공학석사학위논문

Suggestion of Design Guideline for Joint in Hybrid Girder

하이브리드 거더 접합부의 설계 지침 제안

2018 년 2 월

서울대학교 대학원

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이 대 규

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Abstract

Suggestion of Design Guideline for Joint in Hybrid Girder

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Hybrid girder consists of steel girder and concrete girder connecting in longitudinal direction. Joint in hybrid girder, connecting steel girder and concrete girder, is composed of the steel plate, filling concrete and shear connector. Joint is critical part because stress concentration can occur the difference of stiffness between two materials. For this reason, it is needed to be careful when design of joint.

Currently there is no domestic design standard for design of joint in hybrid girder. The design standard about stud type shear connector for design of composite section combining steel girder and concrete slab is presented in Korean highway bridge design code, but the applicability of this standard for design of joint is not verified. In this thesis, finite element analysis and experimental test were conducted for suggestion of design guideline for joint in hybrid girder.

Finite element model was developed using interface element to consider slip behavior in tangential direction at the interface between steel and concrete.

Slip behavior should be considered because partial composite behavior was able to occur due to flexural deformation of stud. Target structure was selected which used in previous study conducted by other researcher. As a result of simple verification, the developed model was proper to simulate all types of composite behavior – non composite behavior, partial composite behavior and full composite behavior – just changing material properties of interface element.

Total three specimens were fabricated and experimental test was conducted to find the relation between the number of stud and type of composite behavior. As experimental results, the specimen using the number of stud followed Korean highway bridge design code was shown full composite behavior and the other specimens which using less number of stud was shown non composite behavior. As a result, the design standard about stud in Korean highway bridge design code was applicable to design of joint in hybrid girder.

Parametric study was conducted to find the effect of joint length. Equal total length and steel girder length were used in all analysis case. If the joint length was increased, PSC girder length was decreased. Therefore, the stiffness of structure was increased and finally the maximum load of hybrid girder was also increased. In order to exclude the effect of stiffness, the effect of joint length was calculated by the difference of maximum load increment between full composite behavior and non composite behavior. The results of parametric study showed that the effect of joint length was insignificant, less than about 1.5 % of maximum load.

Keywords: Hybrid girder, Joint, Finite element analysis, Interface element, Parametric study

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1. Introduction

1.1. Research Background

Hybrid girder consists of steel girder and concrete girder connecting in longitudinal direction. When applying hybrid girder to bridge design, in general, steel girder is adopted at main span and RC or PSC girder is adopted at side span. As a result, it is possible to extend the main span length by decreased dead load of main span compared to concrete bridge, and has economic advantages due to reduce the cost and term of construction. In addition, negative reaction can be minimized which occur at support caused by weight difference between main span and side span. Fig. 1.1(b) shows the advantages of bridge adopting hybrid girder.

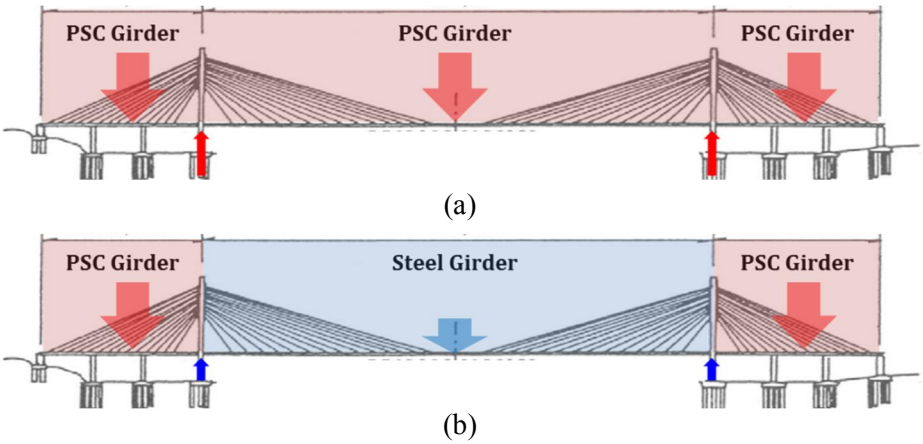


Figure 1.1 Advantages of bridge adopting hybrid girder

Cable-stayed bridges adopting hybrid girder have been constructed since 1970's in Europe and after 2000's in Korea.

Table 1.1 Construction cases of bridge adopting hybrid girder

Bridge	Country	Year
Kurt-Schumacher bridge	Germany	1972
Bybrua bridge	Norway	1978
Flehe bridge	Germany	1979
Iguchi bridge	Japan	1990
Normandie bridge	France	1995
Sun-marine bridge	Japan	1996
Tatara bridge	Japan	1999
Ibi-gawa bridge	Japan	2002
Kiso-gawa bridge	Japan	2002
Cheongpoong bridge	Korea	2010
Kimsimin bridge	Korea	2013
Worldcup bridge	Korea	2020 (under construction)

Figure 1.2 Cheongpoong bridge, Korea

The critical part of hybrid girder is joint which connecting steel girder and concrete girder. In general, joint is composed of the steel plate which encased the joint, filling concrete which filled the inner of joint, and shear connector connecting these parts. It should be careful to design of joint because stress concentration can occur at the joint due to the difference of stiffness between two materials. However, proper design standard for joint in hybrid girder was not implemented. Guideline for spacing and number of stud type shear connector are provided in Korean highway bridge design codes. But it is only applicable to composite section composed of steel girder and concrete slab for composite behavior. Therefore, it should be verified to apply these standard for design of joint.

1.2. Research Objectives

The final goal of this study is to suggest the design guideline for joint in hybrid girder. For this goal, research objectives are defined.

The first is developing finite element model which can simulate the behavior of joint in hybrid girder properly.

Next is fabricating specimen and conducting experimental test to verify the developed model and to find the relation between the number of stud and the behavior of hybrid girder.

The last is conducting parametric study to find the relation between the joint length and the behavior of hybrid girder.

1.3. Outline

Chapter 1 indicates the introduction such as background, objectives and outline of this research.

Chapter 2 presents the basic concept of joint design and literature reviews of previous studies.

In chapter 3, finite element model is developed which simulate the behavior of hybrid girder properly. And the validation of model is confirmed through simple verification.

In chapter 4, experiment is conducted to find the relation between the number of stud and type of composite behavior. Test variable is selected the number of stud.

In chapter 5, parametric study for joint length is conducted. The effect of joint length is investigated from the analysis results.

In chapter 6, conclusions of this study are summarized.

2. Literature Review

Currently proper domestic design standard for design of joint in hybrid girder was not implemented. In this chapter, design standard about stud was presented which applicable to composite section in Korean highway bridge design code. And design procedure of joint using stud was described. In addition, previous studies about joint of hybrid girder were presented.

2.1. Design of Joint in Hybrid Girder

2.1.1. Korean highway bridge design code (2010) (Korea)

The maximum spacing between center to center of studs is presented 3 times the thickness of concrete slab or 600 mm. The minimum spacing between center to center of studs is presented 5 times the diameter of stud or 100 mm in longitudinal direction, and the diameter of stud + 30 mm in transverse direction. The minimum clear distance between the end of flange and the stud is presented 25 mm.

The allowable stress of stud is calculated by Eq. 2.1, neglecting the adhesion between concrete slab and flange of steel girder.

$$\begin{aligned} Q_a &= 9.5d^2\sqrt{f_{ck}} \ (H/d \geq 5.5) \\ Q_a &= 1.74dH\sqrt{f_{ck}} \ (H/d < 5.5) \end{aligned} \tag{2.1}$$

where,

Q_a : allowable shear force of stud (N)

H : total height of stud (150 mm is standard)

d : diameter of stud (19 mm / 22 mm / 25 mm)

f_{ck} : specified compressive strength of concrete (MPa)

2.1.2. Design of joint using prestressing tendon

The basic concept for design of joint is making resistance force larger than the maximum load applying on the joint. Axial force, shear force and bending moment should be transferred smoothly at the joint. In this case, the joint should be designed to resist bending moment under the compressive force including prestress, rather than the axial force. In compression side, stress is directly transferred to the interface between the end of steel girder and concrete. Therefore, strain and stress distribution in the section caused by compressive force or bending moment are assumed in Fig. 2.1, considering this part as RC beam. At this time, the resistance of bending moment is calculated by Eq. 2.2.

$$M_u = T_p(\mathrm{d_p} - \mathrm{y_c}) + \mathrm{C}(\mathrm{y_c} - 0.4\,\mathrm{x}) \qquad (2.2)$$

where,

T_p : axial force at pressing tendon caused by flexural moment

C : resultant force of compression at concrete

$\mathrm{y_c}$: center of the section

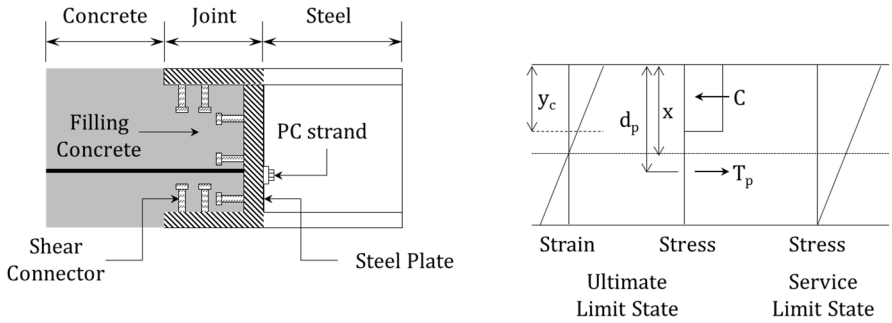


Figure 2.1 Design of joint using prestressing tendon

2.1.3. Design of joint using stud type shear connector

In case of using stud type shear connectors to resist bending moment as seen Fig. 2.2, compressive force and tensile force caused by bending moment are transferred through the stud type shear connectors. In this case, required number of stud type shear connector is calculated by Eq 2.3.

$$M_u = Th = nQ_a h \tag{2.3}$$

where,

T : shear force applied on the stud type shear connector

h : center-to-center distance of stud type shear connectors

n : the number of studs placed at upper or lower steel plate

Q_a : allowable shear force of stud

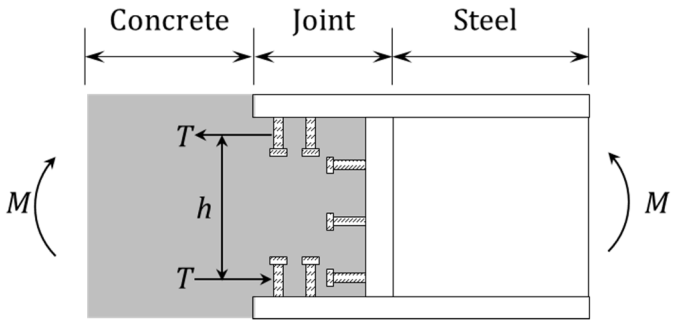


Figure 2.2 Design of joint using stud type shear connector

2.2. Previous Studies

2.2.1. Kim, Kwang-Soo et al (2008)

Kim, Kwang-Soo et al (2008) performed to evaluate joint behavior of prestressed concrete-steel mixed girders throught the flexural test of 14 beams according to embedded length, amount of reinforcing steel, stud arrangement, and prestressing force. From the test results, Prestressing force was more effective ton performance of connection than stud arrangement and reinforcing steel. And the spacing of stud is also more effective than embedding length.

In addition, 3D nonlinear analysis was conducted considering the slip of composite. By changing the slip modulus, As the nonlinear analysis results, the behavior of hybrid girders could be categorized as non composite, partial composite and full composite behavior. As the experimental results, PSC-steel hybrid girders with shear connectors was shown partial composite behavior in ultimate load stage.

2.2.2. Kim, Sang-Hyo et al (2011)

Kim, Sang-Hyo et al (2011) determined and proposed a suitable joint type for spliced hybrid I-girder bridges consisting of steel girders at the mid span and PSC girders at the supports. In order to improve the performance of joint in hybrid girder, seven small scaled steel-PSC hybrid beams with shear stud connector or perfobond rib were fabricated and experimentally tested.

Both the stud type joint with sufficient reinforcement and the proposed joint design are certifiably suitable offering good performance in transferring each member force to the other components, having sufficient strength and stiffness to induce the failure of the PSC section without itself failing.

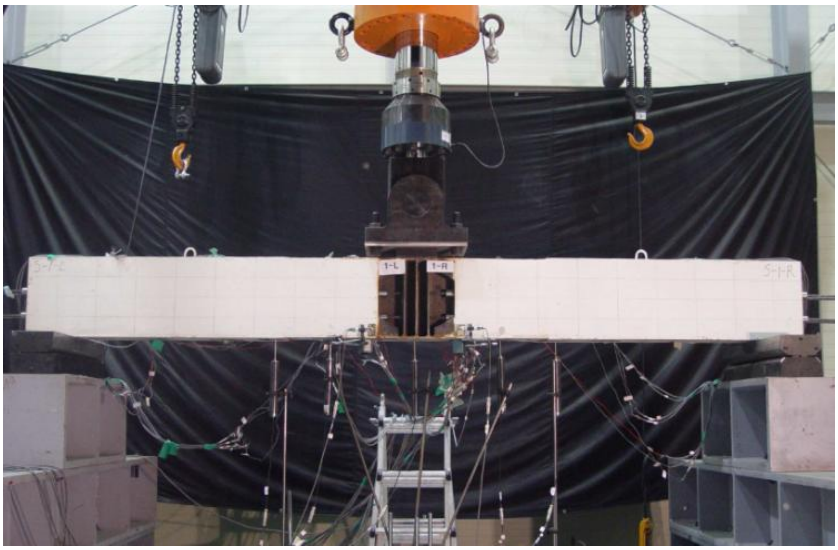


Figure 2.3 Test girders in Kim, Sang-Hyo et al.(2011)

2.2.3. Park, Bong-Sik (2016)

Park, Bong-Sik (2016) conducted parametric study for design of hybrid girder joint. Finite element model was developed based on the girder experimented by other researcher. Parameters were spacing between stud type shear connector, joint length, number of stud type shear connector and area of prestressing tendon.

As results of parametric study, the spacing between stud type shear connector and the area of prestressing tendon were insignificant factors, and joint length and the number of stud type shear connector had influence on joint performance. Generally the longer joint length, the larger maximum load is. If the number of stud type shear connector was larger than specific number, the behavior of hybrid girder had little difference. From the results of parametric study, the required minimum number of stud type shear connectors for composite behavior of PSC girder and steel girder was when spacing between stud type shear connectors was same with height of girder section.

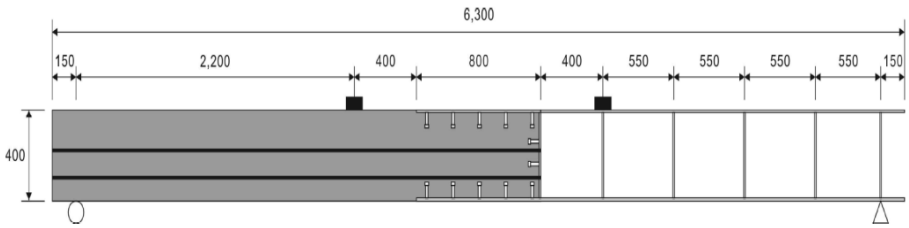


Figure 2.4 Target structure of finite element model in Park, Bong-Sik. (2016)

2.2.4. Limitations of previous studies

In experimental researches about hybrid girder, specimens which had various factors were selected and conducted experimental test. But the number of specimens for comparing the effect of each factor was insufficient. Therefore, it was difficult to find the relation between the factors and the behavior of hybrid girder.

In research of parametric study, the behavior of slip which occur at interface between steel and concrete was not considered. So the result of finite element analysis was inappropriate to simulate the behavior of hybrid which had different type of composite behavior caused by using different number of stud type shear connectors placed at joint.

In order to overcome above limitations, investigation of the relation between the components composing joint and the behavior of hybrid girder was needed. In this study, finite element model considering slip behavior was developed. And relation between the number of stud and type of behavior was investigated through experimental test. Finally parametric study to find the effect of joint length was conducted.

3. Development of Finite Element Model using Interface Element

In this chapter, finite element model was developed to simulate the behavior of joint in hybrid girder using the commercial finite element program DIANA. Analysis model was developed based on the model used in previous study by Park (2016). In general, partial composite behavior occurred at the interface between steel and concrete interface due to flexural deformation of shear connectors. In order to consider the behavior of slip occurred at the interface, interface element was used.

3.1. Interface Element

3.1.1. General

Interface element describes the interface behavior in terms of a relation between the normal and shear tractions and the normal and shear relative displacements across the interface. In the interface element, normal and tangential stiffness are used for describing the interface behavior in normal and tangential direction. The relation of tractions, relative displacements and stiffnesses is calculated by Eq. 3.1.

$$\begin{pmatrix} \Delta t_n \\ \Delta t_t \end{pmatrix} = \begin{bmatrix} K_n & 0 \\ 0 & K_t \end{bmatrix} \begin{pmatrix} \Delta u_n \\ \Delta u_t \end{pmatrix} \tag{3.1}$$

where,

Δt : traction (n : normal, t : tangential) (MPa)

Δt_t : shear traction (MPa)

K_n : normal stiffness (MPa/mm)

K_t : tangential stiffness (MPa/mm)

Δu_n : normal relative displacement (mm)

Δu_t : shear relative displacement (mm)

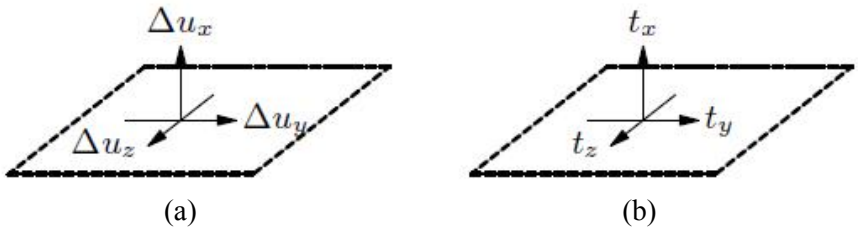


Figure 3.1 Variables of interface: (a) relative displacements; and (b) tractions

3.1.2. Slip properties

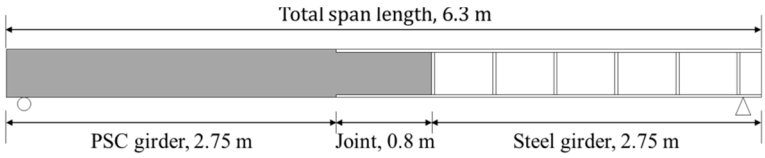
Slip at the interface between steel and concrete occurs in tangential direction. Therefore, tangential stiffness is significant factor to simulate the slip behavior. Jeong et al. (2002) conducted sensitivity analysis to find the relation between the slip properties and type of composite behavior, which was categorized non-, partial- and full-composite behavior and suggested critical values of tangential stiffness at each type of composite behavior. As a result, non composite behavior was shown when using $K_t \leq 10^{-1}$ MPa/mm, partial composite behavior was shown when using $10^{-1} < K_t < 10^{3}$ MPa/mm, and full composite behavior was shown when using $K_t \geq 10^{3}$ MPa/mm. In

this study, these critical values were applied to the slip properties at the interface element.

3.2. Finite Element Model

3.2.1. Geometry of target structure

A half of the girder was modelled because it had a symmetry section. Geometry of the hybrid girder for finite element analysis was shown in Fig. 3.2. The total length of the girder was 6,300 mm (clear span 6,000 mm) including the PSC girder of 2,750 mm at left side, steel girder of 2,750 mm at right side and joint of 800 mm at the center of the girder. The PSC girder had rectangular section which dimension was 200 mm width and 400 mm height. Reinforcing bars of 10 mm diameter were used in the longitudinal direction, and 16 mm diameter were used in the transverse direction for resisting shear force. The steel girder had I-shape section with 200 mm width and 400 mm height. PSC girder was prestressed using four prestressing tendons. One tendon was a single strand of SWPC 7B, 12.7 mm. The diameter of a stud was 16 mm and the height is 70 mm.



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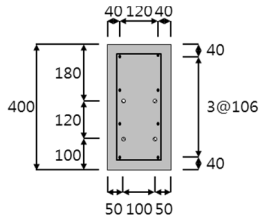

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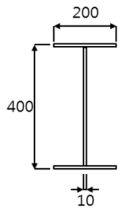

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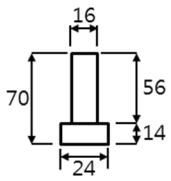


(d)

Figure 3.2 Geomerty of hybrid girder for finite element analysis: (a) Girder elevation; (b) PSC section; (c) Steel section; and (d) Stud type shear connector

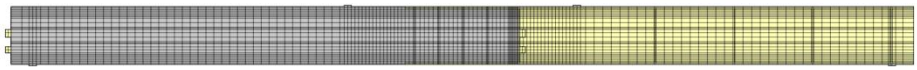
3.2.2. Finite element type and mesh

Finite element model of hybrid girder consists of seven components. They are the concrete, structural steel, stud, reinforcing bar, prestressing tendon, anchorage of tendon and interface.

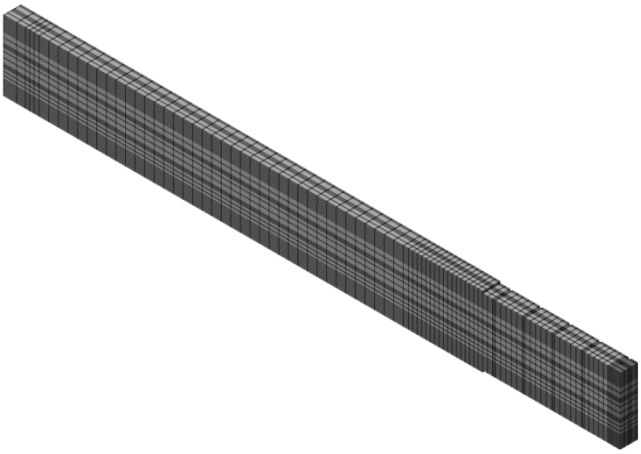
The concrete, structural steel, stud and anchorage of tendon were meshed with solid element HX24L available in DIANA. This element is an eight-node isoparametric solid brick element. It is based on linear interpolation and Gauss integration.

The reinforcing bar was meshed with embedded element. This element is embedded in structural elements, the so-called mother elements. Embedded element does not have degrees of freedom of their own. Instead, the strains in the embedded element are computed from the displacement field of the mother element. This implies perfect bond between the embedded element and the mother element.

Prestressing steel was meshed with L2TRU truss element to apply the prestress. And interface was meshed by Q24IF element between two planes in a three-dimensional configuration. The interface element is based on linear interpolation.



(a)



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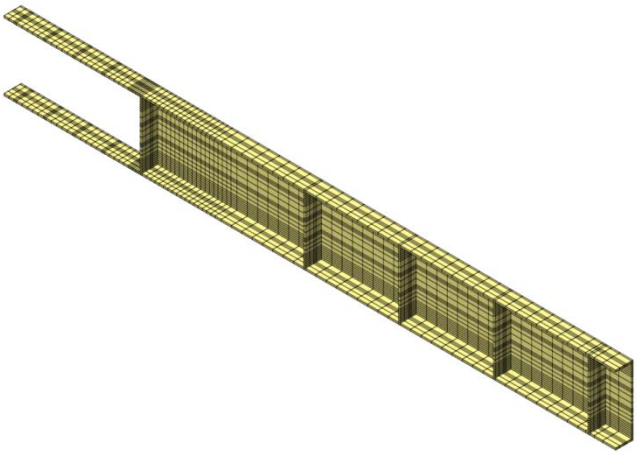

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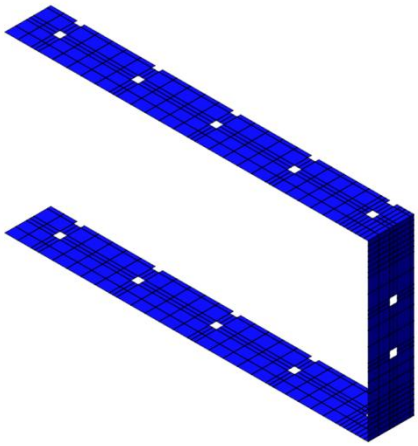


(d)

Figure 3.3 Generated meshes of the girder: (a) Half of the girder; (b) PSC Girder; (c) Steel girder; and (d) Interface between steel and concrete

3.2.3. Material models and properties

3.2.3.1. Concrete

Total strain crack model was used as concrete material model. As shown in Fig. 3.4, parabolic compression curve based on fracture energy was used as compressive behavior of concrete, and linear tension softening curve based on ultimate tensile strain was used as tension behavior of concrete. Tensile strength, elastic modulus, compressive fracture energy of concrete were calculated by Eq 3.2 in CEB-FIP Model Code 1990. Nakamura and Higai (2001) suggested that compressive fracture energy of concrete was 250 times tensile fracture energy. The concrete material properties were shown in Table 3.1.

$$f_{ctm} = f_{ctk0,m}\left(\frac{f_{ck}}{f_{ck0}}\right)_{2/3}$$
$$G_f = G_{f0}\left(\frac{f_{cm}}{f_{cm0}}\right)^{0.7} \qquad (3.2)$$

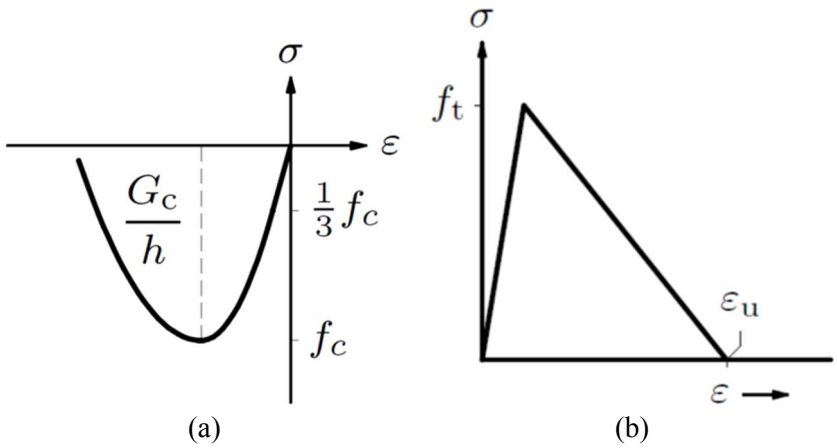


Figure 3.4 Material model for concrete: (a) Parabolic compression curve; and (b) Linear tension softening curve.

Table 3.1 Concrete material properties

Properties	Value
Compressive Strength (f_{ck})	50 MPa
Tensile Strength (f_t)	4.1 MPa
Elastic Modulus (E_c)	31,314 MPa
Compressive Fracture Energy (G_c)	40 N/mm
Ultimate Tensile Strain (ε_u)	0.0017

3.2.3.2. Steel, reinforcing bar, stud and tendon

Elasto-plastic idealized curve was used as stress-strain relation of structural steel, reinforcing bar, stud and prestressing tendon as shown in Fig. 3.5. The mechanical behavior both tension and compression was assumed to be same. Material properties of steel, reinforcing bar, stud and tendon were shown in Table 3.2.

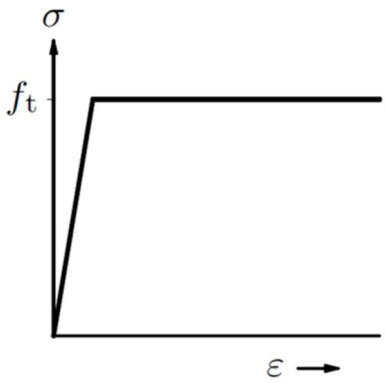


Figure 3.5 Idealized stress-strain relation

Table 3.2 Material properties of steel, reinforcing bar, stud and tendon

Material	Properties	Value
Structural Steel	Yield Strength (f_y)	400 MPa
	Elastic Modulus (E_c)	210,000 MPa
Reinforcing Bar and Stud	Yield Strength (f_y)	400 MPa
	Elastic Modulus (E_c)	200,000 MPa
Prestressing Tendon	Yield Strength (f_y)	1,580 MPa
	Elastic Modulus (E_c)	200,000 MPa

3.3.2.3. Interface

In order to simulate interface behavior, linear elasticity model was used. In case of using interface element, normal stiffness is assumed linear curve and tangential stiffness is assumed nonlinear function in general. In this finite element model, however, relative displacement occurred at the interface was restricted by stud, steel plate and prestressing tendon. Therefore tangential stiffness was also assumed linear curve.

Normal stiffness (K_n) was 10^5 MPa/mm in this analysis. It was determined the intermediate value of two materials to prevent the penetration occurred at the interface between concrete and steel elements. In order to simulate non composite behavior and full composite behavior, tangential stiffness (K_t) was 10^{-1} MPa/mm and 10^5 MPa/mm at each case. These values were the critical values suggested by Jeong et al. (2002).

3.2.4. Constraint conditions

Excepting the elements between structural steel and concrete, all components were assumed to be fully bonded through merging their nodes. The nodes between structural steel concrete elements were not merged but sharing position, and slip interaction was applied at the interface between structural steel and concrete using interface element.

3.2.5. Boundary conditions

The hybrid girder was simply supported in the analysis. The support at steel girder was restricted the translational displacement in longitudinal, transverse and normal direction to apply fixed end boundary condition. And the support at PSC girder was restricted the translational displacement in transverse and normal direction to apply roller end boundary condition.

3.2.6. Loading conditions

In this analysis, displacement control under four point loading was applied. Loading points were placed at 800 mm apart from the center of the joint. Loading plates, which have same material properties as structural steel, were generated at these points to prevent local failure.

3.3. Simple Verification

3.3.1. Comparison model for verification

It was necessary to verify whether the developed finite element model using interface element was able to simulate non composite behavior and full composite behavior. To do this, the comparison models for verification were determined as follows. Equivalent material models, material properties, boundary conditions and loading conditions were applied at each model.

3.3.1.1. Park (2016) model

Comparison model to verify the non composite behavior was the finite element model used in previous study by Park (2016). Park (2016) model was neglected the slip properties at the interface between steel and concrete. Therefore, the analysis result of Park (2016) model was shown non composite behavior.

3.3.1.2. Merging Nodes model

Comparison model to verify the full composite behavior was Merging Nodes model. The nodes between structural steel and concrete were merged in this model. Therefore, the analysis result of Merging Nodes model was shown full composite behavior.

3.3.2. Analysis results

Interface_Non model means the analysis result of developed model applied K_t=10^{-1} MPa/mm of tangential stiffness to simulate non composite

behavior, and Interface_Full means the analysis result of developed model applied K_t=10^3 MPa/mm of tangential stiffness to simulate full composite behavior. Load-deflection relationships of each analysis model were shown in Fig. 3.5. and maximum loads of each analysis model were listed in Table 3.3. As seen in the figure, load-deflection relationships and maximum load of Interface_Non model and Park (2016) model were almost same. And load-deflection relationships and maximum load of Interface_Full model and Merging Nodes model were almost same. From these analysis results, developed finite element model using interface element was good to simulate all types of composite behavior. And the critical values of tangential stiffness suggested by Jeong et al. (2002) were applicable to simulate non composite and full composite behavior in this analysis model.

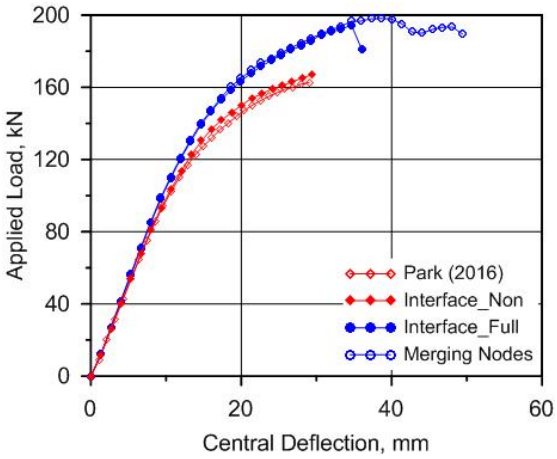


Figure 3.6 Load-deflection relationships of each analysis model

Table 3.3 Maximum load of each analysis model

Analysis Model	Maximum Load (kN)
Park (2016)	163
Interface_Non	167
Interface_Full	195
Merging Nodes	198

3.4. Conclusion

In this chapter, finite element model was developed to simulate the behavior of joint in hybrid girder. In order to consider the slip properties, interface element was used. And critical values suggested by Jeong (2002) was applied to tangential stiffness of interface element to simulate non composite behavior and full composite behavior. As a result, developed model was proper to simulate all types of composite behavior. And critical values were applicable to simulate each type of composite behavior in this analysis.

4. Experimental Verification

In this chapter, experimental test was conducted to find the relation between number of stud and type of composite behavior. In order to verify the test results, finite element analysis based on developed model was also conducted.

4.1. Experimental Program

4.1.1 Test specimens

Equal target structure was used in finite element analysis and experimental test. Therefore, geometry of specimens was same as finite element model in previous chapter. Total three specimens were fabricated, which have different number of stud placed at joint. The number of stud placed at joint was 6, 9 and 15 EA. Details of the arrangement of reinforcement and prestressing tendon were shown in Fig. 4.1.

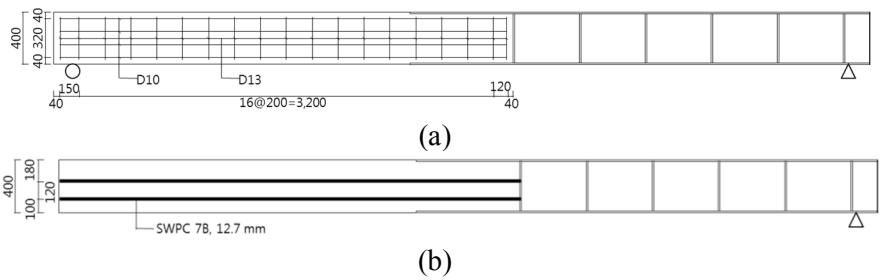


Figure 4.1 Details of the beam specimen: (a) Reinforcement; and (b) Prestressing tendon

15 EA stud was calculated using the design service moment of hybrid girder and allowable stress of stud. The design service moment(M) at joint was determined 61 kN-m, and center-to-center distance of stud(h) was 0.31 m. From Fig. 4.2, shear force(T) applied on the stud was calculated 197 kN. Meanwhile, total height of stud was 70 mm and diameter of stud was 16 mm. So allowable stress of stud was calculated 13.8 kN/EA in Eq. 4.1. As a result, the required number of stud calculated was 15 EA in Eq. 4.2. 9 EA stud was the result of design suggestion proposed by Park (2016). And 6 EA stud was determined to show the non composite behavior. The number and spacing of stud in longitudinal and tangential direction at each specimen was shown in Table 4.1 and Fig. 4.3.

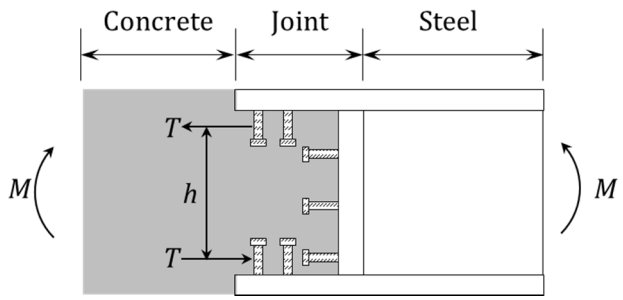


Figure 4.2 Design of joint using stud type shear connector

$$Q_a = 9.5d^2\sqrt{f_{ck}} \ (H/d \geq 5.5)$$
$$Q_a = 1.74dH\sqrt{f_{ck}} \ (H/d < 5.5) \qquad (4.1)$$

where,

Q_a : allowable shear force of stud (N)

H : total height of stud (150 mm is standard)

d : diameter of stud (19 mm / 22 mm / 25 mm)

f_{ck} : specified compressive strength of concrete (MPa)

$$M_u = Th = nQ_a h \tag{4.2}$$

where,

T : shear force applied on the stud type shear connector

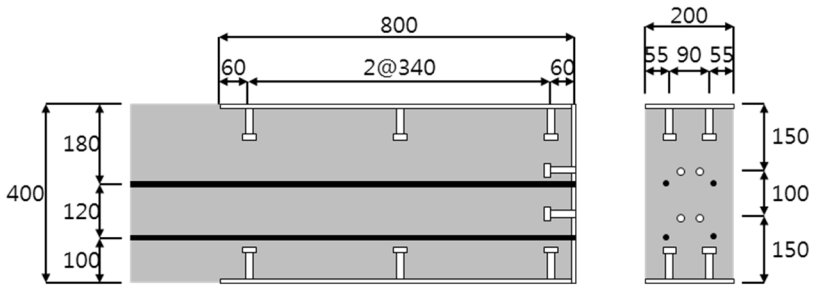
h : center-to-center distance of stud type shear connectors

n : the number of studs placed at upper or lower steel plate

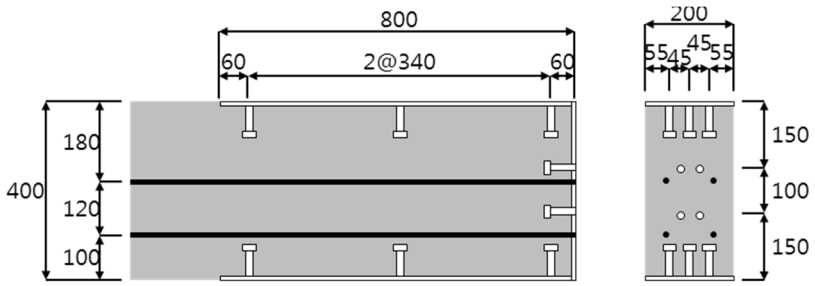
Q_a : allowable shear force of stud

Table 4.1 Arrangement of studs at each specimen

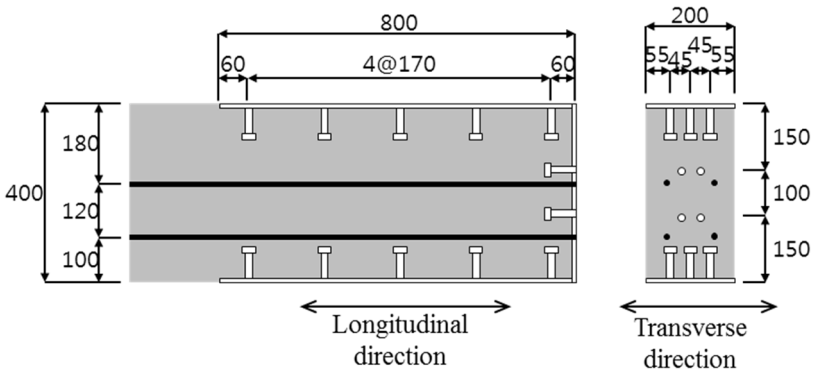
Total Number of Stud (EA)	Longitudinal Direction		Transverse Direction	
	Number (EA)	Spacing (mm)	Number (EA)	Spacing (mm)
6	3	340	2	90
9	3	340	3	45
15	5	170	3	45



(a)



(b)



(c)

Figure 4.3 Arrangement of studs at each specimen: (a) 6 EA stud specimen; (b) 9 EA stud specimen; and (c) 15 EA stud specimen

4.1.2. Material properties

The design compressive strength of concrete was 50 MPa and the cylinder test results was shown 51 MPa on the day of testing. For the steel and connectors, SS400 structural steel was used. The allowable stress was 140 MPa and nominal yield strength was 240 MPa. SD 400 bar was used as reinforcement. The yield strength was 400 MPa. And ultimate strength of the prestressing tendon was 1,860 MPa.

4.1.3. Test set-up

The test condition of girder selected was that of simply supported beam under four point loading. Two loading points were placed at 800 mm apart from the center of the joint. The load was applied with displacement control using hydraulic actuator of 5,000 kN capacity. Test set-up was shown in Fig. 4.4.

Nine LVDT were installed to measure the displacements at various positions between loading points. The positions of LVDT were shown in Fig. 4.5.

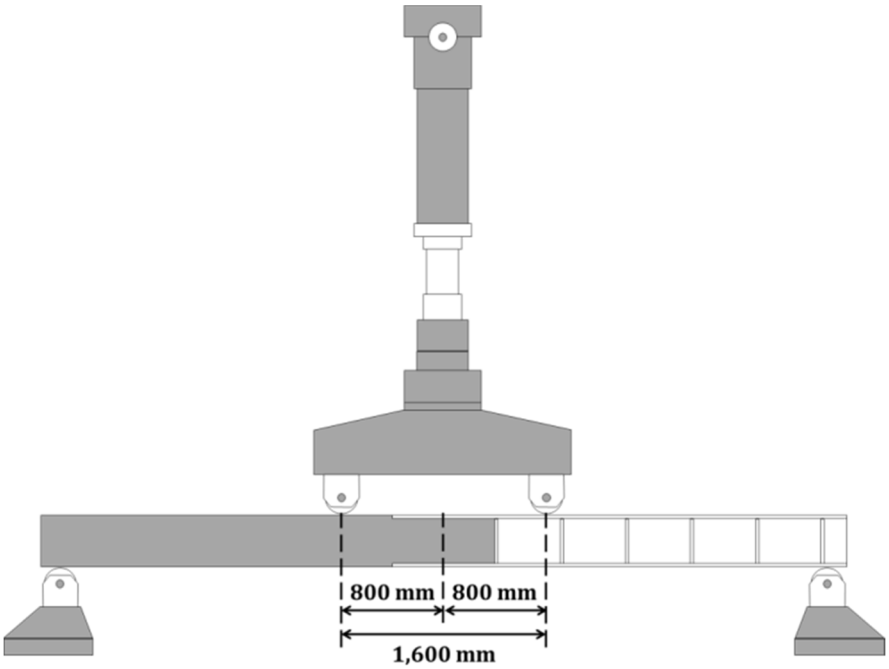


Figure 4.4 Test set-up of experiment

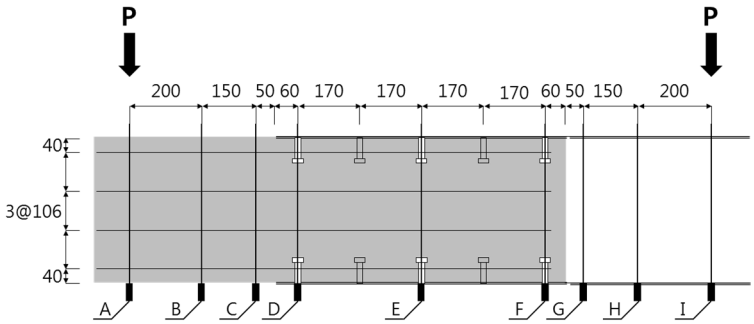
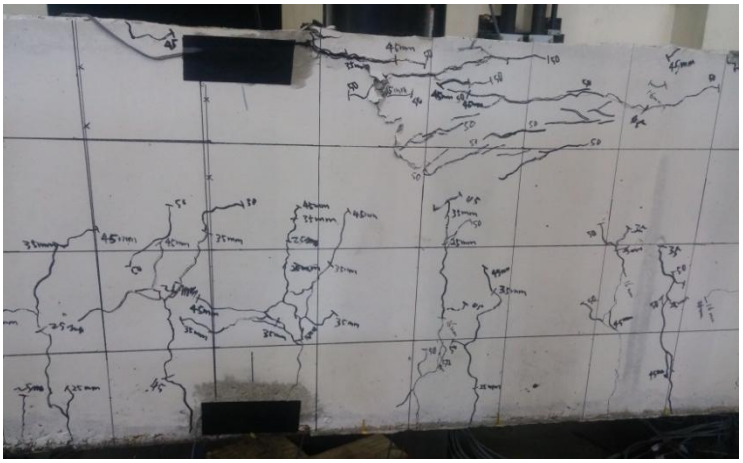


Figure 4.5 Measurement positions

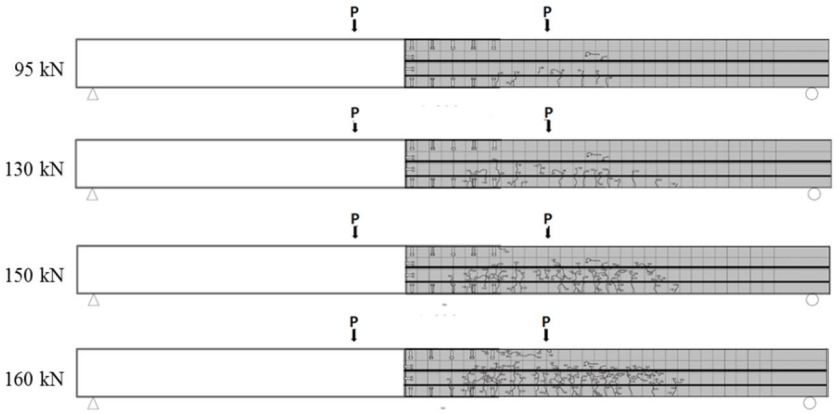
4.2 Test Result

4.2.1. Failure mode and crack pattern

The load was increased up until reaching the maximum load of the beam specimens. The failure mode and crack patterns were plotted in Fig 4.6. Initial crack occurred at the lower part of joint near the PSC girder, where the stud was placed. The cracking loads for all of the specimens were determined to be approximately 70 kN. After that, the flexural cracks were propagated to the upper part of the section. In addition, compressive failure of concrete occurred at the top of the PSC close to the joint.



(a)



(b)

Figure 4.6 Experimental results: (a) Failure mode; and (b) Crack pattern of 15 EA stud specimen

4.2.2. Measurement position-deflection relationship

Deflection at each measurement position in applied load were shown in Fig. 4.7. For typical RC girder, the maximum deflection occurred at the center of beam. But in hybrid girder, the maximum deflection occurred at the joint near the PSC girder, and different deflection occurred at two loading points. The reason of asymmetric deflection was the difference of stiffness between steel and PSC girder.

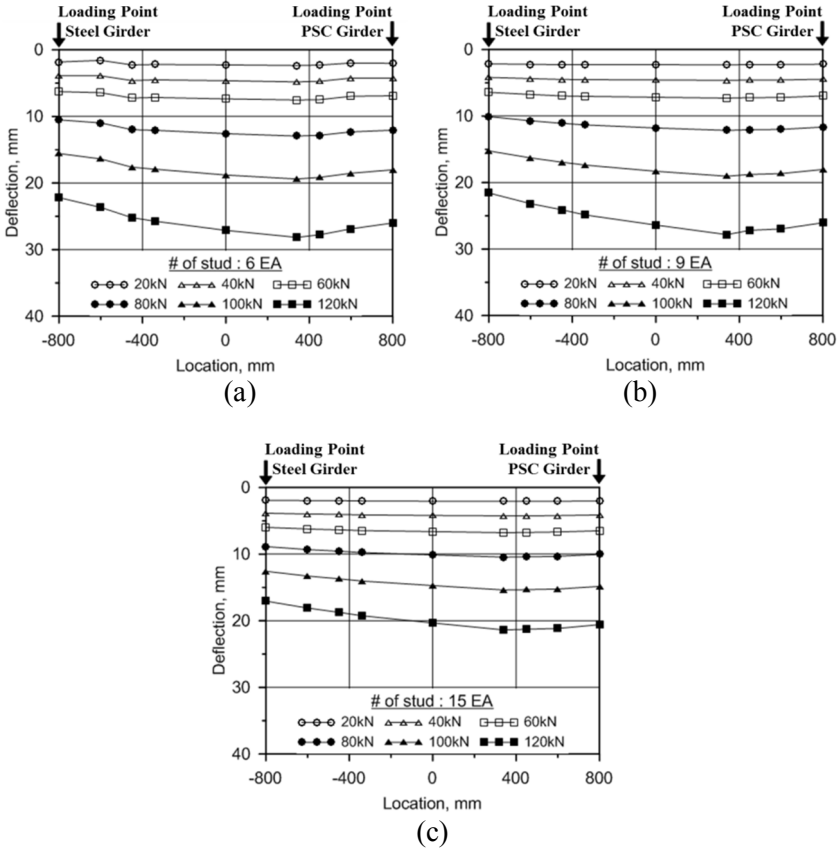


Figure 4.7 Deflection of mesurement points: (a) 6 EA stud specimen; (b) 9 EA stud specimen; and (c) 15 EA stud specimen

4.2.3. Load-deflection relationship

Load-deflection relationships of each specimen were shown in Fig. 4.8. Deflection at the center of the girder was used for load-deflection relationship. As the loads increase, the initial response was shown the linear relationship and all of the specimens had similar curves up to the load of 70 kN, at which initial crack was appeared. After the first crack initiated, the nonlinear behavior was shown and the load-deflection curves of 15 EA stud specimen become distinguishable to 6 and 9 EA stud specimens. The maximum load of 6, 9 and 15 EA stud specimen was 138 kN, 136 kN and 162 kN at each. From the experimental results, the 15 EA stud specimen, which using the number of stud in joint followed Korean highway bridge design code, had larger maximum load than the other specimens.

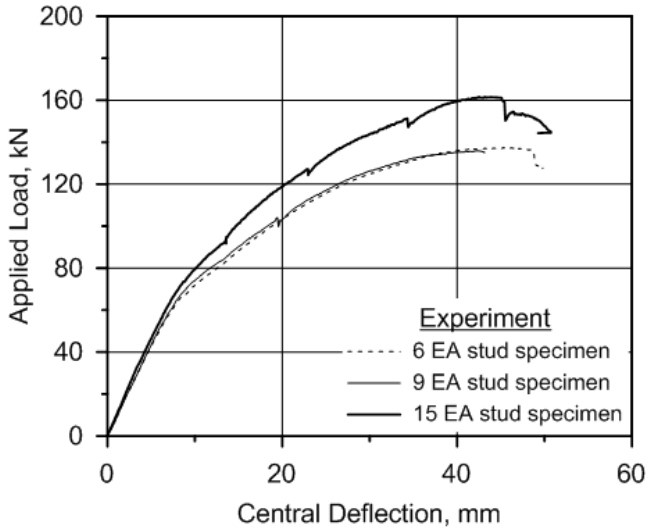


Figure 4.8 Load-deflection relationship of experimental results

4.3. Finite Element Analysis

Finite element analysis at each specimen was conducted. Element type and mesh, material models and properties, constraint conditions and boundary conditions were same as developed model in chapter 3. The position of loading points were same but different displacement was applied considering asymmetric deflection which shown in above result of measurement position-deflection relationship. The load-deflection relationships of experimental and analysis results at each specimen were shown in Fig. 4.9, and the maximum load were shown in Table 4.2. Comparing load-deflection curves and maximum load of each results, 6 and 9 EA stud specimen and was shown non composite behavior. However, 15 EA stud specimen was shown full composite behavior.

Table 4.2 The maximum load of experimental and analysis results

Case	Maximum Load (kN)		
	# of stud : 6	# of stud : 9	# of stud : 15
Experiment	138	136	162
Interface_Non	141	142	147
Interface_Full	153	151	162

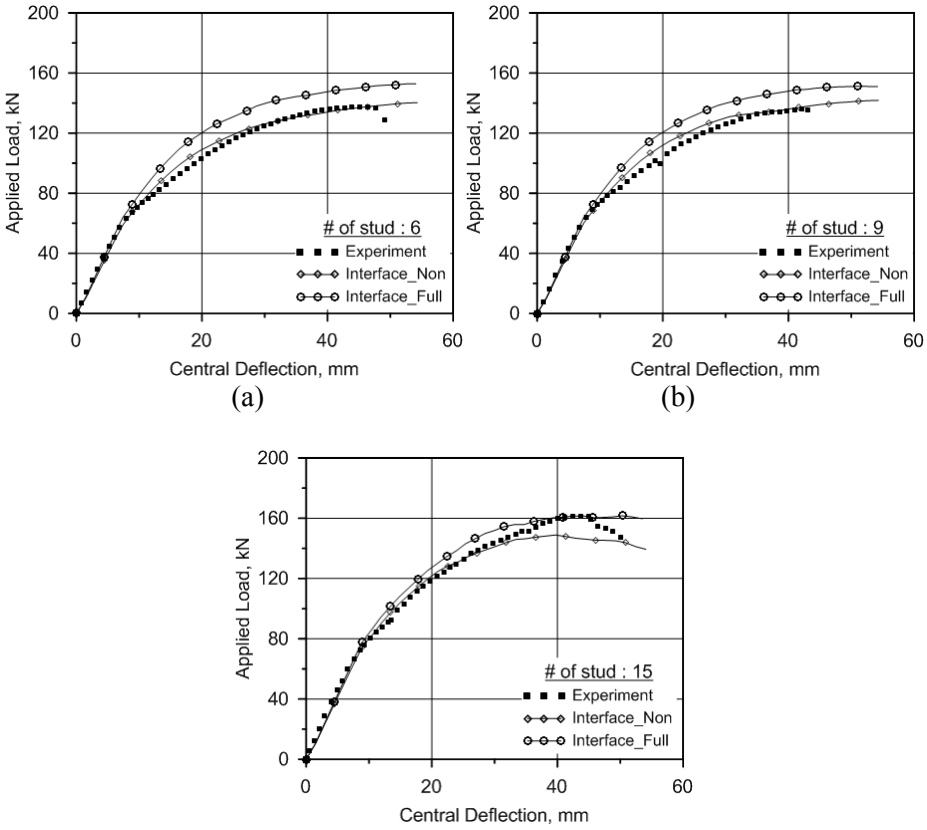


Figure 4.9 Load-deflection relationships of experimental and analysis results: (a) 6 stud specimen; (b) 9 stud specimen; and (c) 15 stud specimen

4.4. Conclusion

In this chapter, experimental test and finite element analysis were conducted to find the relation between the number of stud and type of composite behavior. From the experimental results, 15 EA stud specimen, which using the number of stud followed Korean highway bridge design codes, was shown 15 % larger maximum load than the other specimens maximum load. And from the finite element analysis results, 15 EA stud specimen was shown full composite behavior and the other specimens were shown non composite behavior. As a result, if using the number of stud for design followed Korean highway bridge design code, the hybrid girder was shown full composite behavior.

5. Parametric study

In this chapter, parametric study was conducted to find the effect of joint length. To do this, the length of joint was selected the variable. A quarter of the girder was modelled because it had a symmetry section and it was symmetry in longitudinal direction.

5.1 Finite Element Model

5.1.1 Geometry of target structure

The section of target structure was same as that of previous chapter. In chapter 3 and chapter 4, target structure consists joint, which located at the center of girder, and PSC girder and steel girder, which located at each side. In parametric study, however, the arrangement of girder was changed. Total length 8.5 m of beam was composed steel girder, PSC girder and joint. Steel girder of 1.2 m was located at center, the joint parts were located at the end of steel girder, and PSC girders were located at the end of the both side. And loading conditions was also changed from four-point loading to three-point loading, which applied load at the center of beam. Using this arrangement, it had some advantages such as symmetric deflections occurred and the length of joint had no limitations. The geometry of target structure using parametric study was shown in Fig. 5.1.

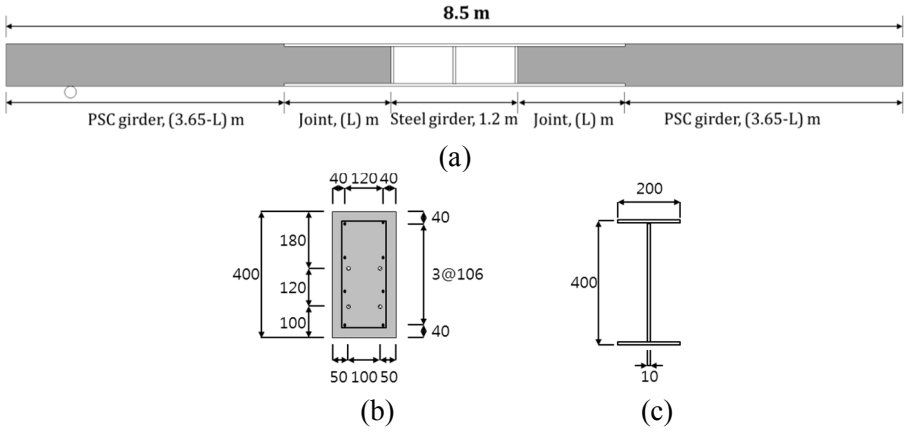


Figure 5.1 Geometry of hybrid girder for parametric study: (a) Girder elevation; (b) PSC section; and (c) Steel section

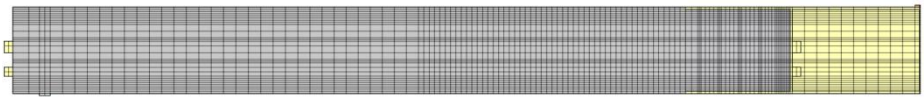
5.1.2. Finite element type and mesh

Concrete, structural steel, stud and anchorage of tendon were meshed with solid element HX24L, reinforcing bar was meshed by embedded element, prestressing steel was meshed by L2TRU truss element and interface was meshed by Q24IF element, which same as chapter 3.

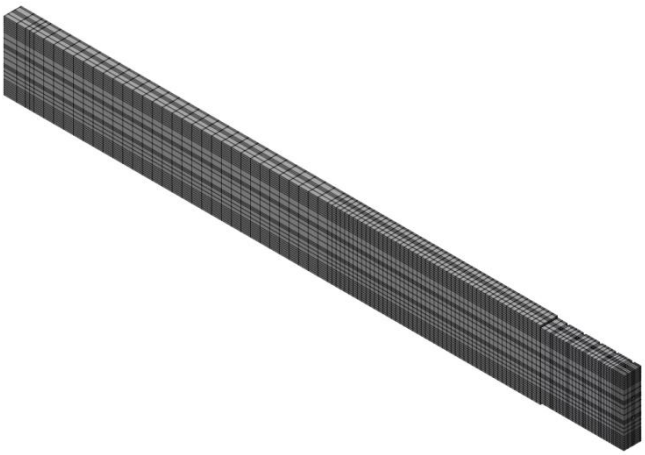
5.1.3. Material models and properties

Material models and properties of all components were same as chapter 3. Parabolic compression curve was used as compressive behavior of concrete, linear tension softening curve was used as tension behavior of concrete, and elasto-plastic idealized curve was used as stress-strain relation of structural steel, reinforcing bar, stud and prestressing tendon. Concrete compressive strength (f_c) was 50 MPa and yield strength(f_y) of structural steel, reinforcing bar, stud was 400 MPa. Reinforcing bars of 10 mm diameter were

used in longitudinal direction, and 16 mm diameter were used in transverse direction for resisting shear force. Four SWPC 7B of 12.7 mm diameter were used in prestressing tendon.



(a)



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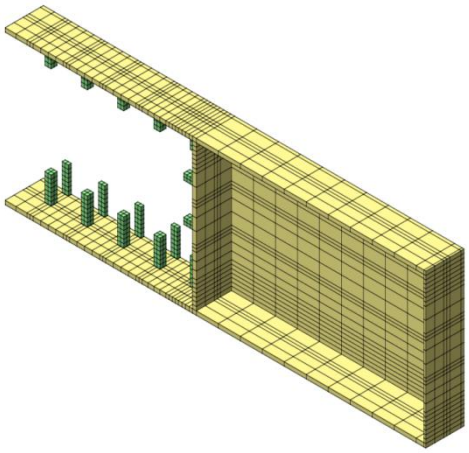


(c)

Figure 5.2 Generated meshes of the girder: (a) Quarter of the girder; (b) PSC girder; and (c) Steel girder

5.1.4. Constraint conditions

Excepting the elements between structural steel and concrete, all components were assumed to be fully bonded through merging their nodes. The nodes between structural steel concrete elements were not merged but sharing position, and slip interaction was applied at the interface between structural steel and concrete using interface element.

5.1.5. Boundary conditions

The target structure was simply supported in parametric study. The support at steel girder was restricted the translational displacement in longitudinal, transverse and normal direction to apply fixed end boundary condition. And the support at PSC girder was restricted the translational displacement in transverse and normal direction to apply roller end boundary condition.

5.1.6. Loading conditions

In this analysis, displacement control under three point loading was applied. Loading point was determined at the center of the girder. Loading plate, which have same material properties as structural steel, was generated above the center of the girder to prevent local failure.

5.2 Parametric Study

5.2.1. Parameter : joint length

The required length of joint was calculated 440 mm, followed the standard about minimum spacing of studs in Korean highway bridge design code. Considering this, the minimum length of joint was determined 500 mm in parametric study. The increment length of joint was 100 mm by steps from 500 mm to 800 mm of joint length and 200 mm by steps from 800 mm to 1,600 mm of joint length. 15 EA stud, which arranged 5 EA in longitudinal direction and 3 EA in transverse direction were used. And 60 mm of clear distance between stud and the end of steel girder was used in all cases. The joint length and spacing of studs in longitudinal direction were shown in Table 5.1.

Table 5.1 Joint length and stud spacing at each analysis case

Joint length (mm)	Stud spacing (mm)
500	95
600	120
700	145
800	170
1,000	220
1,200	270
1,400	320
1,600	370

5.2.2. Assumption to find the effect of joint length

In all analysis cases of parametric study, equal total length and the length of steel girder were used. That is, as joint length was increase, the PSC girder length was decreased. In case of using longer joint length, the maximum load of hybrid girder was increased due to increasing the stiffness of structure. Therefore, it was hard to find the pure effect of joint length.

In order to find the effect of joint length, following assumption was applied. The increment of maximum load in non composite behavior was assumed the effect of stiffness only, and the increment of maximum load in full composite behavior was assumed the effect of stiffness and the effect of joint length. Therefore, the effect of joint length was calculated in Eq 5.1.

$$\Delta P_J = \Delta P_F - \Delta P_N \tag{5.1}$$

where,

ΔP_J : The effect of joint length

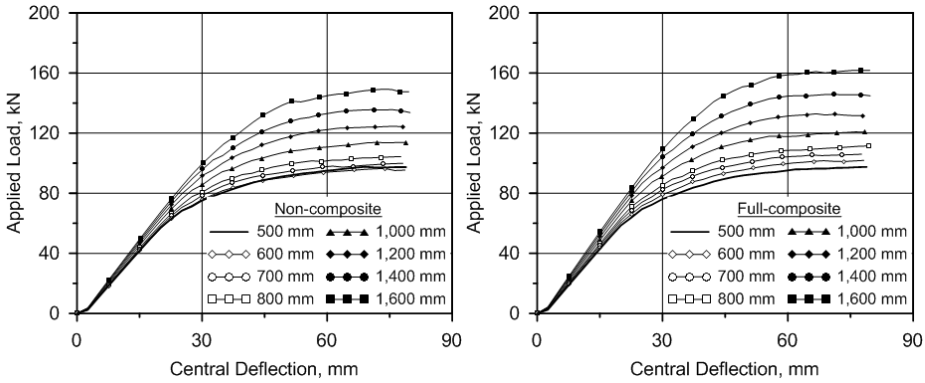
ΔP_F : Load increment of full composite behavior

ΔP_N : Load increment of non composite behavior

5.2.3. Analysis results

The load-deflection relationships at each joint length were shown in Fig. 5.3. The maximum load and load increment at each case were shown in Table 5.2. In analysis cases of 500 mm and 600 mm of joint length in non composite behavior, the maximum load was decreased. The maximum load at 500 mm joint length in non composite behavior and full composite behavior were almost same. Therefore, analysis case of 500 mm joint length in non composite behavior was seemed to be error. Excluding above case, the maximum load was increased as increasing joint length as mentioned earlier.

Comparing the maximum load in full composite behavior and the effect of joint length was shown in Fig. 5.4. And maximum load, the effect of joint at joint length were shown in Table 5.3. The effect of joint was shown less than 2.5 kN. Comparing the maximum load in full composite behavior, the the effect of joint was shown about 1.5 % or less. Consequently, the effect of joint length was insignificant to the behavior of joint.



(a) (b)

Figure 5.3 Load-deflection relationships of the parametric study results :

(a) Non composite behavior; and (b) Full composite behavior

Table 5.2 Load increment by steps of each analysis case

Joint Length (mm)	Non composite behavior		Full composite behavior	
	Maximum Load (kN)	Load Increment (kN)	Maximum Load (kN)	Load Increment (kN)
500	97.56	-	98.08	-
600	96.49	-1.07	101.87	3.79
700	99.92	3.43	106.44	4.57
800	104.56	4.64	111.57	5.13
1000	113.76	9.20	120.84	9.27
1200	124.58	10.82	132.90	12.06
1400	135.64	11.06	145.71	12.81
1600	149.22	13.58	161.76	16.05

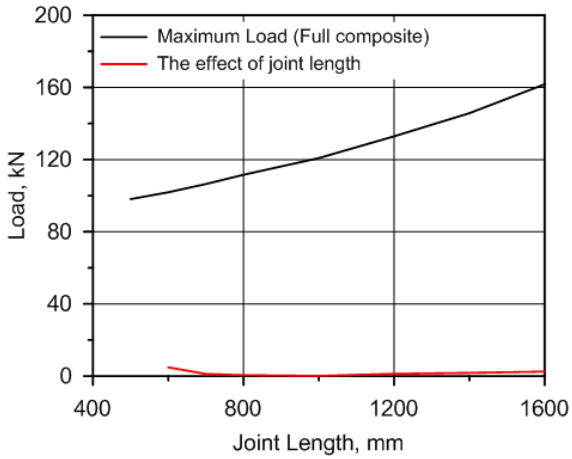


Figure 5.4 Comparing the maximum load and the effect of joint length

Table 5.3 The effect of joint length by steps at each joint length

Joint Length (mm)	Maximum Load (kN) (1)	The effect of joint length (kN) (2)	Ratio (%) (2)/(1)
500	98.08	-	-
600	101.87	4.86	4.77
700	106.44	1.15	1.08
800	111.57	0.48	0.43
1000	113.76	0.07	0.06
1200	124.58	1.24	0.93
1400	135.64	1.76	1.21
1600	149.22	2.47	1.53

5.3 Conclusion

In this chapter, parametric study was conducted to find the effect of joint length based on developed finite element model considering slip behavior. In order to show symmetric deflection, the arrangement of hybrid girder was changed. And loading condition was changed from four point loading to three point loading because the range of joint length was limited less than the distance of loading points in four point loading condition. As a result of parametric study, the effect of joint length was insignificant on the performance of joint. Excluding the effect of stiffness, the effect of joint length was shown about 1.5 % or less compared with maximum load of hybrid girder.

6. Conclusions

6.1 Summary and Conclusions

Hybrid girder consists of steel girder and concrete girder connecting in longitudinal direction. Design of joint in hybrid girder should be careful because of stress concentration. However proper design guideline for design of joint is not presented. Joint in hybrid girder is composed of the steel plate, filling concrete and sutd. In this thesis, finite element analysis, experimental test and parametric study were conducted about the number of stud and the length of joint.

In order to consider slip behavior at the interface between steel and concrete, finite element model was developed using interface element. Target structure was based on the girder used in previous research by other researchers. As a result of simple verification, developed model was proper to simulate all types of composite behavior.

Experimental test was conducted to find the relation between the number of stud and type of composite behavior. The specimen using 15 EA stud followed Korean highway bridge design code was shown full composite behavior, and the other specimens using less number of stud were shown non composite behavior. As a result, Korean highway bridge design code was proper to determine the number of stud.

Parametric study was conducted to find the effect of joint length. The effect of joint, which was assumed the difference of load increment in full

composite behavior and non composite behavior, was shown about 1.5% of less compared with maximum load. As a result, the effect of joint was insignificant factor on behavior of joint performance.

Consequently, components which influence on the behavior of joint was investigated the number of stud only and Korean highway bridge design code was applicable to determine the number of stud.

6.2 Prospects for Further Study

In this study, total three specimens were fabricated and experimented. However, the number of stud placed at joint does not change gradually. Therefore it was impossible to find strictly the relation between the number of stud and the type of composite behavior. In addition, it is necessary to confirm whether the maximum load is maintained or increased even when more studs are placed than required number followed Korean highway bridge design code. And the study about the spacing of stud is also necessary.

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국문초록

하이브리드 거더 접합부의 설계 지침 제안

이 대 규

하이브리드 거더는 강거더와 콘크리트거더를 길이방향으로 접합하여 설계한 거더이다. 강거더와 콘크리트거더를 연결하는 하이브리드 거더 접합부는 일반적으로 강판과 속채움 콘크리트, 그리고 전단연결재로 구성되어있다. 접합부에서는 이종 재료 간의 강성 차이로 응력집중현상이 발생할 수 있어 설계 시 주의가 요구되는 부분이다. 현재 국내에는 하이브리드 교량 접합부 설계를 위한 설계기준이 존재하지 않는 상황이다. 전단연결재와 관련하여 국내 도로교 설계기준에는 강거더와 콘크리트바닥판으로 이루어진 합성단면에 대한 스터드형 전단연결재에 대한 규정이 존재하나 이를 접합부 설계에 적용 가능한지에 대해서는 검증 과정이 필요하다. 본 연구에서는 해당 규정의 적용 가능성을 확인하기 위해서 해석 및 실험적 연구를 수행하였다. 추가적으로 접합부를 구성하는 강판의 길이, 즉 접합부의 길이가 하이브리드 거더에 미치는 영향에 대해서 매개변수 연구를 추가적으로 수행하였다.

하이브리드 거더 접합부에서는 스터드의 휨변형으로 인해 부분합성거동이 발생하므로 접선 방향의 슬립물성을 고려한 해석모델을 정립하였다. 해석적 연구에 사용된 거더는 기존 연구자의 해석적 연구에서 사용한 거더를 사용하였다. 간단한 검증을 수행한 결과 정립한 해석모델은 접선 방향의 물성에 따라서 비합성 거동과 부분합성 거동, 완전합성 거동으로 구분되는 합성거동의 유형을 잘 모사할 수 있었다.

다음으로 해석 모델의 설계 상세를 기반으로 스터드의 개수를 실험 변수로 하여 총 3 개의 실험체를 제작하고 하중재하실험을 수행하여 합성거동의 유형과의 관계를 분석하였다. 실험 결과 접합부 내부에 배치된 스터드의 개수에 따라 실험체는 비합성 거동과 완전합성 거동을 보이는 것을 확인할 수 있었다. 또한 도로교 설계기준에 제시된 합성단면에 적용하는 스터드에 대한 설계기준을 하이브리드 거더 접합부 설계에 적용할 경우 완전합성 거동을 보이므로 해당 규정을 적용 가능하다는 사실을 확인할 수 있었다.

접합부의 길이에 대한 영향을 확인하기 위해 매개변수연구를 수행하였다. 모든 해석에서 총 길이와 강거더의 길이는 동일하게 설정하였기 때문에 접합부의 길이가 증가할수록 PSC 거더의 길이가 짧아지고 구조물의 강성이 커지므로 거더의 최대하중은 증가하게 된다. 증가된 구조물의 강성에 의한 효과를 제거한 순수한 접합부 길이에 대한 효과를 얻기 위해 동일한 길이에서 비합성 거동과

완전합성 거동의 최대하중 차이를 길이 효과로 가정하고 접합부 길이 증가에 따른 변화를 확인하였다. 매개변수연구 결과 접합부 길이가 증가함에 따라 발생하는 길이 효과는 최대하중 대비 약 1 % 내외로 미비한 것으로 나타났다.

주요어: 하이브리드 거더, 접합부, 유한요소해석, 경계면 요소, 매개변수연구

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