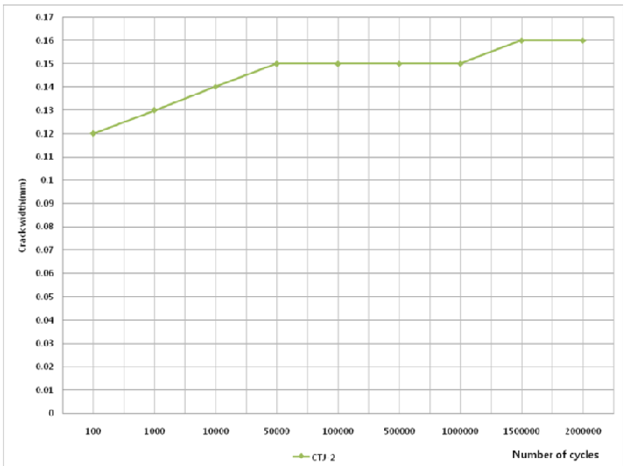
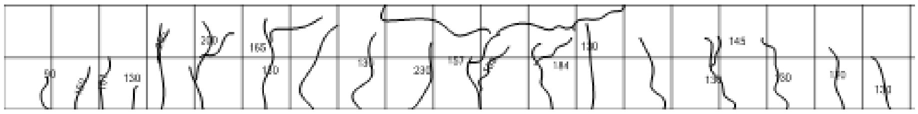
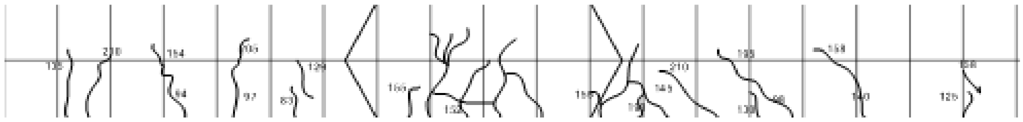


Fig. 16 CTJ-2 Crack width

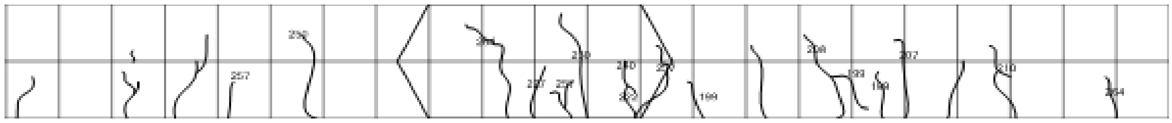
Fig. 16 plots concrete crack width versus number of 2 million cycles for the CTJ-2. The maximum crack width was 1.6mm after cyclic test. It satisfied the allowable crack width (0.3mm) in the range of service load [10].



(a) CTS-1



(b) CTJ-1



(c) CTJ-2

Fig. 17 Crack surface

C. Crack Behavior

Fig. 17 illustrates the cracks surface of the specimens after cyclic tests. CTJ-1 and CTJ-2 exhibited different crack pattern of CTS-1, possibly due to structural and material differences. In case of CTS-1, the first concrete crack occurred at mid span section on the tension face and the cracks were growing, characteristic of an under-reinforced concrete beams. However, in case of CTJ-1 and CTJ-2, the first concrete crack occurred at the tensile side connections, the cracks were growing to the precast members gradually, and then the cracks increased at mid span section on the tension face of connection as shown in Fig. 18.

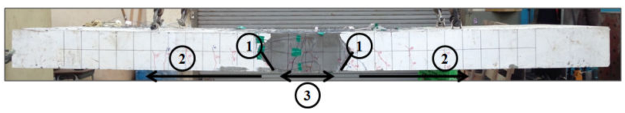


Fig. 18 Crack growth of segmental specimens

V. CONCLUSIONS

In this study, in order to investigate the behavior of transverse connection of girder-type modular bridge, integral and segmental specimens were tested under static and cyclic load. The following conclusions were drawn from this study.

1) Through the bending test, the segmental specimens (STJ-1, STJ-2, and STJ-3) had about 94% of the integral specimen's (STS-1) maximum moment. This result shows that the moment was higher than nominal bending moment of specimen's cross-section.
2) CTJ-1 was not failure at proposed cyclic load range that was between 10% and 60% maximum static load (about 260% of service load) which was obtained through a bending test of STS-1. This result shows that the segmental specimen had enough safety in the range of higher than the service load.
3) CTJ-1 exhibited increases of about 2.11~4.08mm in maximum deflection and increases of about 0.22~0.78mm in residual deflection over CTS-1, respectively. This difference was small versus the length of the specimen. This result shows that it had enough serviceability in deflection.
4) CTJ-2 showed that the maximum crack width was 1.6mm under cyclic load ranging between 10% and 100% service load with 2 million cycles. It satisfied the allowable crack width (0.3mm) of Design Code of Concrete Bridge. Therefore, Segmental specimens had enough serviceability in crack width.
5) In case of CTS-1, the first concrete crack occurred at mid span section on the tension face and the cracks were growing. However, in case of CTJ-1 and CTJ-2, the first concrete crack occurred at the tensile side connections, the cracks were growing to the precast members gradually, and then the cracks increased at mid span section on the tension face of connection. This crack behavior was possibly due to structural and material differences between precast members and transverse connection.

Segmental specimens were difficult to compare with an integral specimen for the crack behavior because there are a small number of integral and segmental specimens in the cyclic test. Later, to observe more detailed crack behavior than this study, additional experiments increasing specimens and using different load ranges are required.

ACKNOWLEDGMENT

This study has been performed by research funding of 'Construction Technology Innovation Project (10 technological innovation B01)' sponsored by Ministry of Land, Infrastructure

and Transport.

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