Fifth International Conference on Construction in the 21st Century (CITC-V)
"Collaboration and Integration in Engineering, Management and Technology"
May 20-22, 2009, Istanbul, Turkey

A Revolutionary Concept in PSC Bridge Girder Design Having Holes in the Web

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Abstract
Prestressed concrete (PSC) I-type girders have been widely used at the superstructures of bridges due to the simple design and low maintenance cost. Nevertheless, the traditional I-type PSC girders are limited in their length due to allowables stress limitation in the member. In this study, two revolutionary concepts have been combined to make longer bridge spans possible upto about 70 meters; 1) A numerous number of holes was introduced at the web of girders. Some of the anchorage devices was moved into the holes, and the magnitude of negative moment developed at the girder ends was cut down and stress concentration was reduced. 2) Prestressing force was introduced through multistages. This concept of incremental prestressing overcomes the prestressing force limit restrained by the allowable stresses at each loading stage. A full scale 50 meter long girder was fabricated and tested. Test results showed that the Holed Web Prestressed Concrete (HWPC) girders had a great advantage against conventional I-type concrete girders for long span bridges.

Keywords
HWPC, Holed web girder, Incrementally prestressed concrete girder, PSC, Bridge girder

1. Introduction

PSC I-type girders are popular and typical for superstructures of bridges. The factor which determines the maximum girder length is the allowable stresses in concrete. Prestressing force which is large enough to compensate the total external loads can't be implemented in the girder at the beginning since tensile stresses which are larger than the allowable stress of concrete could be developed. It can be overcome using multistage prestressing. At the first stage, prestressing force is partially applied and compensates only self-weight of the girder and deck slab. After the deck slab was cured, the second prestressing force is applied to compensate the total design loads. This method will overcome prestressing force limit restrained by the allowable stresses at each loading stage (Han and Hwang, 2002; Han *et al.*, 2003).

Generally the prestressing force at the girder ends is unnecessary, and it only introduces high compressive stresses near the anchorage. After holes were made in the girder web, several anchoring devices were moved into the hole, and the magnitude of compressive stresses developed at the girder ends is reduced. In this way, several other advantages can be obtained. Not only thick end diaphragm can be removed from the girder ends, but also self-weight of the girder and wind load can be reduced. Also, girders are aesthetically more attractive too. Research about transverse openings in strcutrual members have not been observed except relatively small size holes for utility duct and pipes (Mansur *et al.,* 1999).

These two design concepts were combined together to form a whole new concept of HWPC (Holed Web Prestressed Concrete) girder.

2. Concept of HWPC Girders

A typical appearance of HWPC girders is given in Figure 1. Circular holes are inserted in the web except near the girder ends where prestressing tendons are closely spaced and stress concentration is high.

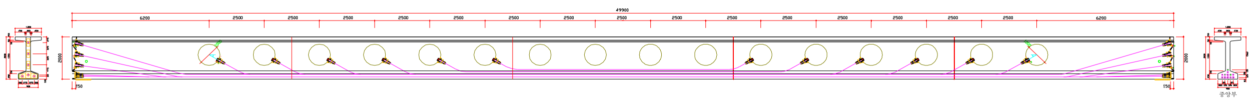

Figure 1: HWPC Girder Configuration

Half of the total anchorages were moved inside the hole as shown in Figure 1, and the other half was left at the ends. It reduces the amount of unnecessary negative moments developed near the ends, and consequently, the thickness of the web can be reduced down to the same thickness of the rest of the girder. It will also make the concrete formwork easier. The prestressing force introduced at anchorages at the hole is a little bit smaller than at ends, and exact values can be calculated based on allowable stressess developed in the member at different loading stages.

One important concept embedded in the HWPC girders is the multistep prestressing which can compensate and change the stress distribution of the girder at each loading stage (Han and Hwang, 2002; Han *et al.*, 2003). A significant reduction of girder height and the increase of girder length can be achieved by applying the prestress force incrementally according to the increase of load imposed on the girder. If two loading stages are used, the initial prestressing stage will balance the girder self-weight and fresh slab concrete weight and the second prestressing stage will compensate the additional dead and live loads. One important feature in the incrementally prestressing girder is its self strengthening function. The function will be useful when the girder is damaged, which is pretty rare. Another advantage will be the ease in the construction of continuous bridges. Because of the exposed anchoring system, inserting continuous tendons and prestressing specific tendons after the completion of slab construction will be very easy. Therefore, two or three span continuous girder bridges become much more economical than conventional continuous PSC girder bridges.

Figure 2 illustrates the stress distributions in the girder through the incremental prestressing procedure at different loading stages. Initial prestressing is applied when there exits only self-weight of the girder, and the stress distributions at this stage can be shown as line ①, and it becomes line ② when slab concrete is poured on the girder. Once the slab concrete has been hardened, girder and slab becomes a composite member. Additional prestressing will be applied after slab concrete hardens, then the stress distribution be changed. If additional dead and live loads are applied, top and bottom stresses becomes line ③. Line ④ shows the case when part of prestressing force is lost, and line ⑤ is for additional dead load, and line ⑥ is for entire long term loss of prestressing force. When live load is applied the distribution becomes line ⑦.

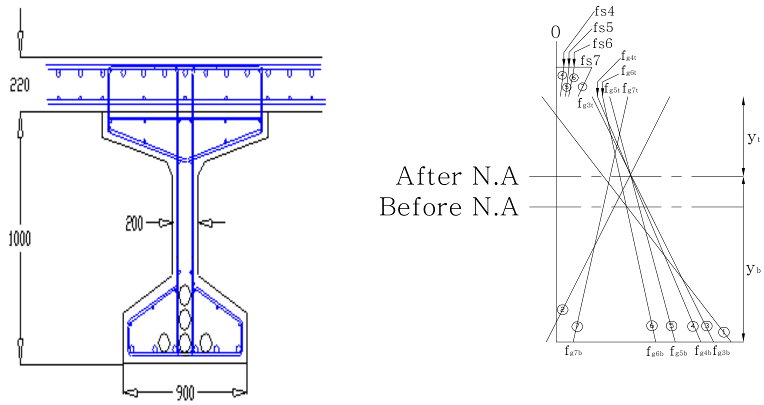

Figure 2: Stress Changes at Different Loading Stages (Han and Hwang, 2002)

Concrete girders based on incremental prestressing concept can be designed longer than other girders developed so far by 20-30%. They include NEBT (Richard and Puckett, 1997), PCI BT and ASHTO Ⅱ type, which are PSC girders developed by New England Highway Department, Prestressed Concrete Institute, and AASHTO, respectively (Alexander *et al*., 1997; PCI, 1995; Kathryn, 1992; Francis, 1991).

3. Full Scale Test of HWPC Girders

3.1 Girder Fabrication and Experimental Setup

A HWPC girder with the length of 50 meters was fabricated and tested (Figure 1). There were 18 holes equally spaced in the web, and center to center distance between two adjacent holes was 2.5meter. The diameter of the hole was 1meter. A hole was not made close to the girder ends since it was too close to the passage of tendons. Among 18 holes, 12 holes which locate outside of 6 middle holes had anchorages in them. Since the number of anchorages at girder ends was reduced, the web thickness at girder ends was the same as at the other portion of the girder, and it will simplify the formwork process. The compressive strengths of concrete for the girder and deck slab were 55MPa and 30MPa, respectively. Total weight of a girder was 850kN. Figure 3 shows reinforcement details.

For the prestressing, 1,765kN was applied for each anchorage located at girder ends, and 1,236kN was applied for each anchorage inside a hole. All those 6 anchorages at girder ends were used for the first stage prestressing, and the other 6 anchorages located inside holes were used for the second stage prestressing. Fabrication process can be viewed through Figure 4 to Figure 6.

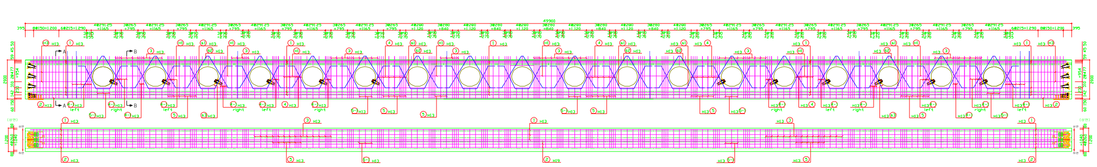

Figure 3: Reinforcing Details of the Girder

Figure 4: Reinforcement and Formwork

Figure 5: Demolding and First Stage Prestressing

Figure 6: Deck Slab Casting and Final Appearance

3.2 Loading Process and Results

Four point bending test was performed using two actuators placed at the center of the girder. Each of the actuators had the maximum load capacity of 2,000kN, and maximum stroke of 930mm. The center to center distance between two actuators was 5 meters. When load was applied up to certain level, shear cracks started to develop in the web, and as the load further increases numerous diagonal shear cracks were formed as shown in Figure 8. These shear cracks might have developed continuously and resulted in abrupt failure, but, due to an anchor problem happened at the strong floor during the test, load was not applied to the full capacity of the girder. Shear reinforcement for the current test girder was put based on regular girder design which does not have holes in order to examine the shear resistance of holed web girder. By adding more shear reinforcement, flexural failure can be ensured.

Figure 7: During Loading Process

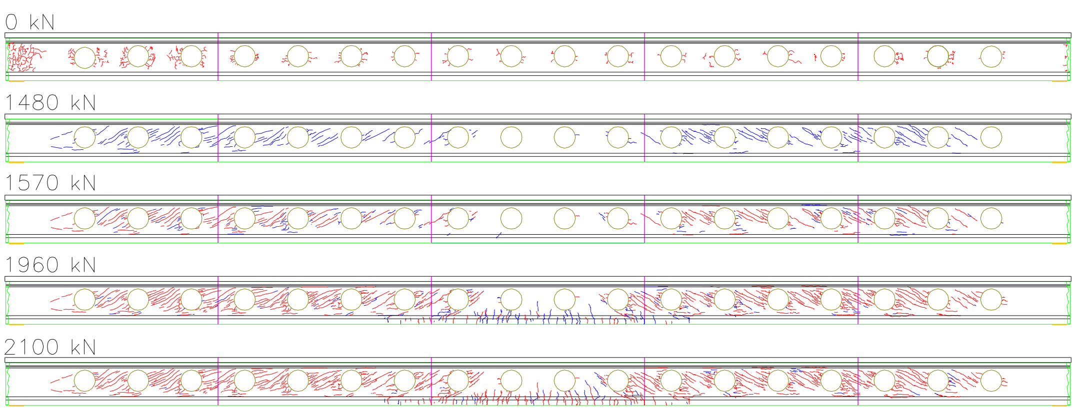

Figure 8: Crack Patterns Observed on the Girder Web

The load-deflection behavior of the girder is given in Figure 9. The magnitude of loads in Figure 9 was summed of those two values from each actuator. Figure 10 reveals the longitudinal strain distribution through the depth at the middle of the girder according to the increase of loads. In order to achieve the maximum flexural strength of 3,000kN obtained from analysis.

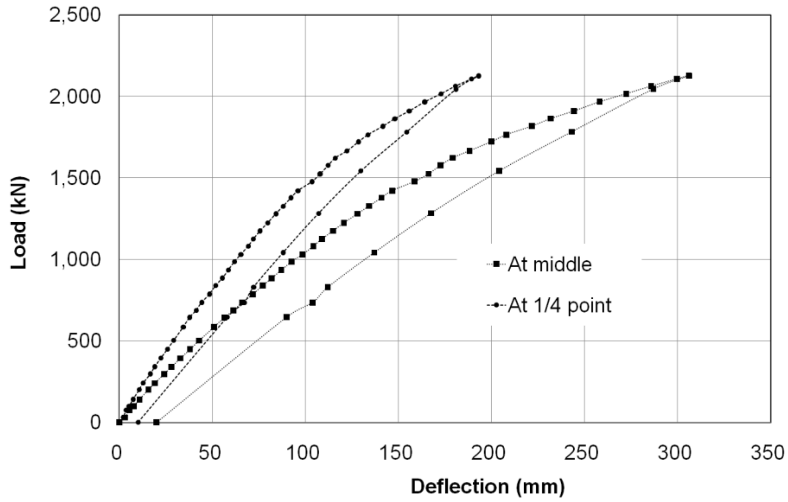

Figure 9: Load-Deflection Relation of the Girder

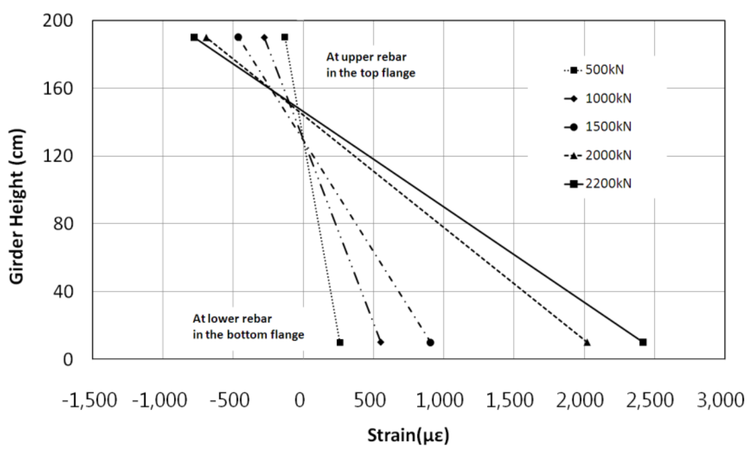

Figure 10: Change of Longitudinal Strains at the Middle of the Girder

Figure 11 shows the longitudinal strain development at the middle of the girder according to the loading stages. Figure 12 shows the longitudinal steel strains developed at different load levels measured from a point which locates 1m from the lower bottom of the bottom flange, and it can be seen, at about 160kN of load, that shear cracks developed significantly in the web at the quarter point of the girder.

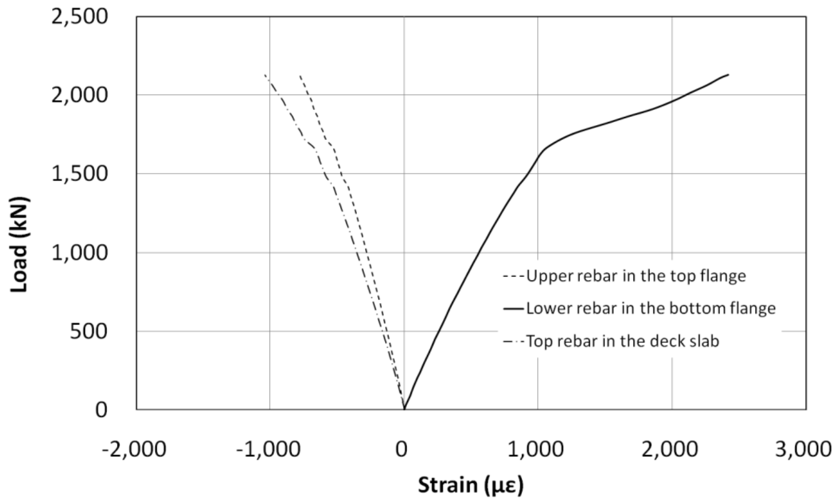

Figure 11: Longitudinal Steel Strains at the Middle of the Girder

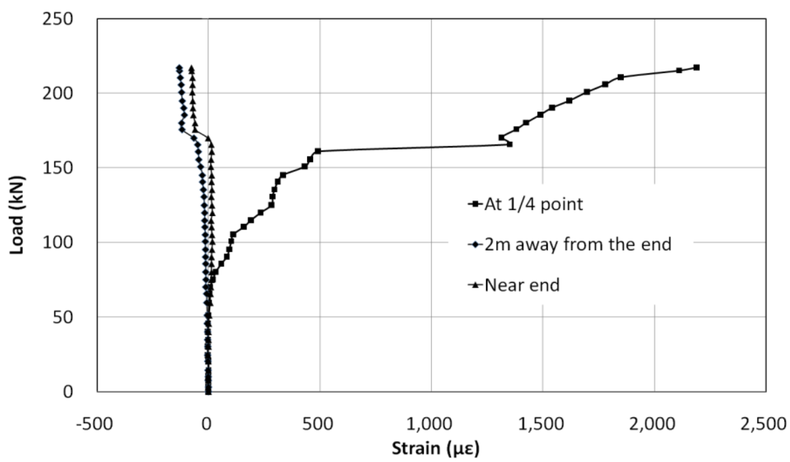

Figure 12: Shear Steel Strains at Different Locations

4. Conclusions

Holed web prestressed concrete (HWPC) girder is a revolutionary concept that has many advantages against a conventional I-type concrete girder. It will make longer spans possible for I-type concrete girders. Several conclusions are made from up to date experimental results.

1) Unified girder design concept that combines the holed web concept and incremental prestressing shows a very promising future.

2) Holed web concept makes it possible to reduce the number of anchorages at girder ends, and consequently, the thick end diaphragm can be removed too.

3) Incremental prestressing concept introduces only certain level of stresses in a member at each loading stage, and longer span length can be achieved with the same girder depth.

It has been planned to design more shear reinforcement in the web during the preparation of girders for the next upcoming experiment, and it will ensure ductile flexural failure.

5. Acknowledgments

This research was supported by a grant from Construction Technology Innovation Program (CTIP, 05' D02-01) funded by Ministry of Land, Transportation and Maritime Affairs (MLTM) of Korean government.

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