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A Study of the Bolt Connection System for a Concrete Barrier of a Modular Bridge

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Abstract

Modular technology has been recently studied to reduce the construction periods in the field of bridge construction. However, this method is restricted to the pier, girder, and deck, which are the main members of a bridge, and incidental facilities such as concrete barriers have been rarely studied. Thus, in this study, the connection system of a concrete barrier for modular bridges was developed, and a static loading experiment was performed to verify the structural capacity of the proposed system. The variables of the experiment were the vertical and horizontal bolt connections and the construction method. The barrier and plate were fabricated using match casting methods in which nuts were first inserted into the plates rather than anchor bolts using the conservative method. Moreover, a comparison with the conventional in situ barrier was also performed. The experiments were conducted according to the AASHTO LRFD standard. Consequently, the specimen using the vertical bolt connection had a structural capacity that was equal to 85% of that of the conventional specimen and exhibited similar crack patterns compared with the conventional specimen. In the case of the horizontal bolt connection, the separation in the connection area occurred with the application of the initial load and this specimen exhibited a poor performance because of the increase in the separation distance with the application of the maximum load.

Keywords: modular bridge, fabricated bridge, concrete barrier, vertical bolt connection, horizontal bolt connection

1. Introduction

Problems have arisen recently in regard to the conventional methods that have been used for the construction, repair, or replacement of bridges, including economic losses from long-term traffic control, environmental issues from dust scattering, and the assurance of structural quality during the winter. Research on modular fabricated bridges is being actively conducted to overcome these problems. In foreign countries, numerous modular bridges constructed using the precast segmental construction methods are currently in progress. In Korea, the research and construction of modular bridges are gradually becoming more prominent. However, most of these efforts are still limited to the main bridge structures, such as piers, girders, and decks, whereas research on service structures, such as the barriers that are responsible for the structural safety during service, is still lacking.

Most studies on the barriers have been interpretations of clashes and have mainly focused on stability. Since the first interpretive research in 1993 on the overturning by an automobile clash (Ross et al. 1993) [1], research studies have focused on

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the causes and patterns of cracking in the median barrier and guardrail concrete of reinforced concrete (RC) bridges (Choi et al. 2014) [2] and on the rating of concrete barriers (Jeon et al. 2007) [3–4]. Additionally, the verification of the barrier performance by fiber-reinforced concrete (Lee et al. 2013) [5], the development of a precast concrete barrier wall system for bridge decks (Patel et al. 2014) [6], and the development of prefabricated concrete bridge railings (Sri et al. 2015) [7], are areas that have also been researched. Although there are ongoing research efforts on precast concrete barriers utilizing loop joints, the conventional construction method does not guarantee easy replacement because semi-permanent repairs and reinforcements are required. Additionally, non-shrink mortar is also needed for curing over a certain period of time. Therefore, the bolted joints presented in this study would be an alternative option in terms of constructability. In contrast, there is another case in which the Federal Highway Administration (FHWA) implemented precast concrete can be used as a median barrier. However, it is difficult to be considered as an external barrier for a bridge because it does not have the exact connection fabrication form.

Examining the current state of barrier constructions in Korea reveals that there are two methods for cast-in-place constructions, one of which utilizes the onsite formwork, and the other which employs a slip-form machine (as shown in Fig. 1). However, both construction methods have problems. The former is expected to delay the duration of installation and dismantling of the formwork, whereas the latter is inconvenient for a construction on a bridge. Moreover, the aforementioned cast-in-place construction has a disadvantage that the barriers would be required to repair because of unexpected concrete cracking and collapse as depicted in Figs. 2 and 3, respectively. In recent years, studies on precast prefabricated bridges have been actively conducted regarding the use and installation of barriers with wall forms. Using a slipform machine has many demerits, such as the maintenance costs, in instances when it either requires some repairs, or when construction delays are associated with the problems outlined above. In addition to the consideration of the connection with other members it seems to be impossible for the slipform machine to be applied to prefabricated bridges. While one of the advantages of prefabricated bridges is the ease of their replacements, cast-in-place barriers are impossible to be removed. Thus, research on the methodologies adopted to connect the girders to concrete barriers for application in prefabricated bridges is essential. In this study, a prefabricated concrete barrier was presented and the connection systems were examined using experimental methods.

The recent increase in the population and the rapid growth in the automobile demand dramatically escalated the roadway occupancy and traffic volume in Korea. Correspondingly, with the increase in the number, weight, and speed of automobiles, human and material damages per traffic accident have been increasing in spite of the decrease in the road traffic accident (RTA) rates. This is emerging as a socio–economic problem that is shedding light on the importance of barriers for bridges and roadsides in preventing the automobiles from falling or colliding in the long-span bridges. For example, the Incheon bridge bus accident in 2010 in which a bus fell down the bridge underlined the importance of the structural integrity and road safety of the facilities for the lives of the automobile drivers and passengers, and emphasized how an improper installation of such facilities can cause economic losses. In view of these types of problems, stricter ratings of barrier designs as well as the enlargement of the barrier section are presently being implemented. The road safety facilities in Korea are defined by the legal framework of Article 3 of the Road Act and Article 37 of the Regulation on Facilities and Standards of Roads to provide a safe and smooth circulation of road traffic, thus playing a critical role in enhancing the function and service standards of the road facilities by ameliorating risks associated with incomplete road structures. In particular, such safety facilities for automobile protection utilizing median barriers, barriers for bridges and roadsides, and shock absorbers, are destined to prevent fatal traffic accidents. Therefore, it is crucial to install facilities that are sufficiently capable of functioning. Despite this importance, the studies on modular bridges are limited to girders and decks, as described above. Thus, research on methodologies describing how to develop appropriate barriers for modular bridges by verifying their structural performances seems necessary.

Fig. 1 Slipform machine

Fig. 2 Crack in barrier

Fig. 3 Barrier collapse

In this study, test pieces were developed as connection systems utilizing bolted joints between the concrete barrier and deck. The structural performances of these connection systems were verified, and another test piece was developed whose specifications were similar with those of the existing barriers. To examine the behavior of the connection, static structural experiments were performed based on concentrated loading, and the behaviors of the test pieces were analyzed.

2. Experimental Program

2.1. Experimental materials

To develop an appropriate method for connecting the concrete barriers in modular bridges, vertical and horizontal bolted connections were set up as alternatives and were compared experimentally with the existing solid-body barriers. The concrete used for the experiment was ready-mixed concrete with a design compressive strength of 24 MPa for the barrier and 30 MPa for the deck. For each barrier and deck casting, test pieces of Φ100×200 mm were produced, and their compressive strengths were tested after 28 d of curing according to Table 1-a. The deformed SD30 bars defined by KSD 3504D were used. Their material properties are listed in Table 1-b. For the deck, D19 bars were used as tensional and compressive bars. Correspondingly, for the fixative part and the location on the deck where the maximum moment was exerted, D16s were used as reinforcing bars, while for the concrete barrier, D13s were used. Moreover, for connecting the barrier and deck, F10TM25 high-tensional bolts were used. Their properties are summarized in Table 1-c.

2.2. Experimental variable

The variable for the static experiment is in the form of the bolted connection between the deck and barrier, as presented in Table 2. Accordingly, three types of test specimens were produced: existing cast-in-place solid–body types (ST), vertical connections (VC), and horizontal connections (HC) between the barrier and the deck. The number of productions and bolts for each test specimen are listed in Table 2. To examine their applicability for a modular bridge, they were cast together with nuts embedded in advance. The nuts used here are shown in Fig. 4. To prevent local failure around the bolts during loading after the installation of the concrete barrier and deck, spiral bars were used as depicted in Fig. 5.

Table 1 Experimental material

a. Compressive Strength Results				
Type	Compressive Strength of Concrete Cylinders(MPa)			Average(MPa)
Deck(30MPa)	32.1	30.0	36.8	33.0
Barrier(24MPa)	20.9	20.4	20.1	20.5
b. Steel Properties				
Classification	Diameter (mm)	Cross section (mm^2)	Tensile Strength(MPa)	Yield Strength(MPa)
SD30	12.7	126.7	More than 440	More than300
c. Bolt Properties				
Classification	Diameter (mm)	Cross section (mm^2)	Tensile Strength (MPa)	Yield Strength(MPa)
F10T M25	25.0	352.5	1,000-1,200	Over 900

Table 2 Experimental parameter

Experimental Model	Parameter	Number of Specimens	Number of Bolts	Remarks
ST	-	1	0	Cast-In-Place
VC	Vertical Bolt Connection	2	4	Precast
HC	Horizontal Bolt Connection	2	4	

2.3. Specimen shape and fabrication

The test specimens were produced in a series of processes as illustrated in Fig. 6. The details of the specimens according to the type of connection are displayed in Fig. 7. The ST specimen was produced as follows: after the fabrication of the bars in the deck and barrier, concrete was first placed on the deck, and the concrete used for the barrier was then poured. Both the VC and HC specimens were produced by the match-casting construction method. The construction sequences are as follows: first, the shuttering of the deck was installed after fabricating the reinforcement followed by the placement and curing of the concrete. Once the deck concrete cured, the barrier formwork was installed on top of the deck and the concrete was poured and set. Moreover, to maintain the initial wet condition of the concrete after casting without the harmful effects of low temperatures, dryness, and rapid temperature changes, the test specimens were hardened by steam curing and fabricated by a torque wrench.

Fig. 4 Shape of nut

Fig. 5 Shape of spiral bar

(a) Installation of bar

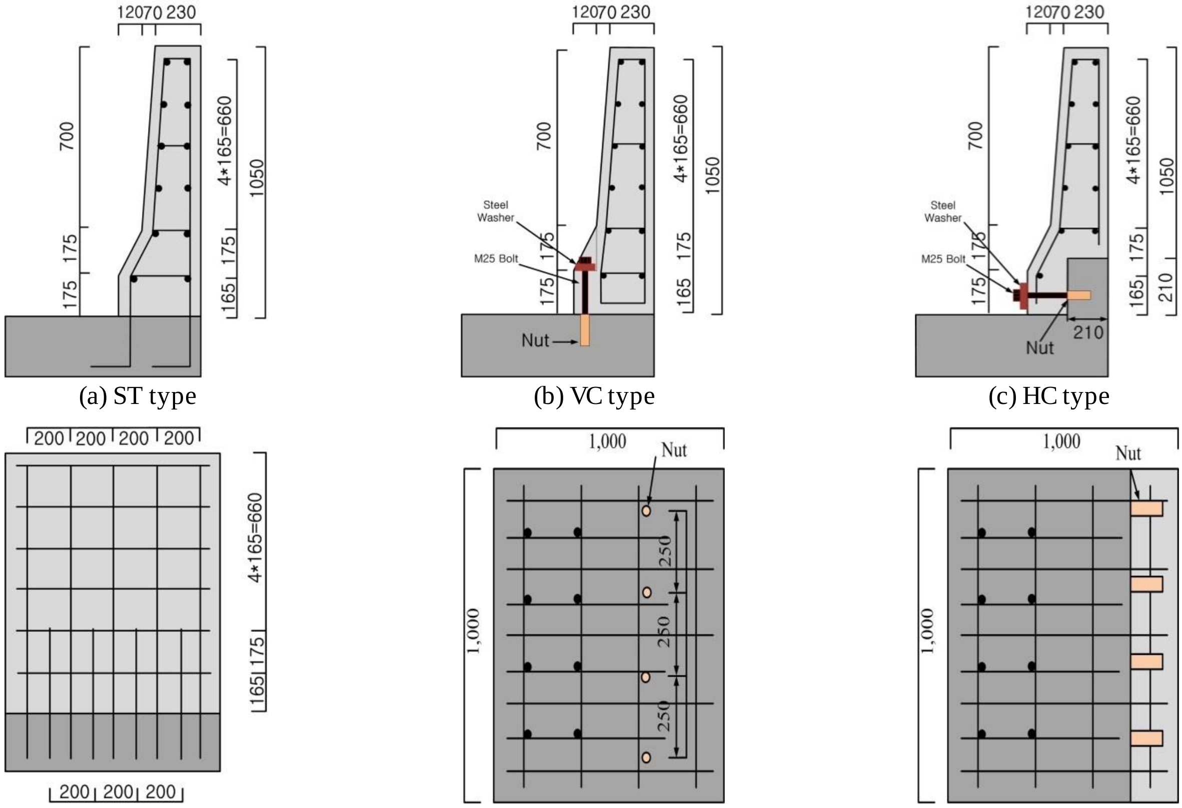
(b) Installation of cast and placement of concrete in the deck

(c) Installation of cast and placement in the barrier

(d) Steam curing

(e) Connection of barrier and deck

Fig. 6 Adopted procedure for building specimens



(a) ST type (b) VC type (c) HC type

(d) Steel datail of specimen (e) VC Deck (f) HC Deck

Fig. 7 Dimensions of each constructed specimen

2.4. Loading

The form of the static loading experiment on the barrier is similar to that of the colliding surface in an automobile collision. The Korean Highway Bridge Design Code (2005) suggests the consideration of the estimated horizontal collision force as a uniformly distributed load at a constant height in reference and usage to the deck design. The American association of state highway and transportation officials (AASHTO) loads & resistance factor design (LRFD) Bridge Design Specifications (2007) provides relatively detailed information on the form of loading and on collision loads. However, the experiment in this study was focused on the structural performance of the connection system and not on the barrier itself. Additionally, the test specimens were also produced with unitary (1 m) lengths. Thus, a concentrated load was applied until failure occurred according to the AASHTO specifications. The load was applied at a height of 810 mm for controlling the displacement at a rate of 1 mm/min using a 500 kN actuator. Load cells were installed to obtain accurate loading data, and the system of loading test pieces is that shown in Fig. 8.

Fig. 8 The shape of an actuator

2.5. Measurement

To determine and analyze the behavioral characteristics of the concrete barrier, a connection system was installed that was fit for the modular bridge, gauges, and linear variable differential transformers (LVDTs). To examine the strain on the steel in each test piece, steel strain gauges were attached prior to the concrete placement, while for the examination of the strain of the concrete, concrete strain gauges were attached to both the deck and barrier of each specimen. The installation spots of the gauges are illustrated in Fig. 9, and the purposes of installation are listed in Table 3. Moreover, to measure the lateral displacement of the concrete barrier and deck deflection after the integration of the barrier and deck, LVDTs were installed in the vertical and horizontal directions, as shown in Fig. 9.

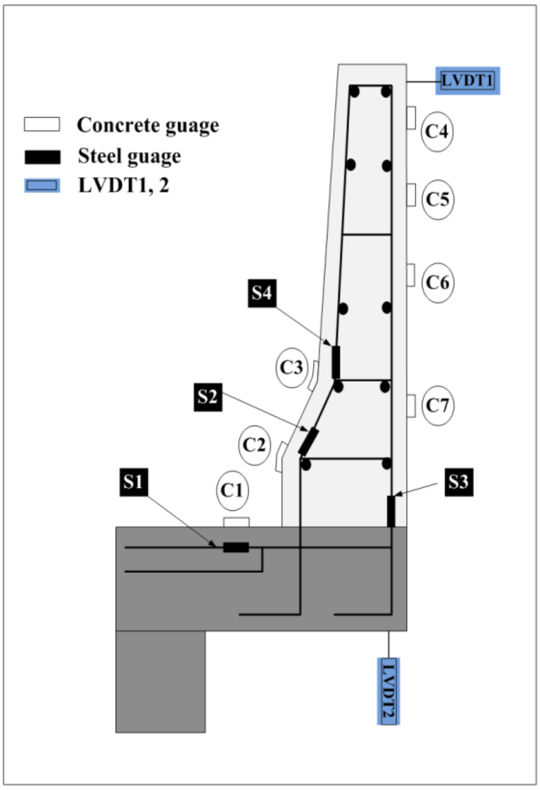


Fig. 9 Locations of strain gauge and LVDT

Table 2 Measuring instruments

ID	Measuring Instrument	Purpose
L1	LVDT	Measures Lateral Displacement along the Load Direction
L2	LVDT	Measures the Vertical Displacement of the Deck
GS1	Steel Strain Gauge	Measures the Strain of the Main Reinforced Bar
GS4	Steel Strain Gauge	Measures the Vertical Steel Strain at the Front of the Barrier
GC1	Concrete Strain Gauge	Measures the Strain at the Top of the Deck
GC3	Concrete Strain Gauge	Measures the Vertical Strain at the Back of the Barrier
GC7	Concrete Strain Gauge	Measures the Horizontal Strain at the Back of the Barrier

3. Analysis of Experimental Results

The AASHTO equation was used (Eq. 1) to calculate the collision force of the barrier and was adopted to analyze the load-carrying capacities of the test pieces of the vertical and horizontal connections. Consequently, it revealed a satisfactory capacity of 161% for the vertical connection and an unsatisfactory capacity of 93% for the horizontal connection. For a more detailed analysis of the outcomes, this chapter examines the load–deflection curve, steel strain, concrete strain, and the crack pattern.

$$R_w = \left(\frac{2}{2L_c - L_t}\right) \times \left(M_b + 8M_w + \frac{M_c L_c^2}{H}\right) \quad (1)$$

where

R_w: Total transverse resistance of the concrete barrier
H: Height of concrete barrier
L_c: Critical length of yield line failure pattern
L_t: Longitudinal length of distribution of impact force
M_b: Additional flexural resistance of beam in addition to Mw , if any, at top of the concrete barrier
M_w: Flexural resistnace of the concrete barrier about its vertical axis
M_c: Flexural resistance of cantilevered concrete barrier about and axix parallel to the longitudinal axis of the bridge

3.1. *Lateral displacement*

Loading was applied for controlling the displacement at a rate of 1 mm/min. Correspondingly, the load–deflection curve was drawn based on the deflection values measured at the center of the upper part, as shown in Fig. 10. The crack load and maximum strength of each test specimen measured in the experiment are summarized in Table 4. Compared with the solid–body type (ST) specimen, VC1 and VC2 exhibited strengths that were approximately equal to 75–85 % and strengths that were approximately equal to 42–50% in the HC1 and HC2 specimens. These differences arose because of the difference in the resisting section areas that carried the loads of the HC and VC specimens. For the HC specimen, the resistible section area was parallel to the direction of the loading, and thus the bolts were pulled out from the deck. This led to the gap distance between the barrier and deck that shifted most of the loading to the bolts. Hence, a larger variation in the deflection occurred at relatively smaller loadings, as shown in Fig. 10. In contrast, for the VC specimen, the resistant section area was perpendicular to the direction of the loading so that it had a carrying capacity that was much better than that of the HC specimen. Furthermore, the cooperative resistance of the concrete and bolts enabled a lesser change in the deflection compared to the HC specimen. Consequently, the experiment of the lateral deflection, which could represent the state of damage owing to the impacts and the horizontal connection of the HC specimens, could be considered as an inapplicable design for the modular bridge, whereas the vertical connection of the VC specimens would be considered as an alternative design. Moreover, compared with the standard load of 46.5 kN calculated by the AASHTO code, the load of the VC specimen in this study was 75 kN on average, which exceeded the standard value by 61%. Correspondingly, the load of the HC specimen was 43.35 kN, which was 7% less compared to the standard load.

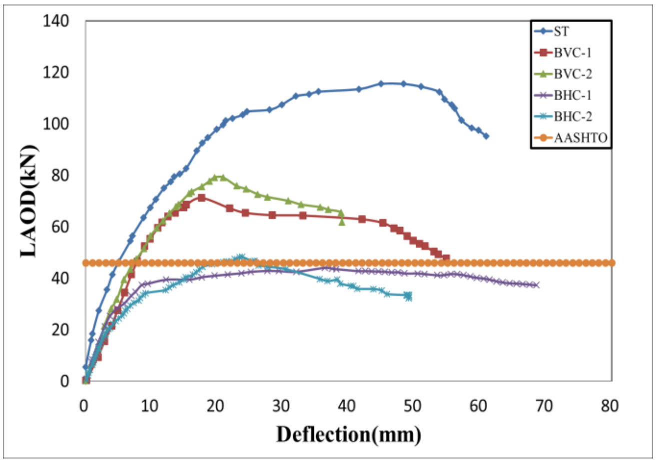


Fig. 10 Load-deflection curve at LVDT1

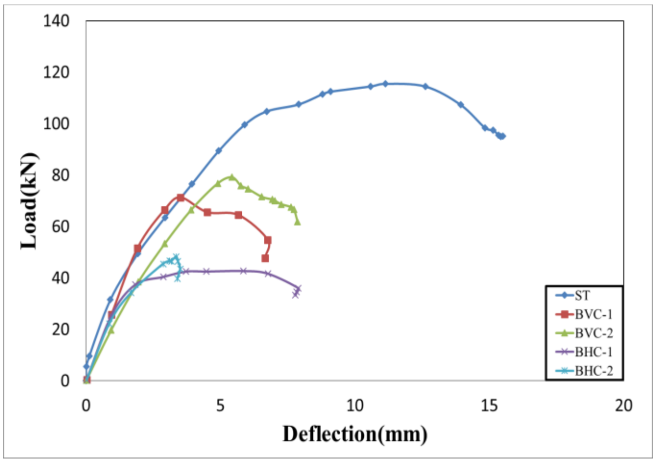


Fig. 11 Load-deflection curve at LVDT2

3.2. *Vertical deflection of the deck*

Once the loading was applied, the maximum moment load occurred at the intersection of the deck and barrier. Because this load was delivered throughout the barrier to the deck, it led to a vertical deflection. Fig. 11 shows the vertical deflection of the deck, which is similar to the measurement of the lateral deflection of the barrier. Particularly, compared with the VC and ST specimens, the connection between the barrier and the deck of the VC specimens could be considered as a fully integrated member based on the similar relationships elicited for the load and deflection.

3.3. Steel strain between the deck and girder

The deck was designed by considering the loads applied to the barrier, and the loads generated the strain on the steel. Fig. 12 shows the steel strains at the GS1 points of the test pieces. Similar to the previously described load–deflection curve, in the cases of the HC specimens, it is observed that the bolts endure most of the loads instead of transferring them to the deck as the distance between the connected surfaces increases.

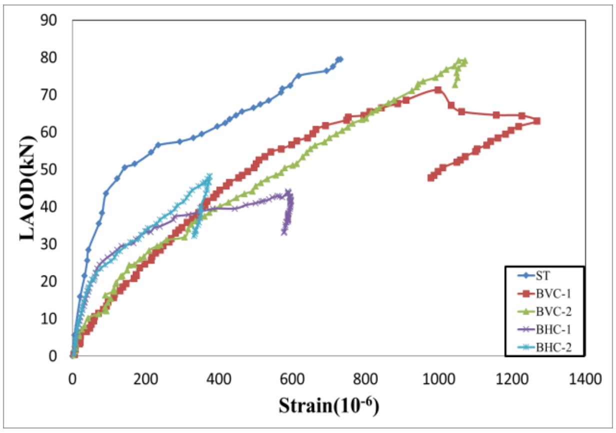


Fig. 12 Strain curve at GS1

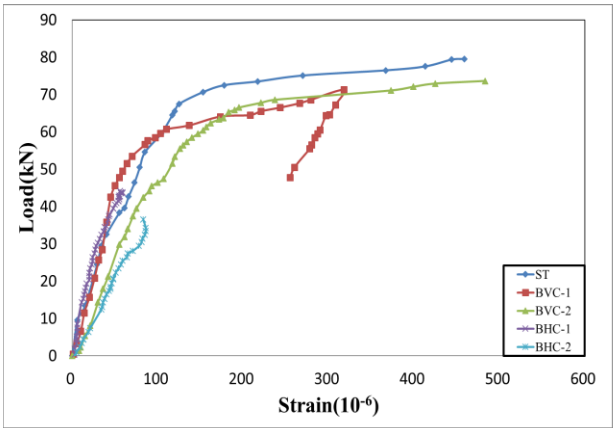


Fig. 13 Strain curve at GS4

Table 3 Cracking and maximum load

Type	Cracking Load(kN)	Maximum(kN)
ST	41.6	94.33
VC1	46.0	71
VC2	33.2	79.2
HC1	20.6	40.0
HC2	19.9	46.7

3.4. Steel strain in barrier

Fig. 13 shows the steel strain at the variable cross-sections of the ST and VC specimens where the strain dramatically increases after the occurrence of the initial crack in the barrier. Although the strain continues to increase in the ST specimen, for the HC specimens, the strain did not continue to increase in the reinforcements because some of the loads would be delivered to the bolts after the initial crack.

3.5. Concrete strain in the front side of the barrier

Fig. 14 displays the load–strain curves obtained from the GC2 concrete gauge that was located at the front side of the barrier at the location at which the largest crack and tensional strain occurred. Even though the ST and VC specimens generated no significant changes of the strains because of the composite behavior of the reinforced concrete, the HC specimen did yield a significant strain change because of the increased load to the barrier concrete owing to the distance between the connected surfaces.

3.6. Concrete strain in the rear side of the barrier

Fig. 15 illustrates the load-strain curve measured by the GC3 concrete gauge, which was attached on the rear side of the barrier. Because GC3 was placed at the largest compressive strain, the VC and HC specimens showed a relatively less significant strain compared with the strain of the ST specimen. This is because the bolts at the connected surface were pulled out as the applied load increased. Moreover, this circumstance led to the disconnection of the barrier, but the compressive force did not affect the rear side of the barrier of the VC and HC specimens apart from the ST specimens.

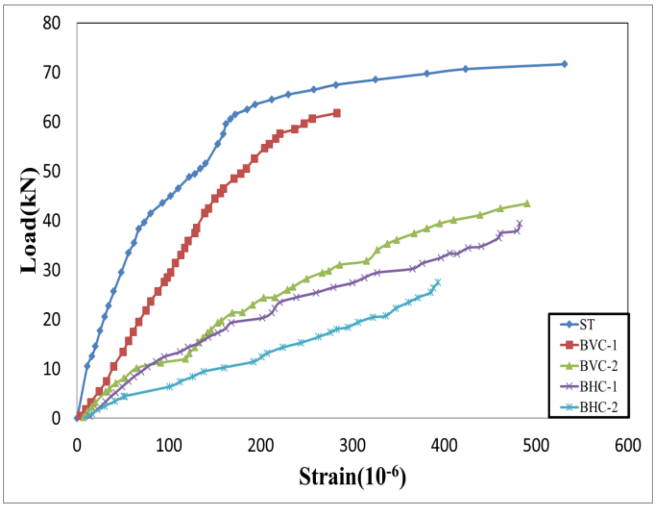


Fig. 14 Strain curve at GC3

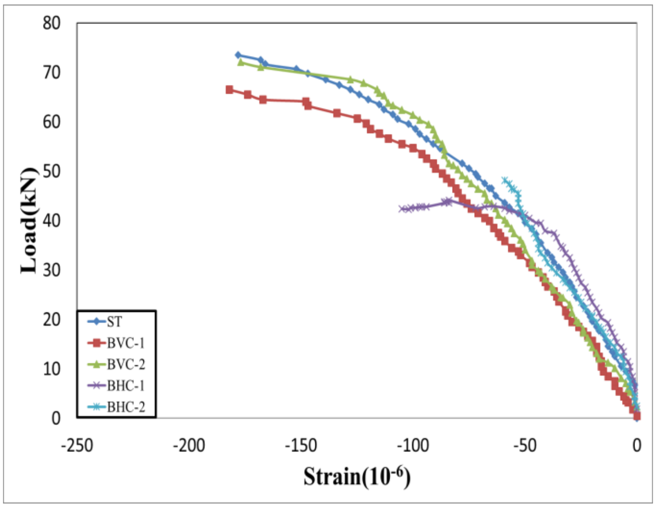


Fig. 15 Strain curve at GC7

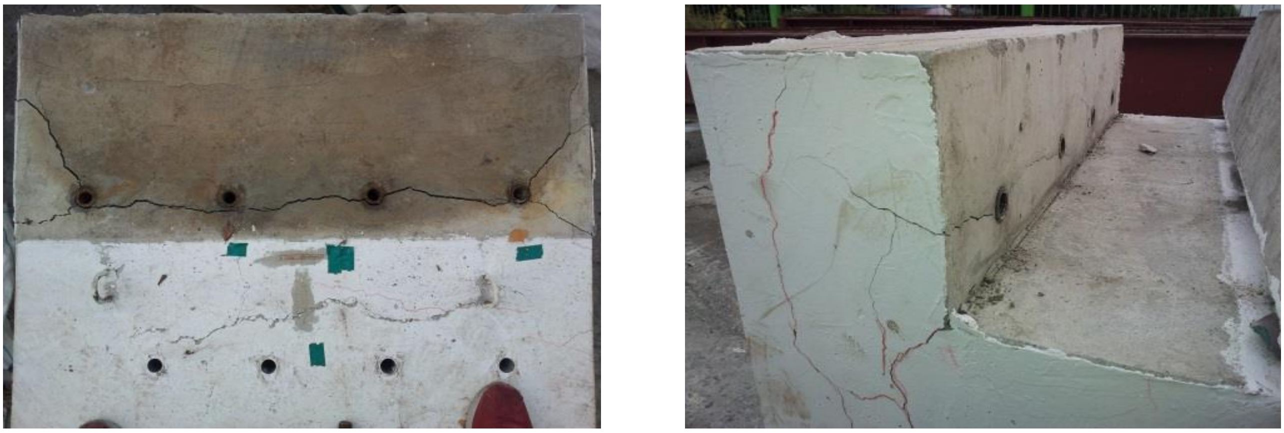
3.7. *Crack pattern*

The crack patterns observed in the static experiment of the concrete barrier are shown below. As indicated in Fig. 16, the ST and VC specimens yield almost similar crack patterns, whereby the initial crack occurs vertically from the endpoint of the barrier to the deck. As the applied load increases, the bending–shear cracks and the cracks at the front-side section begin to grow, the displacements and widths of the cracks increase, and a vertical crack pattern appears around the bolts that are fixed to the deck.

(a) ST specimen (b) VC specimen (c) HC specimen

Fig. 16 Crack patterns of specimens

For the HC specimens, the initial crack in the deck has a similar crack pattern, but as the loading increases, a separation between the connected surfaces occurs, and the distance between the connected surfaces continues to increase until the maximum load is reached. The crack patterns at the barrier could not be investigated. Vertical cracks are created at the intersection between the barrier and the deck's edge as the distance of the separation increases. Additionally, without increasing the load, the crack width increases with time. The barriers and decks of the VC and HC specimens were respectively separated to investigate the crack formation at the intersection between the deck and the barrier. Consequently, the embedded nuts prior to the deck casting are observed to be pulled out, thus suggesting that significant cracking occurred around the nuts. This is as shown in Fig. 17.



(a) VC connection (b) HC connection

Fig. 17 Crack patterns at the connected surface

4. Conclusions

This study proposed concrete barrier connection systems with the use of bolted connections on a modular bridge. To evaluate the structural performances of the connection systems, comparative static experiments were performed by producing the test specimens of the cast-in-place concrete barriers and modular barriers with varying vertical and horizontal bolted connections. The main conclusions from these experiments were as follows:

(1) Because of the integration with a vertical bolted connection, the VC specimens exhibited a load-carrying capacity of 75 kN on average, which is equal to 75–85% of that of the ST specimen. Thus, considering the economic advantages of labor-saving and duration shortening, the vertically connected barrier was found to be appropriate for a modular bridge connection system.

(2) Given that the main purpose of a bridge barrier is to prevent the overturning and falling of automobiles, the HC specimens yielded a load-carrying capacity of approximately 43.35 kN on average, which was less that of the standard specimen. It is thus inappropriate for use in the modular bridge connection system.

(3) Test specimens were separated to examine the crack patterns at the decks of the VC and HC specimens in which the nuts were embedded. There was almost no pull-out of the nuts, but significant cracking was observed around them. These findings suggested the necessity of using a reinforcing material to prevent the local failure around the nuts.

(4) Considering the barrier performance, it is necessary to prepare the standards for rating the modular barriers and improve the performance of the vertically connected barriers, as observed in this study, by conducting further research on the structural changes of the bolts.

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