World Academy of Science, Engineering and Technology
International Journal of Structural and Construction Engineering
Vol:11, No:6, 2017

Evaluation of Applicability of High Strength Stirrup for Prestressed Concrete Members

J.-Y. Lee, H.-S. Lim, S.-E. Kim

Open Science Index, Structural and Construction Engineering Vol:11, No:6, 2017 publications.waset.org/10007191/pdf

***Abstract*—**Recently, the use of high-strength materials is increasing as the construction of large structures and high-rise structures increases. This paper presents an analysis of the shear behavior of prestressed concrete members with various types of materials by simulating a finite element (FE) analysis. The analytical results indicated that the shear strength and shear failure mode were strongly influenced by not only the shear reinforcement ratio but also the yield strength of shear reinforcement and the compressive strength of concrete. Though the yield strength of shear reinforcement increased the shear strength of prestressed concrete members, there was a limit to the increase in strength because of the change of shear failure modes. According to the results of FE analysis on various parameters, the maximum yield strength of the steel stirrup that can be applied to prestressed concrete members was about 860 MPa.

***Keywords*—**PSC members, shear failure mode, high strength stirrups, high strength concrete, shear behavior.

I. Introduction

THERE have been many studies on high strength concrete for the past 30 years, but there are not many studies on high strength steel bars for reinforced concrete (RC) or prestressed concrete (PSC). In order to secure the space of human activity and increase the space utilization due to the increase of the population of the future society, the giganticization of structures (skyscrapers, long span bridges, large space structures, huge ocean structures, huge underground structures, etc.) is inevitable trends. In order to construct these mega structures, large amounts of structural steel or high strength steel are required. When high-strength steel is used for large-scale structures, it is lightweight, and economical construction is possible due to decrease in usage of steel bars. In case of using high-strength steel reinforcement, it is possible to prevent dense laying of reinforcing bars to smooth concrete pouring and improve the durability and quality of concrete.

There have been great advances in concrete technology during the last ten decades. The improvement in high-strength, high performance, fiber-reinforced, and other material and structural properties in concrete achieved earlier are now accepted as routine and various types of advanced high strength concrete have been widely used [1]. For last two decades, much research on the high yield strength of reinforcement has been conducted in USA, Japan, and European countries [2]-[5].

When high-strength steel bars are used as stirrups, there may be a change in shear failure mode. The ACI 318-14 design code [6] calculates the shear strength of RC or PSC members in the condition that the shear reinforcement must yield before web concrete crushing. When the high-strength stirrup is used in a member, there is a possibility that the member fails in shear due to web-concrete crushing before the yielding of stirrup because the yield strain of high-strength stirrup is greater than that of normal-strength stirrup. In addition, when high-strength steel bars are used as stirrups, shear-bond failure may occur. The bond strength of RC and PSC members is strongly influenced by presence and spacing of transverse steel bars. In case of using high strength stirrups, the spacing of shear reinforcing bars increases, and the bond strength between the concrete and the reinforcing bars is reduced. Particularly, when a member is subjected to seismic load, the members using high-strength reinforcing bars may be more vulnerable to bond failure.

Next is the serviceability problem caused by using the high-strength stirrups for RC and PSC members. In the ACI 318-14 design code, the minimum shear reinforcement ratio and the maximum spacing are specified in consideration of the serviceability and deformability of members. In the case of using the high-strength steel reinforcement, the diagonal crack width may be widened because the spacing of stirrups increases.

According to the ACI 318-14 design code [6], for non-prestressed flexural members, the yield strength of longitudinal tension steel used in design calculations shall not exceed 550 MPa to reserve adequate deformability and control deflections and cracking [1]. The ACI 318-14 code also limits the yield strength of shear reinforcement used in shear design to 420 MPa for two reasons; first to provide a control on diagonal crack width and second to prevent possible sudden shear failure due to concrete crushing before yielding of stirrups due to over shear reinforcement [1].

In this study, the following two topics were studied through FE analysis. The first is to investigate the increase of shear strength of PSC members with high strength stirrups. It is well known from previous studies [2], [5], [7], [8] that high strength steel reinforcement has a greater effect on shear strength improvement than ordinary steel reinforcement when using the same amount of reinforcement. Shear strength improvement is one of the main goals of using the high strength steel reinforcement. Therefore, in this study, the change of shear strength due to high strength steel reinforcement was studied.

The second is to measure the change in shear failure modes by using the high-strength stirrups for PSC members. When a high-strength stirrup is used, more than a certain amount of shear-rebar cannot be used due to the limitation on the

J.-Y. Lee is with the School of Civil and Architectural Engineering, Sungkyunkwan University, Suwon, Republic of Korea (corresponding author, phone: +82-31-290-7564; fax:+82-31-2907570; e-mail: jungyoon@skku.edu).

H.-S. Lim and S.-E. Kim are with the Department of Civil, Architectural, and Environmental Engineering, Sungkyunkwan University, Suwon, Republic of Korea (e-mail: hyesssun@hanmail.net, se21008@naver.com).

Open Science Index, Structural and Construction Engineering Vol:11, No:6, 2017 publications.waset.org/10007191/pdf

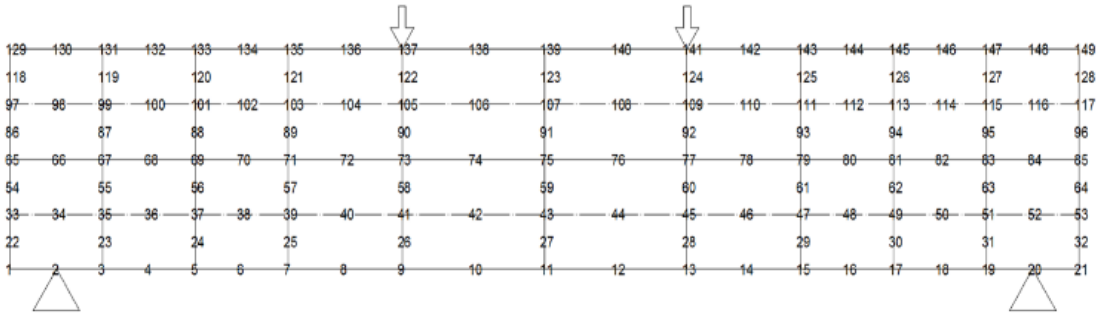
maximum amount of shear reinforcement. In this study, the shear failure modes of PSC members were evaluated considering the relationship between the yield strength of reinforcing bars and high strength concrete.

II. FE Analysis for PSC Beams

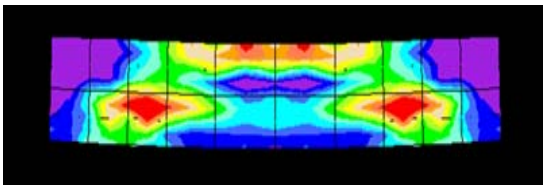
A. Element Segmentation and Beam Specimens

This study used the two-dimensional nonlinear FE analysis program, RCAHEST (RC Analysis in Higher Evaluation System Technology) [9] to perform the numerical analysis for the shear-critical PSC beams. RCAHEST is based on FEAP, a FE analysis program developed by Taylor of the University of California at Berkeley, to evaluate the nonlinear behavior of RC and PSC members by applying a user-required material model such as a RC plane stress element, a prestressed tendon element. Shear strength, deflection, and the yield of shear reinforcement of post - tensioned PSC beams using high - strength shear reinforcement were analyzed utilising RCAHEST.

In order to evaluate the accuracy of RCAHEST, shear behavior of eight PSC beam specimens tested by Lim [10]. PSC members are composite materials consisting of concrete, longitudinal steel bars, shear reinforcing bars, and prestressed steel bars. The nonlinear material model of RCAHEST can be expressed as a superposition of these constituent materials as shown in Fig. 1. In RCAHEST, the PSC member was modeled with two-dimensional RC plane stress element with eight nodes and the linear tendon element with two nodes.



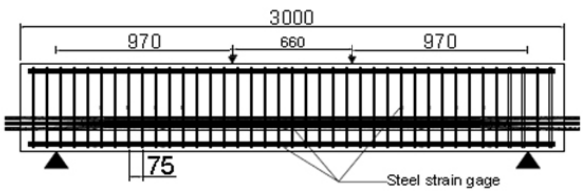
(a)



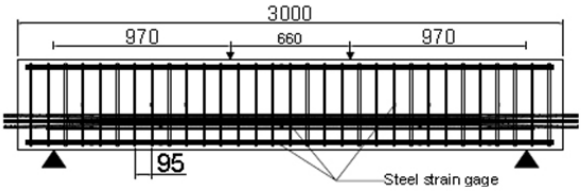
(b)

Fig. 1 FE analysis: (a) element segmentation and (b) stress distribution

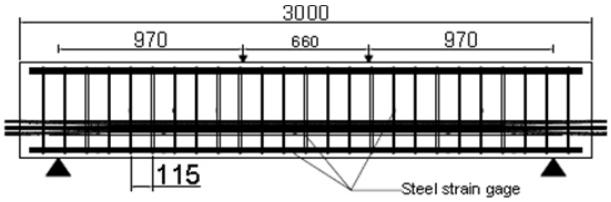
Fig. 1 shows the element segmentation and material model applied to RCAHEST. In the analysis, the specimens were divided into a total of 80 elements consisting of 40 RC plane stress elements and 40 linear tendon elements. In order to give the same conditions as the experiment test specimens, the loading and supporting points were modeled as a simple boundary condition. The load was applied to 350 steps, and the displacement was controlled to 35 mm.



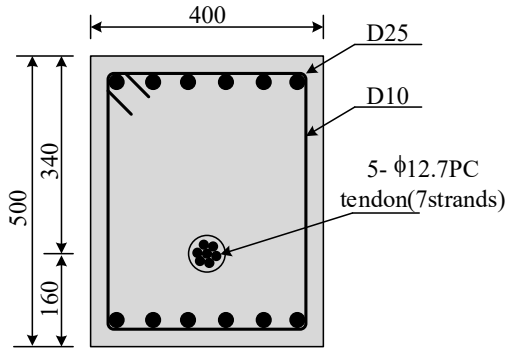
(a)



(b)



(c)



(d)

Fig. 2 Analyzed PSC beam (Unit : mm): (a) PSC420, PSC535a, and PSC 675a, (b) PSC535b, (c) PSC675b, and (d) beam section

TABLE I
DETAILS OF SPECIMENS

PSC beams	Longitudinal reinforcement			Shear reinforcement				
	No.	f_y (MPa)	ρ_l (%)	No.	s (mm)	f_{yt} (MPa)	ρ_t (%)	$\rho_t \times f_{yt}$
PSC420					75	419.6	0.48	2.00
PSC535a					75	535.7	0.48	2.55
PSC675a	6-D25	691.8	1.79	D10	75	674.6	0.48	3.21
PSC535b					95	535.7	0.38	2.01
PSC675b					115	674.6	0.31	2.09

f_y: yield strength of longitudinal steel bars, ρ_l: longitudinal reinforcement ratio, f_{yt}: yield strength of stirrup, ρ_t: shear reinforcement ratio, s: spacing of stirrups

The PSC beams compared in the analysis were tested by Lim [10]. Totally five simply supported PSC beams were tested to evaluate the shear behavior related to the yield strength of shear reinforcement. Concrete strength was 53 MPa, and yield strengths of stirrups were 420, 535, and 675 MPa. A cross-sectional dimension of PSC beams was 400 mm × 500 mm (15.7 in. × 19.7 in.). Five post-tensioning strands were implemented at the bottom of the beams. All the stirrups were designed and located in accordance with section 9.6.3 and 22.5.10 of ACI 318-14 [6]. The stirrup spacing of specimen, 75, 95, and 115 mm was designed to have a nearly identical stirrup amount ($\rho_t \times f_{yt}$) as yield strength of stirrup increases. Details of specimens can be seen in Fig. 2 and

TABLE I.

The shear span-depth ratio (a/d) of all the beams was planned 2.3. D29 deformed steel bars with 691.8 MPa yield strength were used for the longitudinal compressive and tensile steel bars. For the shear reinforcement, D10 deformed steel bars were used to be perpendicular to longitudinal axis. According to the presence of shear reinforcement and yield strength, five PSC beams have a different yield strength of shear reinforcement as listed in Table I. Fig. 2 shows the overall dimensions of tested PSC beams.

B. Load and Deflection Curves

Fig. 3 shows the analysis and experimental results. It can be seen that the results of the FE analysis predict the actual experimental results with reasonable agreement. For the ratio of the observed and predicted shear strength, the average value is 0.99, and the coefficient of variation is 5.43 percent. As the yield strength of the shear reinforcement increases, the calculated and observed shear strength of the specimen increases. In addition, even in the case of yield strength of 646.6Mpa, the specimens PSC675a and PSC675b, the analytical and experimental test results showed that all the specimens showed shear tension failure, i.e. the beams fail in shear due to web concrete crushing after the yielding of shear reinforcement. In Fig. 3, the predicted displacement in the analysis is greater than the experimentally observed one. This is because the elastic modulus of the concrete used in the analysis is smaller than the modulus of elasticity of the actual concrete.

TABLE II
COMPARISON OF TEST AND ANALYSIS RESULTS

Specimen	Test results		RCAHEST		ACI 318-14	$V_{RCAHEST}$ / V_{test}
	Shear strength (kN)	Deflection (mm)	Shear strength (kN)	Deflection (mm)		
PSC420	2036.2	16.95	1898.0	12.01	1271.3	0.93
PSC535a	2014.5	16.31	2075.3	12.99	1453.5	1.03
PSC675a	2190.8	18.19	2232.3	14.29	1678.8	1.02
PSC535b	1963.4	16.06	1902.2	11.85	1269.5	0.97
PSC675b	1929.5	16.30	1912.4	11.85	1295.5	0.99

Table II compares the shear strength and deflection measured in experiments and analyses. Shear strength calculated by ACI 318-14 design code is also compared with the shear strength measured in the experiment test and the strength.

III. ANALYSIS RESULTS

A. Parameters

The shear behavior of PSC members was estimated by simulating the FE program, RCAHEST, considering the effect of two parameters: yield strength of shear reinforcement and compressive strength of concrete, to the shear behavior of PSC beams. These variables are considered as the most important factors affecting the shear strength and shear failure mode of PSC beams.

B. Effect of Yield Strength of Stirrups

The shear behavior of PSC beams with various yield strength of stirrups, 750 MPa, 800 MPa, 850 MPa, and 860 MPa, was compared using the analysis program. Table III shows the details of PSC beams used in the analysis. The compressive strength of concrete is 53.7 MPa, and the yield strength of longitudinal reinforcement is 691.8 MPa. The shear

Open Science Index, Structural and Construction Engineering Vol:11, No:6, 2017 publications.waset.org/10007191/pdf

Open Science Index, Structural and Construction Engineering Vol:11, No:6, 2017 publications.waset.org/10007191/pdf

span-to-depth ratio of the specimens was 2.3. A cross-sectional dimension of PSC beams was 400 mm × 500 mm. Five post-tensioning strands were implemented at the bottom of the beams.

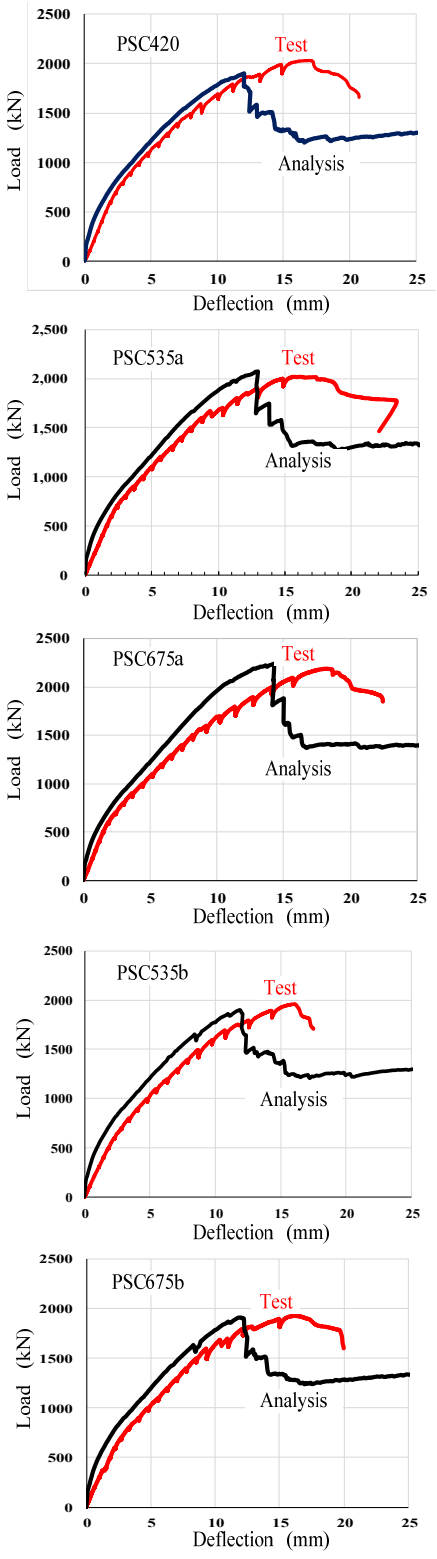


Fig. 3 Comparison of experimental and analytical load-deflection curves

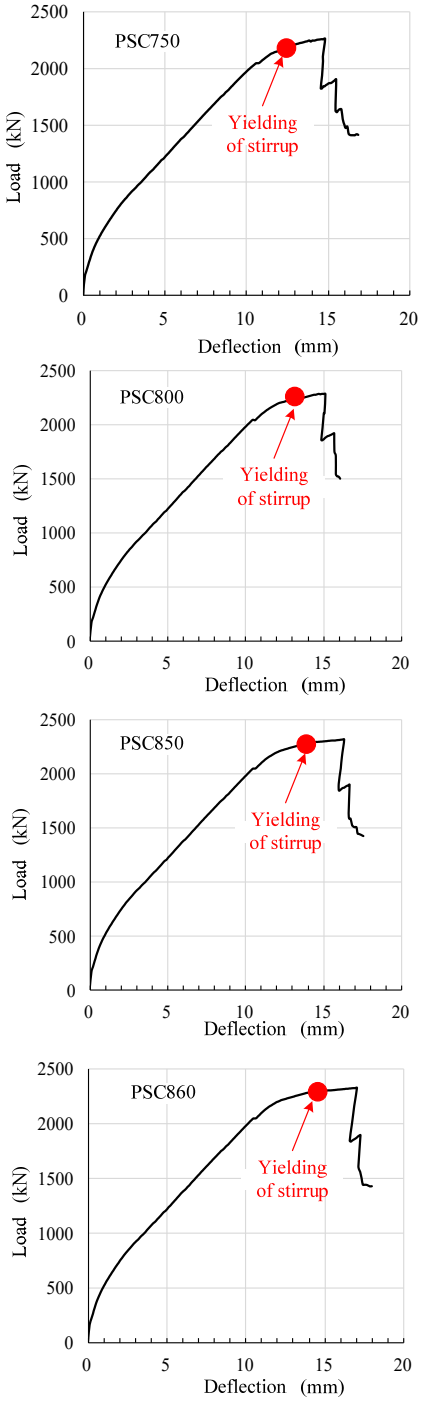


Fig. 4 Comparison of experimental and analytical load-deflection curves of PSC beams with various yield strength of stirrups

TABLE III
DETAILS OF THE SPECIMENS WITH VARIOUS YIELD STRENGTH OF STIRRUPS

Specimens	FC' (MPA)	Longitudinal reinforcement		Shear reinforcement		
		fy (MPa)	ρl (%)	s (mm)	fyt (MPa)	ρt (%)
PSC750	53.7	691.8	1.79	75	750	0.48
PSC800	53.7	691.8	1.79	75	800	0.48
PSC850	53.7	691.8	1.79	75	850	0.48
PSC860	53.7	691.8	1.79	75	860	0.48

The load deflection curves of the PSC beams measured in the

Open Science Index, Structural and Construction Engineering Vol:11, No:6, 2017 publications.waset.org/10007191/pdf

analysis are shown in Fig. 4. In the analysis, it was measured whether the shear reinforcement of each specimen reached its yield strength. As the yield strength of the shear reinforcement increases, the yield point of the shear reinforcement tends to approach the maximum strength of the member, as shown in Fig. 4. In addition, as the yield strength of the shear reinforcement increased, the shear strength of the PSC beam increased at a constant rate. The ratio of the load at stirrup yielding to maximum load of specimen, PSC750, PSC800, PSC850, and PSC860 was 0.78, 0.81, 0.83, and 0.83, respectively. In the analysis, when the yield strength of stirrup exceeded 860 MPa, the failure mode changed from shear tension failure to shear compression failure. That is, when the yield strength of the stirrup exceeds 860 MPa, the PSC beam fails due to web concrete crushing without the yielding of shear reinforcement. Considering that the limit value of the yield strength of shear reinforcement in the ACI 318-14 design code is 500 MPa, the maximum yield strength of the shear reinforcement measured in the analysis is 860 MPa. Therefore, the yield strength limitation in the ACI 318-14 design code may be conservative.

C. Effect of Ratio of Compressive Strength of Concrete and Yield Strength of Stirrup

The shear failure modes of PSC beams are affected by the yield strength of stirrups and the compressive strength of concrete. The shear behavior of four PSC beams was evaluated using the ratio of compressive strength of concrete and yield strength of stirrup as a parameter. In the analysis, the shear strength and shear failure modes of PSC beams using the compressive strength of concrete 36 MPa and 48 MPa, which is smaller than the compressive strength of concrete 53.7 MPa used in the test specimens (Table III) to investigate the effect of the yield strength of stirrup, were evaluated. The compressive strength of the concrete, f_c', used in the specimens with yield strength of stirrup 420 MPa was 36 MPa, and the compressive strength of concrete, f_c', used in the specimens with yield strength of stirrup, 535 MPa and 675 MPa, was 48 MPa, as listed in Table IV. Same as the test specimen for evaluating the effect of the yield strength of shear reinforcement, the shear span-to-depth ratio of the specimens was 2.3. A cross-sectional dimension of PSC beams was 400 mm × 500 mm, and five post-tensioning strands were implemented at the bottom of the beams.

Fig. 5 shows the load vs. deflection curves of the specimens with various compressive strength of concrete. As shown in Fig. 5, the shear strength of PSC beams increases as the compressive strength of concrete and the yield strength of stirrup increase. The load of the PSC beam when the shear reinforcement yields is shown in Fig. 5. The shear reinforcement of all specimens yielded before reaching the shear strength. The ratio of the load at stirrup yielding to maximum load of specimen, PSC36-1, PSC48-1, PSC48-2, and PSC48-3 was 0.91, 0.79, 0.81, and 0.86, respectively. As the compressive strength of concrete increases, the ratio of the load at stirrup yielding to maximum load of specimen increases.

TABLE IV
DETAILS OF THE SPECIMENS WITH VARIOUS COMPRESSIVE STRENGTH OF CONCRETE

Specimens	f_c' (MPa)	Longitudinal reinforcement		Shear reinforcement		
		f_y (MPa)	ρ_l (%)	s (mm)	f_{yt} (MPa)	ρ_t (%)
PSC36-1	36.0	691.8	1.79	75	419.6	0.48
PSC48-1	48.0	691.8	1.79	75	419.6	0.48
PSC48-2	48.0	691.8	1.79	75	535.7	0.48
PSC48-3	48.0	691.8	1.79	75	674.6	0.48

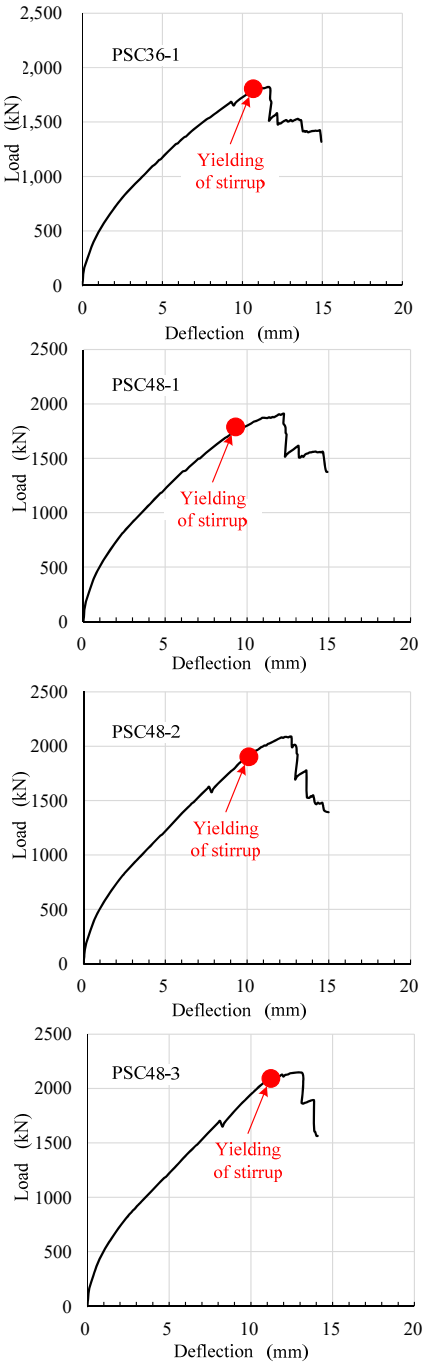


Fig. 5 Comparison of experimental and analytical load-deflection curves of PSC beams with various compressive strength of concrete

Open Science Index, Structural and Construction Engineering Vol:11, No:6, 2017 publications.waset.org/10007191/pdf

IV. Conclusions

In this study, the shear behavior of PSC beams with high strength materials was predicted by simulating an FE analysis. The shear strength and shear failure modes were predicted by simulating the analysis varying three parameters: shear reinforcement ratio, yield strength of shear reinforcement, and compressive strength of concrete. The analytical results can be summarized as:

1) The ACI318-14 design code limits the yield strength of shear reinforcement for PSC beams to 500 MPa, but the analytical results show that the PSC beams with the yield strength of shear reinforcement of 860 MPa showed shear tension failure. As a result, it may conclude that the yield strength limitation of shear reinforcement in the ACI318-14 design code is very conservative.
2) The shear failure mode of PSC beams was strongly related with the ratio of compressive strength of concrete and yield strength of stirrup. As the compressive strength of concrete increased, the maximum yield strength of shear reinforcement of PSC beams showing shear tension failure increased.

Acknowledgment

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (grant number: 2015R1D1A1A01056612).

References

[1] H.-S. Lim, B.-K. Jun, D.-I. Shin, and J.-Y. Lee, "Shear Capacity of Post-Tensioning Pre-Stressed Concrete Beams with High Strength Stirrups," *International Journal of Structural and Civil Engineering Research*, vol. 5. no. 4, 2016, pp.258-264.

[2] A. Munikrisha, A. Hosny, S. Rizkalla, and Zia, P., "Behavior of Concrete Beams Reinforced with ASTM A1035 Grade 100 Stirrups under Shear," *ACI Structural Journal*, vol. 108. no. 4, 2011, pp.34-41.

[3] A. Hosny, H. M. Seliem, S. Rizkalla, and P. Zia, "Development Length of Unconfined Conventional and High-Strength Steel Reinforcing Bars," *ACI Structural Journal*, vol. 109, no. 5, 2012, pp.655-664.

[4] H. Aoyama, *Design of Modern Highrise Reinforced Concrete Structures*, Imperial College Press, 2001, 442pp.

[5] J.-Y. Lee and I.-J. Choi, "Shear Behavior of Reinforced Concrete Beams with High-Strength Stirrups," *ACI Structural Journal*, vol.108, no.5, 2011, pp. 620-629.

[6] ACI Committee 318, *Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary*, Farmington Hills, MI: American Concrete Institute, 2014, 520 pp.

[7] J.-Y. Lee, D.-H. Lee, J.-E. Lee, and S.g-H. Choi, "Shear Behavior and Diagonal Crack Width for RC Beams with High Strength Shear Reinforcement," *ACI Structural Journal*, vol. 112, no.3, 2011. pp. 323-333.

[8] J.-Y. Lee, S.H. Choi, and D.-H. Lee, "Structural behaviour of reinforced concrete beams with high yield strength stirrups," Magazine of Concrete Research, vol. 68, no.23, 2016. pp. 1187-1199.

[9] Hyun mok, Shin, Tae hoon, Kim, Jae Geun, Park, Dae Jeong, Seong. (2008). *Nonlinear Finite Element Analysis of Reinforced Concrete Bridge*, 2008, 190pp

[10] H.-S. Lim, *Evaluation for Shear Behavior of PSC beams with High Strength of Shear Reinforcement*, Sungkyunkwan University, MS dissertation, 2017

Jung-Yoon Lee is a Professor in the Dept. of Civil, Architectural and Environmental System Engineering at Sungkyunkwan University, Republic of Korea. He is involved in the committees, Shear and Torsion and Seismic Design, of the Korean Concrete Institute Committee. He has performed extensive research on the shear behavior and seismic design of reinforced and prestressed concrete buildings.

Hye-Sun Lim received his BS degree from SungKyunKwan University at Suwon, Republic of Korea in 2015. Her research interests include the shear behavior of prestressed concrete structure. She is in a master's degree course in the Dept. of Civil, Architectural and Environmental System Engineering at SungKyunKwan University, Republic of Korea.

Sung-Eun Kim received his BS degree from SungKyunKwan University at Suwon, Republic of Korea in 2016. Her research interests include the torsional behavior of reinforced concrete structure. She is in a master's degree course in the Dept. of Civil, Architectural and Environmental System Engineering at SungKyunKwan University, Republic of Korea.