（16）NUMERICAL STUDY OF COMPOSITE BEAMS SUBJECTED TO COMBINED SHEAR AND BENDING

Kang LIU[1], Weiwei LIN[2], Kiyoshi ONO[3], Takeshi MIYASHITA[4] and Masahiro SHIRATO[5]

[1]Member of JSCE, Dept. of Civil and Environmental Eng., Waseda University
(3-4-1 Okubo, Shinjuku-ku, Tokyo 169-8555, Japan)
E-mail:lkxld@akane.waseda.jp
[2]Assoc. Prof., Dept. of Civil Eng., Aalto University
(Rakentajanaukio 4 A, 02150 Espoo, Finland)
E-mail: weiwei.lin@aalto.fi
[3]Member of JSCE, Prof., Dept. of Civil and Environmental Eng., Waseda University
(3-4-1 Okubo, Shinjuku-ku, Tokyo 169-8555, Japan)
E-mail: k-ono@waseda.jp
[4]Member of JSCE, Assoc. Prof., Dept. of Civil and Environmental Eng., Nagaoka University of Technology
(1603-1 kami-Tomioka, Nagaoka, Niigata 940-2188, Japan)
E-mail: mtakeshi@vos.nagaokaut.ac.jp
[5]National Institute for Land and Infrastructure Management
(1 Asahi, Tsukuba City, Ibaraki 305-0804, Japan)
E-mail: shirato-m92ta@mlit.go.jp

In comparison with traditional steel or concrete structures, the steel-concrete composite structure may have relatively low construction cost, by achieving higher resistance or strength from its composite action. The plastic mechanical behavior of the steel-concrete composite structure needs to be studied. In order to investigate the plastic behavior of such structures, three composite beams with different configurations were tested in this study. In the experiments, three-point static loading tests were conducted, and the results were used to investigate both flexure and shear strength of the steel-concrete composite beams. Based on the experimental observations and the results obtained in this study, a nonlinear finite element model capable of simulating such beams were built, and its validity was confirmed by comparing the numerical results with the test results. In addition, the parametric study was performed to further investigate the behavior of such beams. In this paper, the effects of web width-thickness ratio and flexure-shear ratio on plastic behavior, as well as the correlation between bending capacity and shear capacity of steel-concrete composite beams were discussed.

Key Words : *numerical study, loading test, composite structure, plastic behavior, parametric study*

1. INTRODUCTION

In recent years, steel-concrete composite structures have been widely used in both renewal of existing bridges and construction of new bridges due to economic and other considerations. Although similar evaluation methods as those used in Eurocode and AASHTO have also been proposed in Japan, no design method considering partial plasticity of steel girders has been standardized in Japanese design specifications[1)]. On this background, the shear strength and the bending-shear interaction of the steel-concrete composite beam is investigated under the project “Development of Partial Factor Plastic Design Method for Steel Girder” supported by the research contract with the National Institute for Land and Infrastructure Management of Japan.

Meanwhile, limited information on partial plasticity of composite girders, development of plastic design methods is available. With the purpose of proposing a new design methodology accouning for the plastic moment and shear strength in the design of the composite bridge, numerical modeling method is performed in this study to evaluate the load carrying capacity of the steel-concrete composite beam based on the experimental results.

(2) Bending Strength Evaluation

The ductility equations are often used for evaluating the bending strength of composite beams. The reduction rate and conservation of ductility equations for AASHTO[2)] and Eurocode[3)] are slightly different. In addition, the equation proposed by Gupta et al.[4)], are also given below and illustrated in **Fig. 1**.

AASHTO's equation[2)]:

$$\frac{M_u}{M_p}=1.07-0.7\frac{D_p}{D_l} \quad \left(0.10<\frac{D_p}{D_l}<0.42\right) \tag{1}$$

Eurocode's equation[3)]:

$$\frac{M_u}{M_p}=1.09-0.6\frac{D_p}{D_l} \quad \left(0.15<\frac{D_p}{D_l}<0.40\right) \tag{2}$$

Proposed equation by Gupta et al[4)]:

$$\frac{M_u}{M_p}=1.05-0.33\frac{D_p}{D_l} \quad \left(0.15<\frac{D_p}{D_l}<0.40\right) \tag{3}$$

Where, M_u : ultimate bending moment,
M_p : full plastic moment.
D_l : limiting neutral axis depth
D_p : depth of the plastic neutral axis

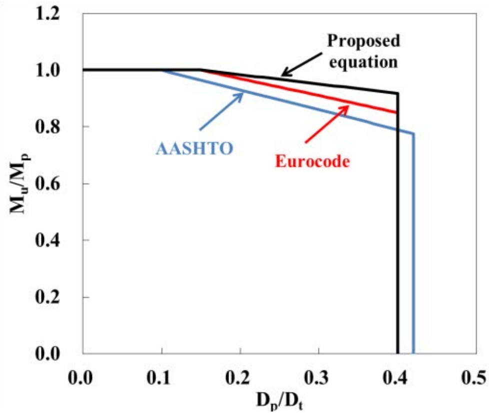

Fig.1 Strength prediction in various equations

(3) Shear Strength Evaluation

Basler's eqution[5)] was used for shear force calculation, the equation works on vertical steel plates, but the contribution of the shear force of concrete slab could not be ignored in composite beam. However, the shear strength of the composite girders were calculated using the Basler's eqution and compared with the results of experiments and analysis.

$$\frac{V_u^p}{V_y^p}=\frac{\tau_{cr}}{\tau_y}+\frac{\sqrt{3}}{2}\frac{1-\tau_{cr}/\tau_y}{\sqrt{1+\alpha^2}} \tag{4}$$

where, V_u^P : ultimate shear load
V_y^P : plastic shear force
τ_{cr} :critical shear stress
τ_y : shear yield stress
α : aspect ratio, α=a/b (*a*: stiffener spacing *b*: girder depth)

The critical shear stress τ_{cr} was calculated according to **Eq. (5)** and **Eq. (6)**.

$$\begin{cases}\tau_{cr}=\tau_{cr}^e & (\tau_{cr}^e\le 0.8\tau_y)\\ \tau_{cr}=\sqrt{0.8\cdot\tau_y\cdot\tau_{cr}^e} & (\tau_{cr}^e\ge 0.8\tau_y)\end{cases} \tag{5}$$

$$\tau_{cr}^e=k(\alpha)\frac{\pi^2 E}{12(1-\nu^2)}\left(\frac{t_w}{b_w}\right)^2 \tag{6}$$

The k(α) was determined from **Eq. (7)**.

$$\begin{cases}k(\alpha)=5.34+4.00\dfrac{1}{\alpha^2} & (\alpha\ge 1)\\ k(\alpha)=4.00+5.34\dfrac{1}{\alpha^2} & (\alpha<1)\end{cases} \tag{7}$$

In the experiment, three composite beams with same aspect ratio(α=1.5) were tested.

(4) Interaction Relationship beween Bending and Shear Capacities

As shown in **Eq. (8)** and **Eq. (9)**, the equation of square law[6)] and the fourth law[7)] were used to discuss interactin relationship between bending strength and shear strength.

$$\left(\frac{M}{M_u}\right)^2+\left(\frac{V}{V_u}\right)^2=1 \tag{8}$$

$$\left(\frac{M}{M_u}\right)^4+\left(\frac{V}{V_u}\right)^4=1 \tag{9}$$

2. EXPERIMENTAL INVESTIGATION

To investigate the mechanical behavior of composite beam subjected to shear and bending, three specimens were fabricated and tested in structural testing laboratory of KOMAIHALTEC Company. The three test specimens are denoted as A, B, and C, repectively.

(1) Details of test specimens

The experimental investigation consists of three composite beams. The overview of one of composite beam is shown in **Fig.2**. The three-point load tests were used on the test specimens, and the longitudinal view of test specimens is shown as **Fig.3**, where the details can be found in **Table 1**. The cross section of the test specimens is shown in **Fig.4**, The thickness and the width of the RC slab are 200mm and 500mm respectively. Reinforcement of type SD345 with 16mm in diameter are used in longitudinal direction, for traversal direction, reinforcing bars with 13mm in diameter are set at intervals of 200mm. The shear studs connecting the RC slab and structural steel was designed according to the JSCE specification[8].

(2) Material properties

The structural steel part of composite beams were fabricated with SM490Y, the material properties of steel was presented in **Table 2**.For concrete, the minimum value of Japan Road Association[6] as the design compression strength (σ_c'=27N/mm^2) of the concrete was used, moreover, the compression strength of the concrete obtained from three cylinder specimens is shown in **Table 2**.

(3) Loading test

The basic principle of loading control was to control the load up to the yield load, and to set displacement control based on the yield displacement after the yield load, several steps was set, and the cycle loading test was conducted at each step.

Fig.2 Overview of the test specimen

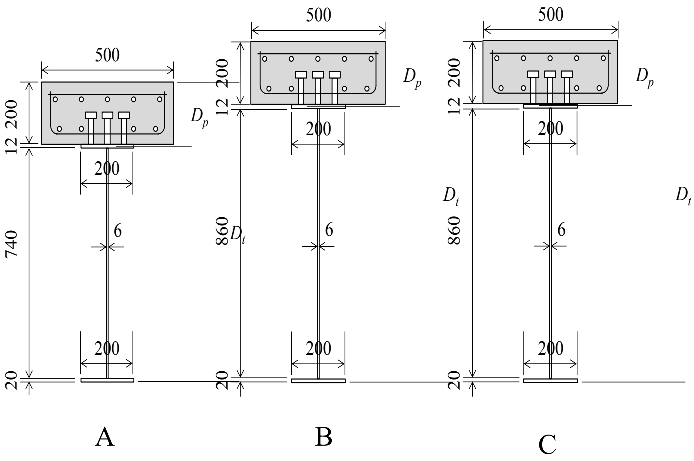

Fig .4 Details of cross sections (unit:mm)

Table 1 Dimensions of test specimens (unit:mm)

Test Specimen	Span length L	Test panel a	Support panel b	Girder height h	Slab thickness c
A	7100	2220	2440	740	500
B	7950	2580	2685	860	500
C	10400	2580	3910	860	500

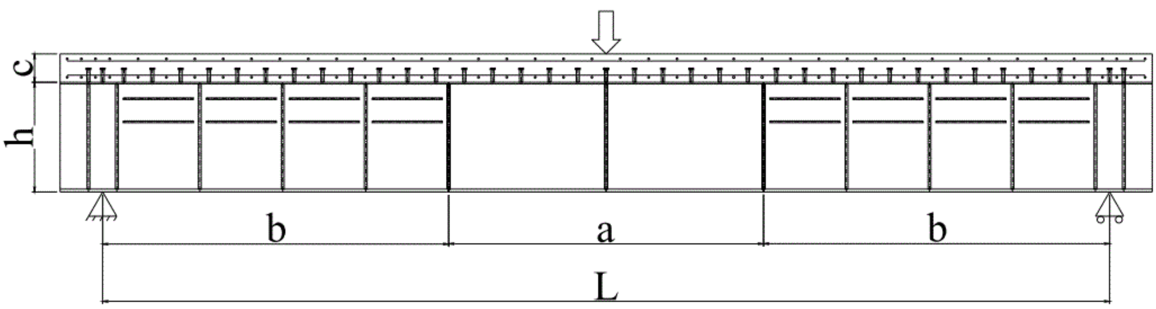

Fig.3 Sideview of the test specimens

(4) Test results

According to experimental results, due to the failure of the concrete slab, composite beams lose load carrying capacity when the load reaches its peak, for all specimens, the failure proceeded to the maximum load after cracks occurred in the concrete slab near the loading point. The concrete slab failure of one specimen could be seen **Fig.5**. As shown in **Fig.6**, vertical displacement is measured at mid-span of point, the load-deflection responses of three composite beams are illustrated in **Fig.7**. The ultimate loads are 1383kN for A, 1468kN for B, 1118kN for C, as shown in **Table 3**.

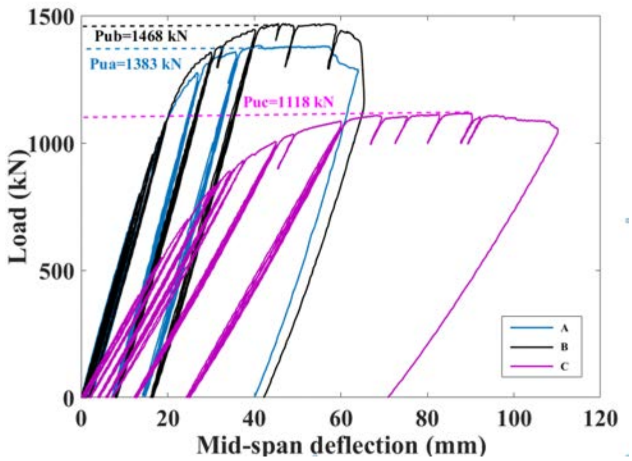

Fig.7 Load-deflection curve of test specimens

(5) Bending-Shear Interaction

Based on the **Eq.(8)**, **Eq. (9)**, and **Table 3**, interaction relationship between bending strength and

Fig.5 Concrete slab of crushing failure

Fig.6 Measurement installation for vertical displacement

Table 2 Material properties

	Specimen No.	A	B	C
Concrete slab	Compression strength (N/mm^2)	36.3	38.3	38.4
Bottome flange	Yield strength (N/mm^2)		403	
	Ultimate tensile strength (N/mm^2)		539	
Web	Yield strength (N/mm^2)		426	
	Ultimate tensile strength (N/mm^2)		554	
Upper flange	Yield strength (N/mm^2)		433	
	Ultimate tensile strength (N/mm^2)		551	

Table 3 Results of experiment and theoretical values

Test Specimen		A	B	C
Calculation results	Py (kN)	1032	1085	829
	Pp (kN)	1274	1352	1046
	Pu from Eq.(4) (kN)	1439	1555	1555
Test results	Pmax (kN)	1383	1468	1118
	Mx/Mp	1.09	1.09	1.07
	Pmax/Pu	0.96	0.94	0.72

shear strength were presented in **Fig.8**, it can be seen that all bending shear strengths are outside the fourth law, which means that there is no correlation between bending and shear capacity.

3. Numerical Models

(1) Numerical simulation

As shown in **Fig.9**, a nonlinear finite element model capable of simulating such beams were built, and its validity was confirmed by comparing the numerical results with the test results. The numerical simulation was adopted by using TNO DIANA 10.2 software[9] for modeling and analyzing the composite beam models. In order to investigate the mechanical behavior of the beam beyond elastic condition, the nonlinear analysis was used in this study. The concrete slab is modeled by using the 8-node solid elements with 24 degrees of freedom. The reinforcement bars are modeled by using embedded bar elements. The steel girders are modeled by 4-node curve shell elements. Beam elements are used for modeling the shear studs and interface elements are used for simulating the interface friction between the concrete slab and top flanges of main gider.

(2) Concrete

The concrete of stress-strain relationship shown in **Fig.10** were adopted in the numerical analyses as suggested by JSCE specifications[10]. The strength and factor were determined by equations, the tensile strength of concrete was calculated according to **Eq.(10)**. The factor k_1 and ultimate compression strain ε_{cu} was calculated according to **Eq.(11)** and **Eq.(12)**.

$$f_t=0.28f_{ck}'^{2/3} \tag{10}$$

$$k_1=1-0.003f_{ck}'\leq 0.85 \tag{11}$$

$$\varepsilon_{cu}'=\frac{155-f_{ck}'}{3000}\ ;\quad 0.0025\leq\varepsilon_{cu}'\leq 0.0035 \tag{12}$$

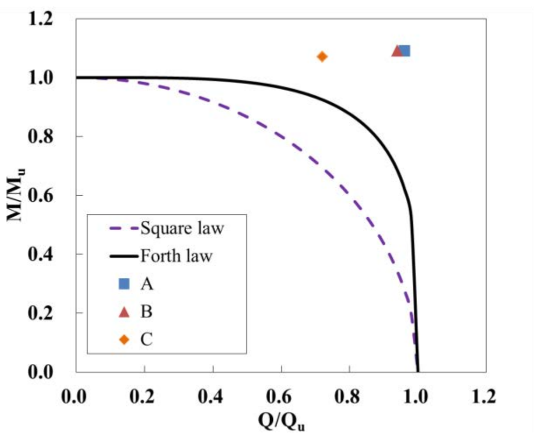

Fig.8 Comparison of correlation relationship

(3) Structural steel ,reinforment and stud

The stress-strain relationship of the structural steel, studs, and reinforcing bar were modeled as an elastic and plastic material as shown in **Fig.11**[11], the von Mises yield criterion and isotropic strain hardening were used in numerical analyses. The yield stress and ultimate tensile strength of the strucural steel based on meterial test, reinforcing bar and studs of the stength were difined as Japanese Industrial Standards[12].

(4) Interface

To model the friction and bond of reaction between the concrete slab and steel girder, interface elements adopted by okada et al.[13], were employed. The bond stress-slip relationship of the interface between steel and concrete is shown in **Fig. 12**.The bond stress-slip relationship was determined from **Eq. (13)** and **Eq. (14)**. The maximum bond stress fbo and corresponding slip at peak bond stress are taken as 0.5 N/mm^2 and 0.06 mm, respectively.

$0\leq\Delta u_t\leq\Delta u_t^0$:

$$f_t=\frac{f_{bo}}{1.9}\left[5\left(\frac{\Delta u_t}{\Delta u_t^0}\right)-4.5\left(\frac{\Delta u_t}{\Delta u_t^0}\right)^2+1.4\left(\frac{\Delta u_t}{\Delta u_t^0}\right)^3\right] \tag{13}$$

$\Delta u_t\geq\Delta u_t^0$:

$$f_{tan}=f_{bo} \tag{14}$$

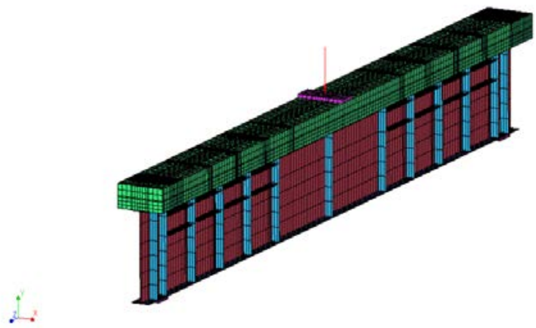

Fig.9 Overview of numerical model

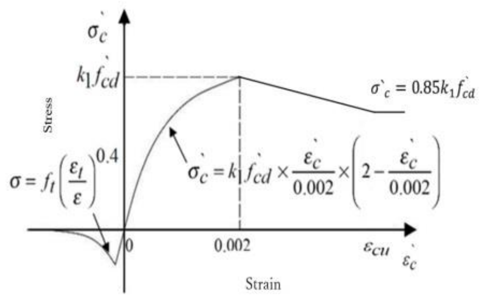

Fig.10 Stress-strain relationship of concrete[10]

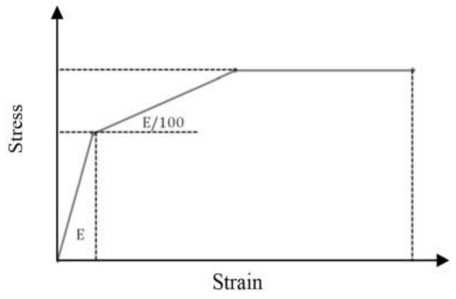

Fig.11 Stress-strain relationship of structural steel, rebars, and studs[11)]

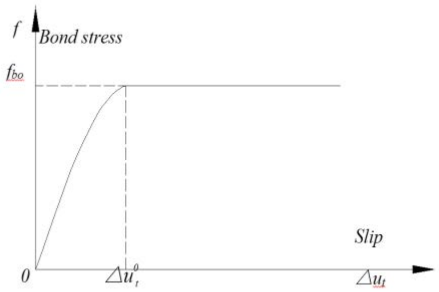

Fig.12 Bond stress-slip relationship of interface[13)]

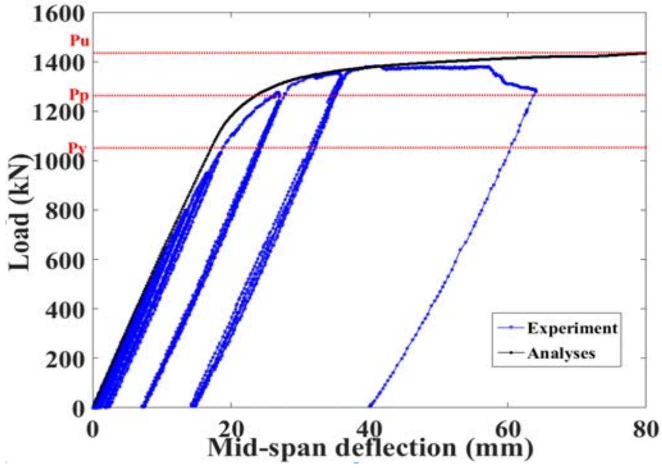

Fig.13 Load-deflection curves of A at mid-span section

(5) Comparison of load-deflection curves

The load-deflection relationships of A, B, and C from numerical analyses is compared with the experimental results, as shown in **Fig.13**, **Fig.14**, **Fig.15**, respectively. Both numerical results and experimental results were taken from vertical deflection at midspan section. Based on the **Table.3** of various theoretical values, P_y, P_p and P_u are marked on the figures.

All the experimental and numerical results enter the plastic deformation state after being larger than P_y, which proves the validity of the theoretical calculation. In the elastic state, both load carrying capacity and the corresponding mid-span deflection is close between experimental results and numerical analyses. In the plastic state, when the deflection is

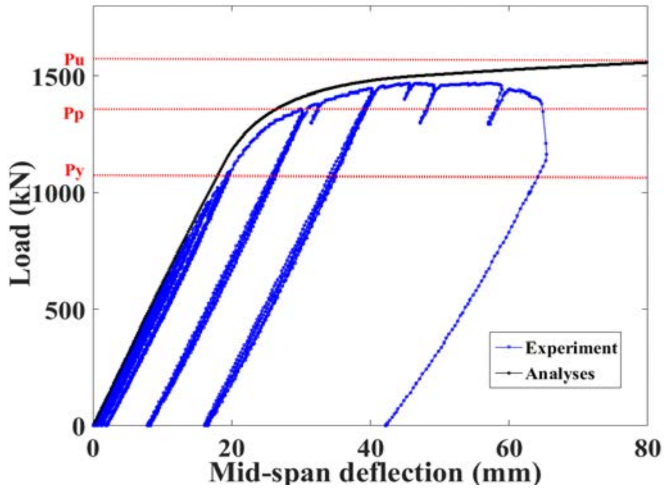

Fig.14 Load-deflection curves of B at mid-span section

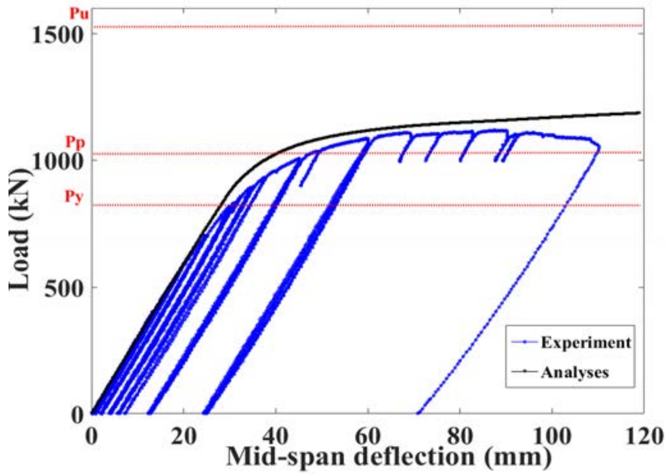

Fig.15 Load-deflection curves of C at mid-span section

the same, the analytical value of the load is slightly larger than the experimental value. There are two possible causes. First, in the setting of this numerical analysis, the residual stress was not considered by welding of the steel girder of the experiment. In this study, the material property of the concrete and steel are calculated according to the JSCE standard specifications. The ideal stress-strain relationship cannot fit the phenomenon of the test specimen. In general, the analytical model was shown good agreement with experimental result.

4. Parametric analyses

The influence of different factors on the load carrying capacity of steel-concrete composite beams in elastic and plastic working stage was obtained by finite element method. In the parametric study, the same element types as used for modeling the test specimens are used.

(1) Concrete of influence

In order to investigate the influence of concrete compressive strength on load carrying capacity of composite beam, two new compressive strength were set, which are 27MPa, 50MPa respectively. The numerical analyses is compared with the experimental results are shown in **Fig.16**, **Fig.17**, **Fig.18**. When the load is the same, as the strength of concrete increases, deflection becomes smaller in numerical analyses that cloud be found. It is proved that the increase of concrete strength can effectively improve load carrying capacity of the composite beam.

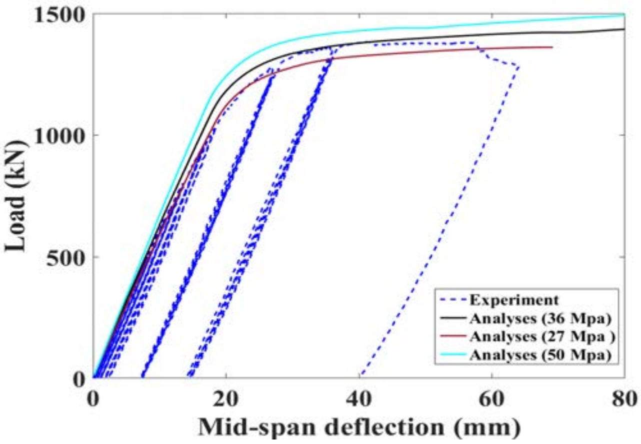

Fig.16 Relationship between concrete compressive strength and load-deflection curve (test specimen A)

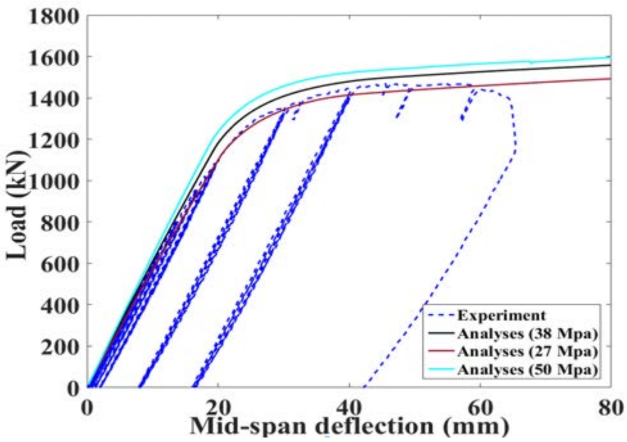

Fig.17 Relationship between concrete compressive strength and load-deflection curve (test specimen B)

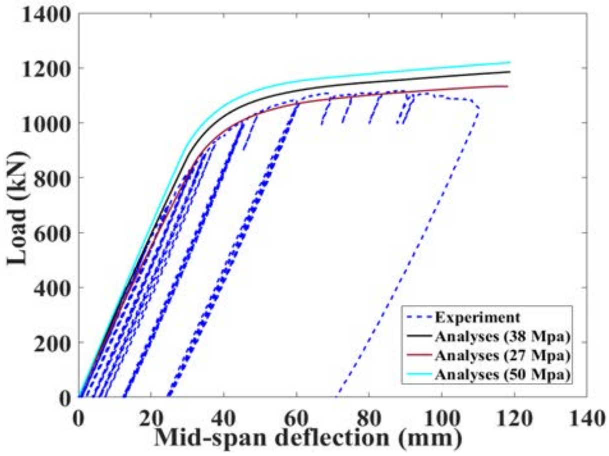

Fig.18 Relationship between concrete compressive strength and load-deflection curve (test specimen C)

(2) Web width-thickness ratio

The relationship of load carrying capacity and web width-thickness was obtained by using different web cross section in numerical study. The web width-thickness ratio parameter R_w was calculated according to **Eq. (15).** According to parameter R_w, each specimen of numerical model with four different web heights were designed. These parameter R_w of information is shown in **Table 4**. The comparison of results are presented in **Fig.19**, **Fig.20**, and **Fig.21**, respectively.

$$R_w = \frac{b}{t}\sqrt{\frac{\sigma_y \cdot 12\,(1 - \nu^2)}{E \cdot \pi^2\, k}} \tag{15}$$

where, b : web hight
t : web thickness
σ_y :yield stress
ν : poisson's ratio
E : young's modulus
k :buckling coefficient

Table 4 Web width-thickness ration parameter

A	web hight b (mm)	740	780	840	900
	parameter Rw	1.23	1.30	1.40	1.50
B	web hight b (mm)	860	900	960	1020
	parameter Rw	1.43	1.50	1.60	1.70
C	web hight b (mm)	860	900	960	1020
	parameter Rw	1.43	1.50	1.60	1.70

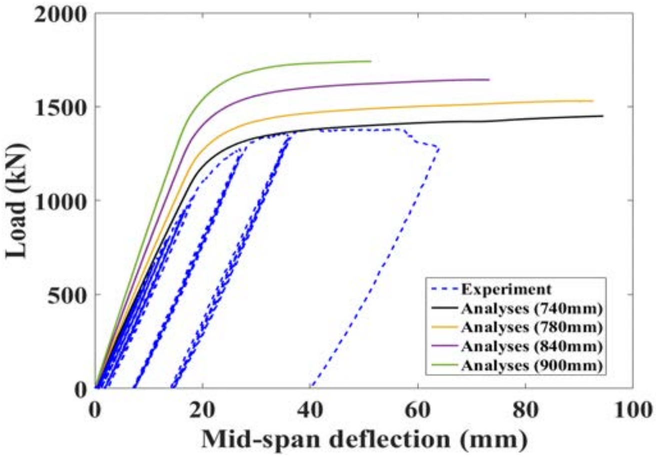

Fig.19 Relationship between width-thickness ratio and load-deflection curve (test specimen A)

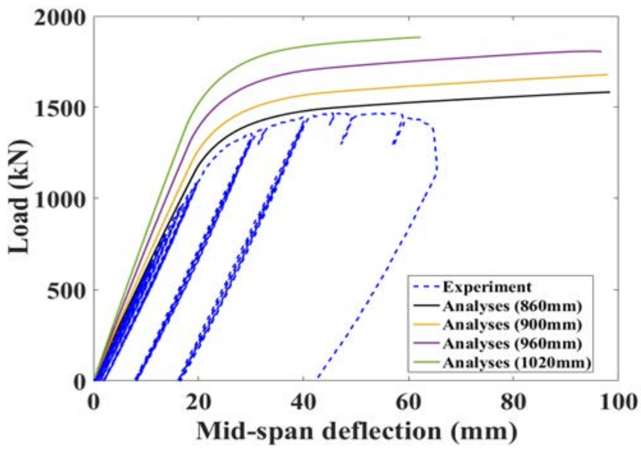

Fig.20 Relationship between width-thickness ratio and load-deflection curve (test specimen B)

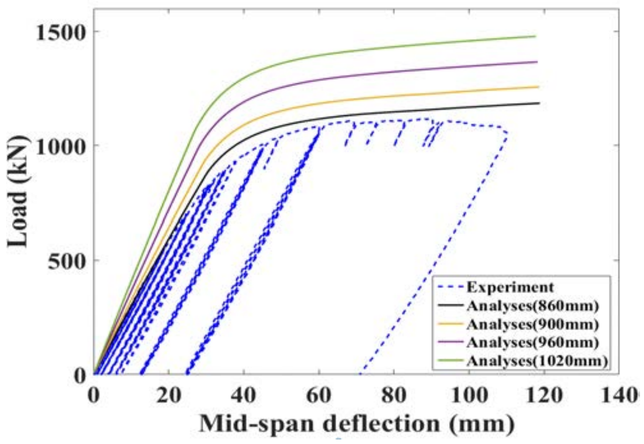

Fig.21 Relationship between width-thickness ratio and load-deflection curve (test specimen C)

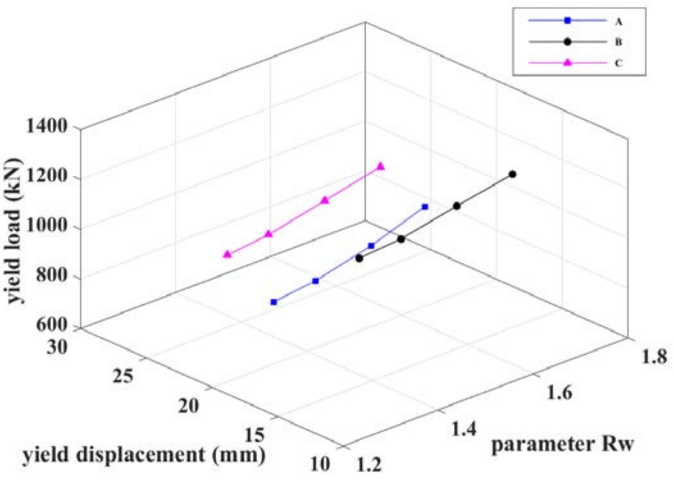

Fig.22 The yield load and displacement in the numerical analyses

Based on material properties, the yield strain of bottome flange was be calculated. The deflection and load corresponding to the yield can be found in numerical analysis with yield strain. **Fig.22** shows the relationship of parameter R_w, yield load and displacement. It has also been found that, for steel girders having high web width-thickness ratio, the loading carrying capacity increases as yield displacement reduces.

6. Conclusions

This study is part of the preliminary study in the evaluation of the load carrying capacity of the steel-concrete composite beam. In this study, both flexure and shear strength of the composite beam of experimental results were reported. By comparing the load-deflection curves obtained from experimental results and numerical analyses, the numerical simulation is proved to be able to accurately simulate the behavior of the composite beam in both elastic state and post-elastic state. In parametric analysis, it is possible to grasp parameters that affect the load carrying capacity of composite girders. In addition, more parameters should be proposed in the future. This research will help develop the composite girders of plastic design method in Japan.

ACKNOWLEDGMENT: This study is investigated under the project “Development of Partial Factor Plastic Design Method for Steel Girder” supported by the research contract with the National Institute for Land and Infrastructure Management of Japan. In addition, We would like to thank the members of Nagaoka University of Technology who completed this experiment. We would also like to thank KOMAIHALTEC Company for providing their laboratory for conducting the experiment.

REFERENCES

1) Japan Road Association : *Japanese design specification for highway bridge*., Tokyo, 2017.
2) AASHTO : *LRFD bridge design specifications -2005 interim revisions*, Washington, D. C., 2005.
3) CEN :Eurocode4, *Design of composite steel and concrete structures*, Part2, General rules and rules for bridges, 2004.
4) Gupta, V.K, Okui, Y., Inaba, N. and Nagai, M. : Effect of concrete crushing on flexural strength of steel-concrete girders, Doboku Gakkai Ronbunshuu A, Vol. 63, No. 3, pp.475-485, 2007.
5) Basler, K. : Strength of plate gieders in shear, *Journal of Structural Division,* ASCE, Vol.87, No.ST7, pp.151-180, 1961.
6) Japan Road Association : Specifications for Highway Bridges, Part I Part II, 2003.
7) Tamada, K., Ono, K., Kawamura, A. and Nishimura, N. : Experimental study for estimating ultimate shear strength of U-shaped steel girders, Doboku Gakkai Ronbunshuu A, Vol. 62, No. 1, pp.14-28, 2006.
8) Japan Society of Civil Engineers : *Standard specification for steel and concrete structures*., 2007.
9) de Witte, F.C. and Kikstra, W.P.: DIANA Finite Element User’s Manual: Analysis Procedures (release 10.2), TNO DIANA b.v., 2017.
10) Japan Society of Civil Engineers : *Standard specification*

for concrete structures., 2002.
11) Japan Society of Civil Engineers : *Standard specification for concrete structures*., 2007.
12) Japanese Industrial Standards : *JIS handbook steel I*.,2012.
13) Okada, J., Yoda, T., and Lebet, J.P. : A Study of grouped arrangement of stud connectors on the shear strength, JSCE Journal of Structural Engineering/Earthquake Engineering, Vol. 23, No.1, pp. 75-89, 2006.

(Received August 30,2019)