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Experimental Study on the Retrofit of RC Frame with the Perforated Steel Plate

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ABSTRACT

Non-seismic designed RC frame is more likely to be damaged at low story drift during earthquakes due to small deformation capacity. As one of stiffness enhancement method steel plate wall is effective for these buildings. Though the steel plate wall has an excellent effect of increasing stiffness and strength, it can't be installed outside due to prevention of lighting and ventilation. In order to compensate for these limitations, the perforated steel plate wall using perforations in the steel plate was proposed.

This experiment was conducted to verify that the equation suggested by Park (2020) for predicting the strength of perforated steel plate without studs, with a ratio of diameter to diagonal distance between each perforation line is greater than 60%, can also be applied to predict the strength of perforated steel plate with stud. The parameters are perforation ratio and diameter.

As a result of the experiment, it was found that the specimens without stud yielded at 0.4% or less, while the specimens with stud yielded at 0.6-1.1%, and the yielding strength was almost the same regardless of the with and without of stud. The strength at the yield point of each specimen was more than 85% of the maximum strength of the specimen, and the strength was maintained after yielding until to story drift 3.5%. Park's equation predicted the strength of perforated steel plates without studs more accurately than previously suggested equation. However, the strength of perforated steel plates with studs was somewhat underestimated.

Keywords: perforated steel plate, seismic retrofit of RC frame, lateral load experiment, stud, perforation ratio

INTRODUCTION

The retrofit of non-seismic designed RC frame include ductility enhancement, which improves the deformation capacity of the building, and stiffness enhancement, which increases the strength of the building. In general, stiffness enhancement methods are used to increase the stiffness and strength of existing buildings by constructing or adding shear walls or bracing to resist seismic loads. The use of shear walls or bracing reduces deformation by increasing the stiffness of the building against lateral forces, thus reducing the lateral displacement for earthquakes [1]. In general, the vulnerability of non-seismic designed RC frames to small deformation is widely recognized, so stiffness enhancement methods are useful for buildings with poor deformation capacity. This method has the advantage of reducing the displacement of the building due to increased stiffness, and the disadvantage of increasing the magnitude of reaction forces due to the concentration of seismic forces in the retrofit reinforcement system.

One of the ways the stiffness enhancement method is to install shear walls, which are placed with RC or steel plates [2]. RC shear wall is the most efficient way to increase stiffness, but it may be difficult to construct. Steel plate shear wall (SPSW) is an excellent way to increase stiffness and strength, but it is limited to interior applications due to light and ventilation issues. To overcome these limitations, researches have been conducted on perforated steel plate that can be installed on the interior and exterior of buildings. A perforated steel plate is a steel wall with perforations for light and ventilation, and by adjusting the diameter and ratio of the perforations, the stiffness and strength of the steel wall can be adjusted.

In this study, experimental research is focused on the lateral force resistance characteristics of perforated steel plates with a larger of ratio of the diameter to the diagonal distance between each perforation lines (perforation ratio, D/S_{diag} , see Figure 1(b)) than in previous studies. In addition, experimental research is executed to see the effect of the stud on the strength of the perforated steel plate by installing stud between the perforated steel plates.

BACKGOROND

Research on circular perforations in shear panels started with Roberts et al.(1992) [3] They conducted a series of quasi-static tests under cyclic diagonal loading on unstiffened steel plate shear panels with center circular openings. The following approximate Eq. (1) was proposed for the calculation of the strength of an unstiffened infill panel with a central circular opening:

$$V_{op} = V_p \left[1 - \frac{D}{d_p}\right] \tag{1}$$

Where, V_{op} and V_p are the strength of a perforated and a solid shear panel, respectively, D is the perforation diameter, and d_p is the panel height.

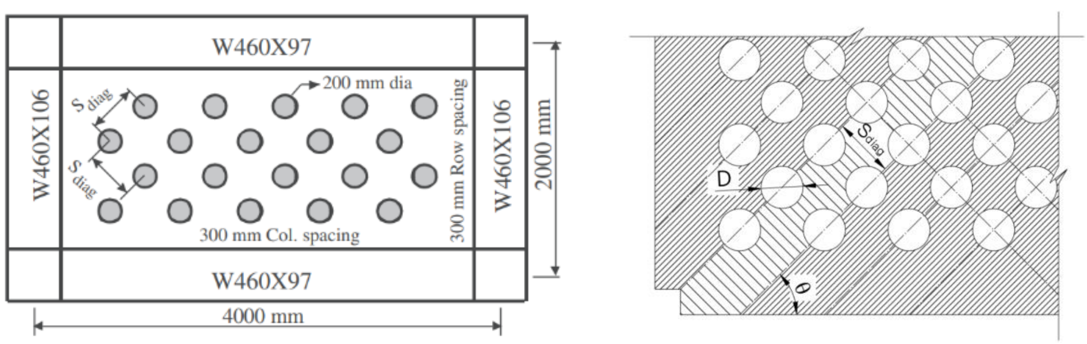
Vian et al.(2005) (see Figure 1(a)) [4] analyzed a perforated steel plate shear wall with multiple regularly-spaced circular perforations was carried out. Eq. (2) proposed for the calculation of the strength of perforated shear plate with multiple regularly-spaced circular perforation.

$$V_{op} = V_p \left[1 - \frac{D}{S_{diag}}\right] \tag{2}$$

Where, S_{diag} (see Figure 1(b)) is the diagonal distance between each perforation line.

Purba et al.(2006) [5], through the work of Vian, conducted a detailed study of individual perforated strip in Figure 1, and calculated the strength of perforated steel plate from the strength of individual perforated strip. Also found that results from an individual perforated strip analysis can accurately predict the behavior of a complete SPSW when perforations ratio D/S_{diag} is less than 60%. The modified Eq. (3) was proposed to calculate the shear strength of perforated SPSWs with the regular perforation pattern used by Vian.

$$V_{op} = V_p \left[1 - 0.7\frac{D}{S_{diag}}\right] \tag{3}$$



(a) *(b)*

Figure 1. (a) Test specimen form Vian[2] (b) Diagonal distance between each perforation line, S_{diag}

Therefore, this experiment was conducted to verify whether the equation for predicting the strength of perforation ratio D/S_{diag} greater than 60% suggested by Park (2020) can also be applied to predict the strength of specimens with stud. The parameters are perforation ratio D/S_{diag} and diameter.

EXPERIMENTS

Experimental design

The experiment was built as a 1/3 scale model based on the exterior frame of a school building built in the 1980s, which is a non-seismic designed RC frame. The building is a three-story reinforced concrete structure with a frame of 4.5 meters by 7.5 meters, and each floor is 3.3 meters high.

The perforation ratio D/S_{diag} greater than 60% for the experiments with and without stud. The experiments were designed with perforation ratio, perforation diameter, and perforation ratio D/S_{diag} as the main variables, and the specimens is shown in Table 1. The perforated steel plate specimen unit 1 is shown in Figure 2, the thickness of the plate is 0.8mm, and galvanized steel is used. The exterior column of the experiment is H-200×200×8×12(SS275 [SS400]) and stud is ⊏-150×75×6.5×10(SS275 [SS400]), and the exterior column is bolted so that only shear force can be transmitted. The beam-column joint is hinged so that the load resistance of the frame does not affect the perforated steel plate, as shown in Figure 3.

Table 1. List of specimens

Specimen	(1) Perforation area (%)	(2) Perforation diameter (D, ㎜)	(3) Perforated strip width (S_{diag}, ㎜)	(4) = (2)/(3) (%)
Unit 1	26	42.5	70.71	60
Unit 2	35	49.62	70.71	70
Unit 3	35	29.8	42.43	70
Unit 4	35	110.5	157.33	70
Unit 5	40	53	70.71	75
Unit 6	-	-	-	
Unit S1	26	42.5	70.71	60
Unit S2	35	49.62	70.71	70
Unit S3	35	29.8	42.43	70
Unit S4	35	110.5	157.33	70
Unit S5	40	53.0	70.71	75
Unit S6	-	-	-	-

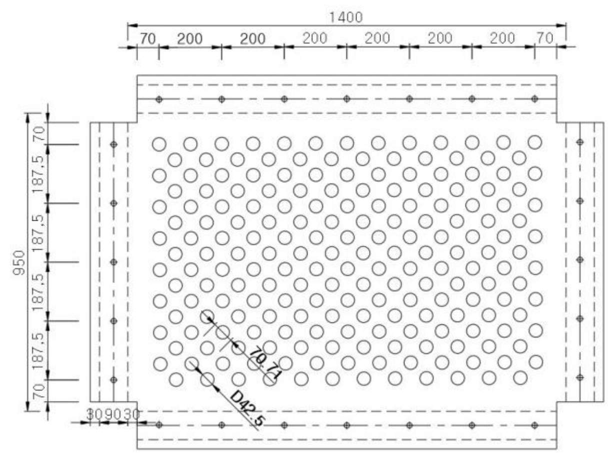
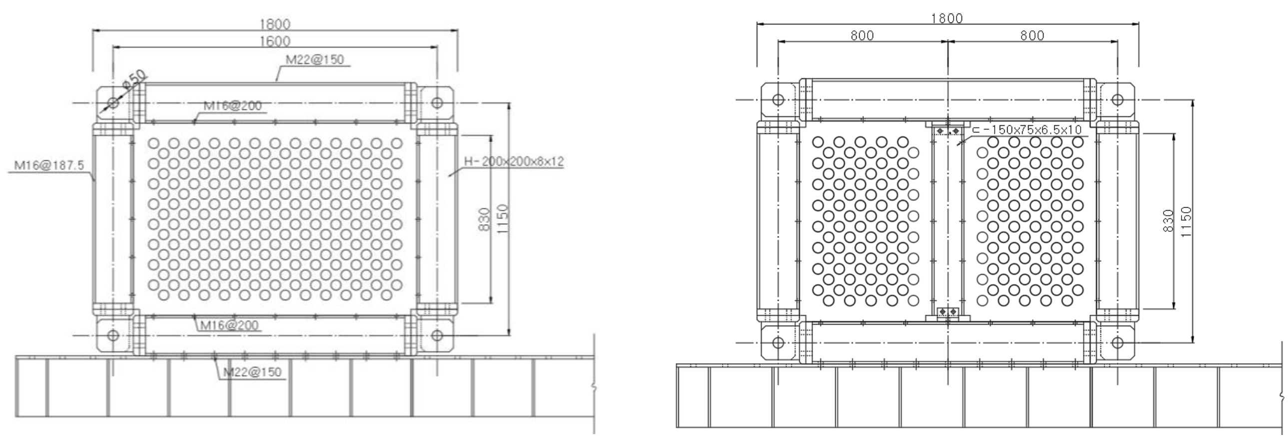


Figure 2. Perforated steel plate (Unit 1)

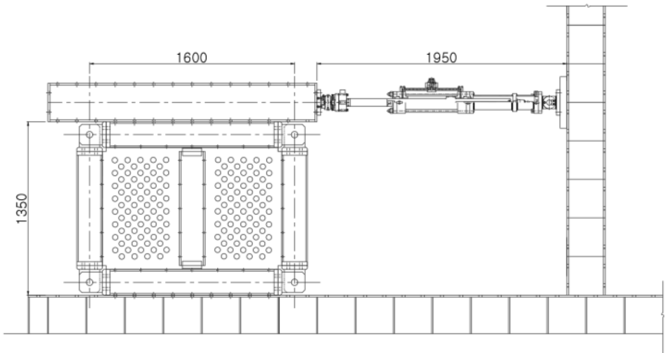


(a) *(b)*

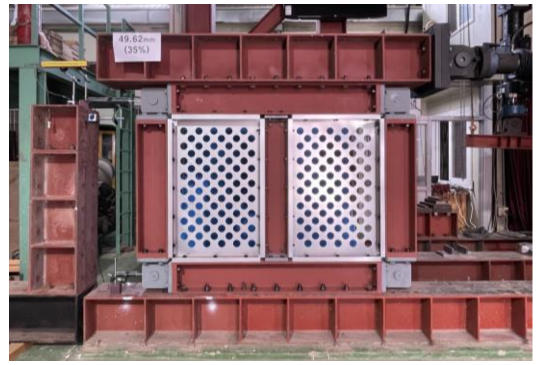
Figure 3. Drawing for specimen; (a) without stud (b) with stud

Experimental setup

The experimental setup is shown in Figure 4. An actuator with a capacity of 250kN was installed on the upper right side of the experiment to repeatedly apply a horizontal load, and a zig was installed on the upper side to prevent twisting.



(a)



(b)

Figure 4. Experimental set up; (a) drawing for lateral loading (b) and its figure

Measurement and loading plan

As shown in Figure 5, story drift was measured at three locations from the bottom of the column, and strain rosettes were attached at ten locations to determine the principal stress direction. The lateral loading was planned according to the loading protocol recommended by ACI 374-05 [6], as shown in Figure 6. The load was applied in 11 steps with displacement control to 3.5% of the story drift and repeated 3 times for the same step.

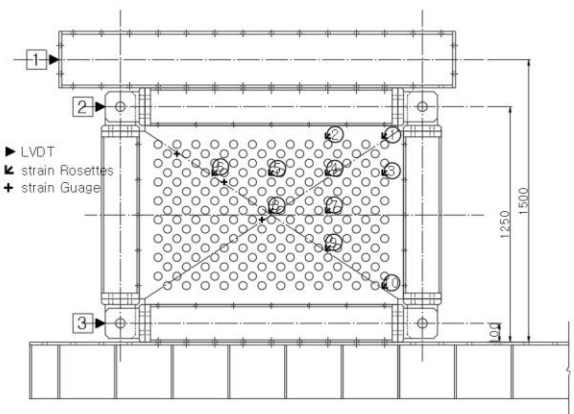


Figure 5. Measuring point of specimen

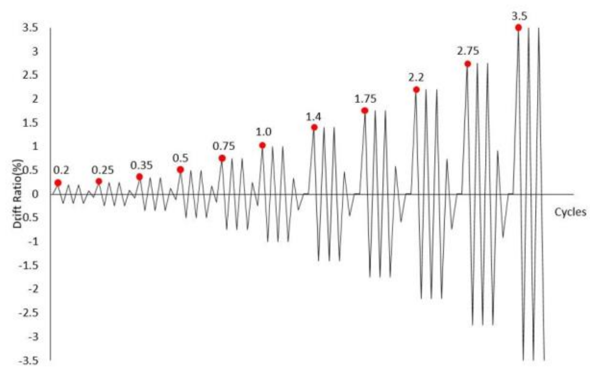


Figure 6. Loading protocol

Material test

The perforated steel plate is galvanized iron (GI), 0.8 mm thickness, and the tensile coupon test results are shown in Table 3. Result of tensile test exceeded the nominal yield strength, but fell short for tensile strength.

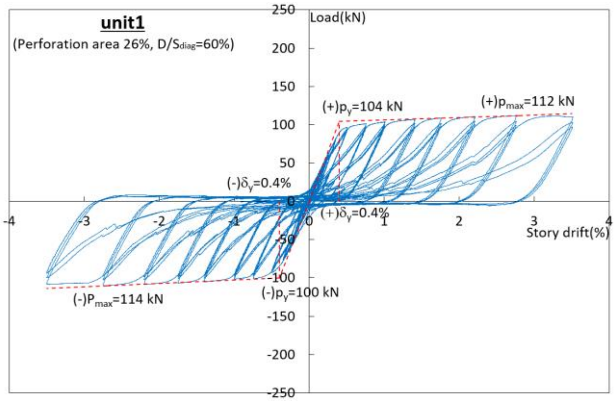
Table 2. Result of tensile test

	Thickness (㎜)		Yield stress (MPa)	Ultimate stress (MPa)	Yield strength ratio (%)
	Nominal	Actual			
SGC400	0.8	0.72	318	370	86

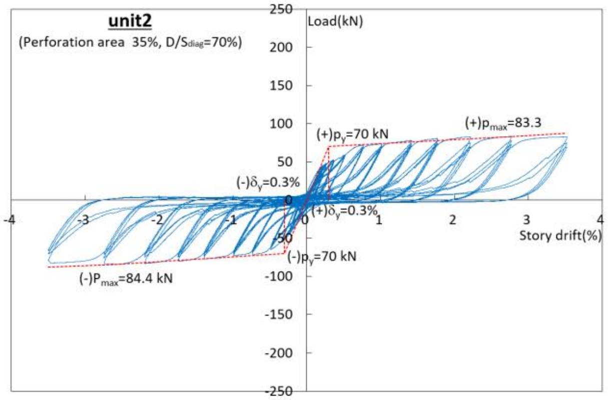
RESULTS AND COMPARISONS

Lateral load - drift ratio of specimens

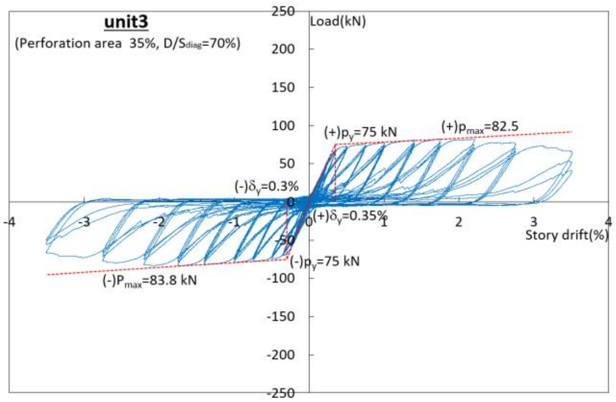
Lateral load-drift ratio of specimens showed similar behavior for all specimens, as shown in Figure 7. The specimens without stud yielded at story drift ratios of 0.4% or less, while specimens with stud yielded at 0.6-1.1%. All specimens exhibited at least 85% of their maximum strength at the point of yield, with maintaining the in strength after yield. The reason why the initial stiffness of the specimen with stud is somewhat lower than the specimen without stud may be the different story drift angles due to the height difference between the exterior columns and the stud. The deformation at the 3.5% story drift ratio in the experiment is shown in Figure 8.



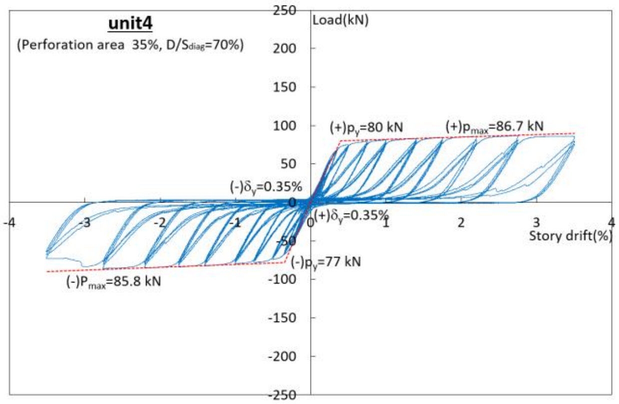
(a) Unit 1



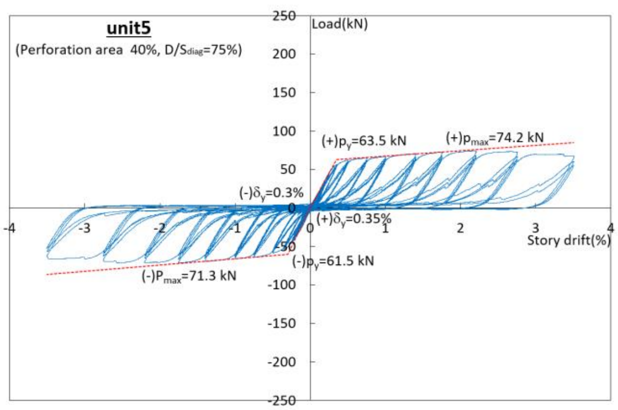
(b) Unit 2



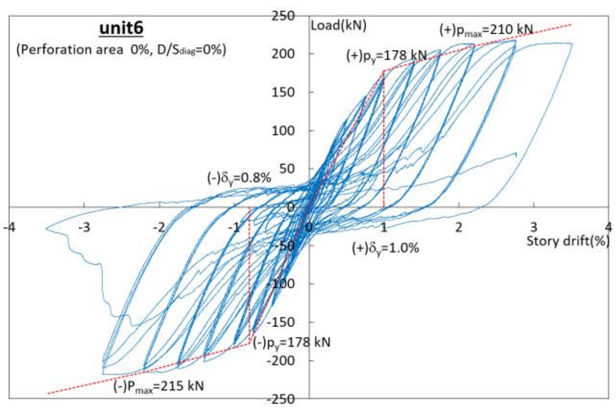
(c) Unit 3



(d) Unit 4

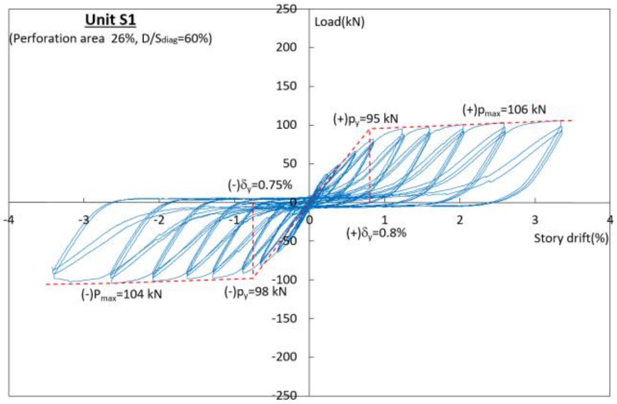


(e) Unit 5

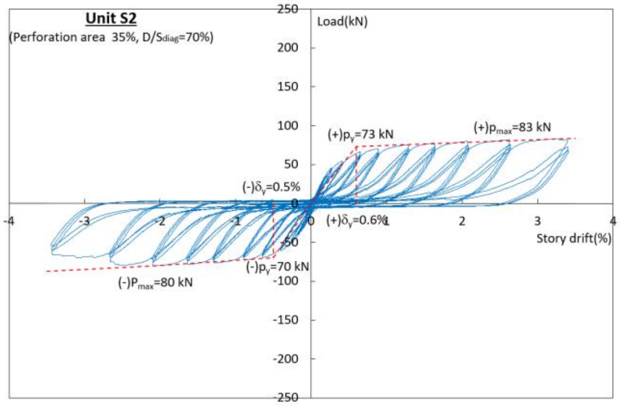


(f) Unit 6

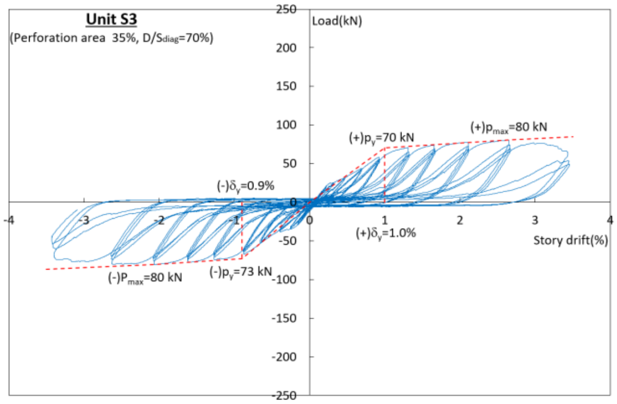
Figure 7. Lateral load - drift ratio of specimens (Cont.)



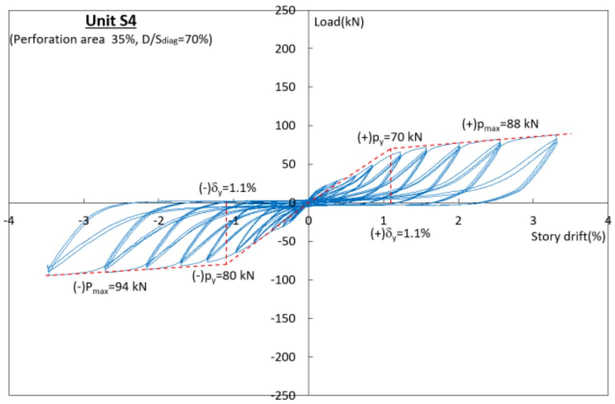
(g) Unit S1



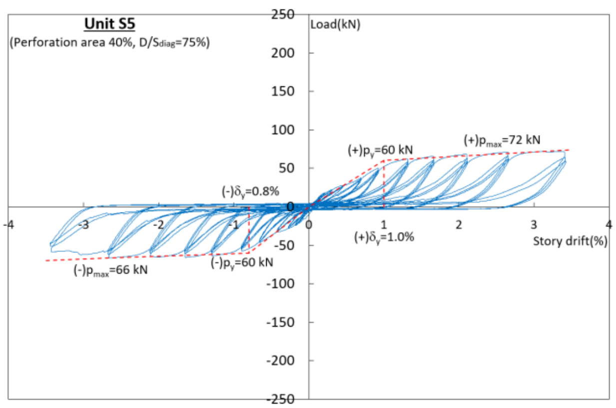
(h) Unit S2



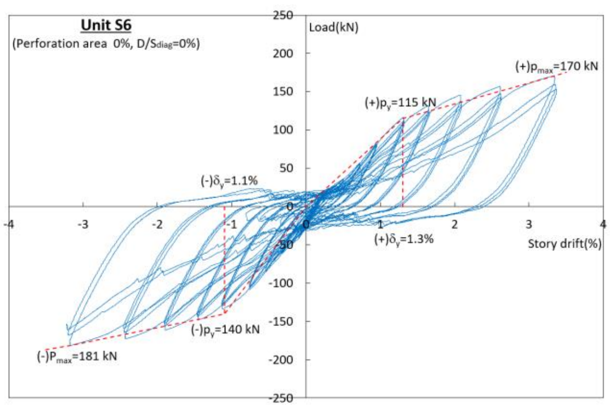
(i) Unit S3



(j) Unit S4

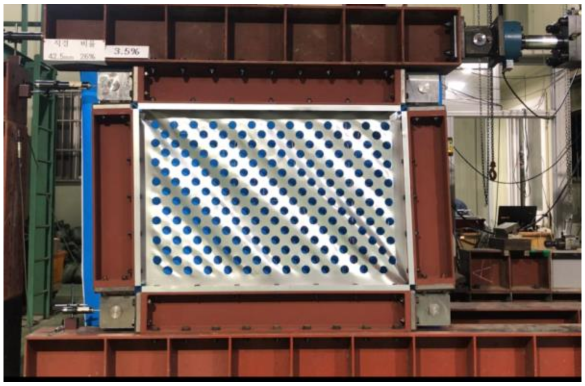


(k) Unit S5



(l) Unit S6

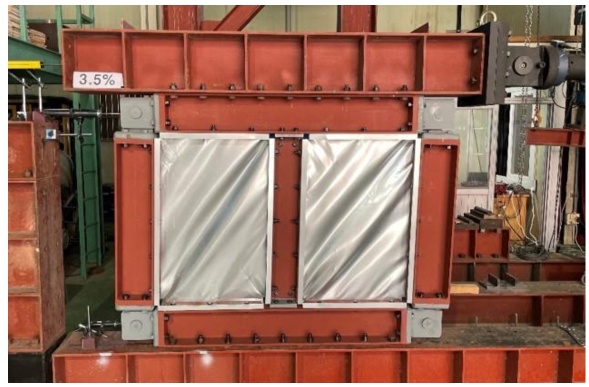
Figure 7. Lateral load - drift ratio of specimens



(a)Unit 1

(b) Unit 6

(c)Unit S1



(d) Unit S6

Figure 8. Deformation of specimens at 3.5% story drift ratio

Yield strength

The yield point of the specimen was calculated so that the area of the load-drift ratio from the experiment and the area of the curve converted to the bi-linear model were similar. The yield strength and yield displacement of the specimen is load-drift ratio converted to a bi-linear model are shown in Table 3. The stiffness of the perforated steel plate was obtained by dividing the yield strength by the yield displacement (column (2) of Table 3).

Strength prediction equation

The results of comparing the strength of the perforated steel plate obtained through the experiment with the equation suggested by Purba (2006) are shown in column (3) of Table 3. The strength of the perforated steel plate was compared based on the maximum strength, while the strength of the Unit 6 and Unit S6 without perforations was compared based on the yield strength because the strength continued to increase after yield until the maximum lateral displacement ratio of the experiment was 3.5%. To predict the intensity for experiments with perforation ratio D/S_{diag} greater than 60%, the Purba's equation (2006) was modified with the intensity obtained as the average value of perforation ratio D/S_{diag}, and the result is shown in Figure 9. Through this process, the strength prediction equation for perforated steel plates with a perforation ratio D/S_{diag} greater than 60% was suggested by park (2020) as shown in equation (4) [7].

$$V_{op} = V_p \left[1.33 - 1.24 \frac{D}{S_{diag}}\right] \tag{4}$$

Table 3. Comparison of experimental results by strength prediction equation

Specimen	D/S_{diag} (%)	(1) Maximum load(kN)	Yield point								Strength prediction equation					
			Positive loading(+)				Negative loading(+)				Purba et al.(2006)		Park(2020)			
			P_y (kN)	δ_y (㎜)	Story drift (%)	(2) K_y (kN/㎜)	P_y (kN)	δ_y (㎜)	Story drift (%)	K_y (kN/㎜)	(3) Strength (kN)	(4) Strength Ratio =(3)/(1)	(5) Strength (Eq. 4) (kN)	(6) Strength Ratio =(5)/(1)	(7) Strength (kN)	(8) Strength Ratio =(7)/(1)
Unit 1	60	112.0	104	3.5	0.4	29.5	100	3.5	0.4	28.4	103.3	0.92	103.5	0.92		
Unit 2	70	83.3	70	2.6	0.3	26.5	70	2.6	0.3	26.5	90.82	1.09	81.4	0.98		
Unit 3	70	82.5	75	3.1	0.35	24.3	75	2.6	0.3	28.4	90.82	1.10	81.4	0.99		
Unit 4	70	86.7	80	3.1	0.35	25.9	77	3.1	0.35	25.0	90.82	1.05	81.4	0.94		
Unit 5	75	74.2	63.5	3.1	0.35	20.6	61.5	2.6	0.3	23.3	84.59	1.14	70.3	0.95		
Unit 6	-	178.0*	178	8.8	1.0	20.2	178	7.1	0.8	25.2	178.1	-	178.1	-		
Unit S1	60	106	95	7.1	0.8	13.5	98	6.6	0.75	14.9	92.22	1.15	92.4	0.87	103.5	0.98
Unit S2	70	83.0	73	5.3	0.6	13.8	70	4.4	0.5	15.7	81.09	1.02	72.7	0.88	81.4	0.98
Unit S3	70	80.0	70	8.8	1	7.9	73	8.0	0.9	9.2	81.09	0.99	72.7	0.91	81.4	1.02
Unit S4	70	88.0	70	9.7	1.1	7.2	80	9.7	1.1	8.2	81.09	1.09	72.7	0.83	81.4	0.92
Unit S5	75	72.0	60	8.8	1.0	6.8	60	7.1	0.8	8.5	75.53	0.95	62.8	0.87	70.3	0.98
Unit S6	-	115*	115	11.5	1.3	10.0	140	9.7	1.1	14.4	159.0	-	159.0	-	-	-

* Yield load for Unit 6 & Unit S6

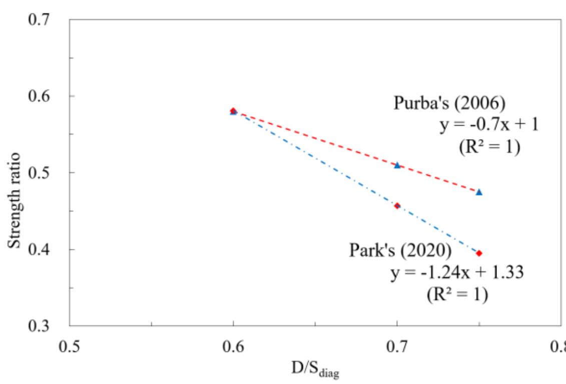


Figure 9. The suggested equation

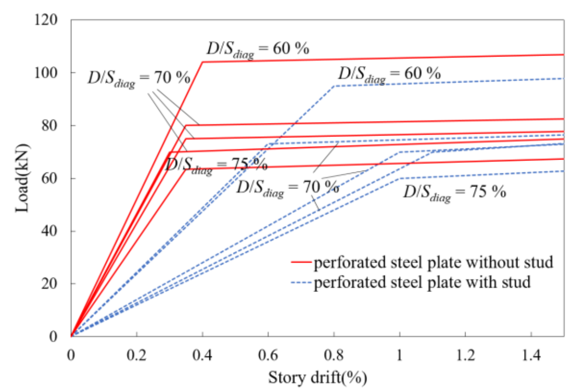


Figure 10. Initial stiffness by yield strength

By comparing the experimental results of the perforated steel plate without stud with the strength prediction equation, Park's equation (2020) was more accurate than the existing Pruba's equation (2006), but the value of the Park's equation was somewhat lower in the case with the stud. In the case of with stud the predicted strength is calculated by dividing the steel plate into two and summing their respective strengths, which reduces the effective area of the actual steel plate(column (5) of Table 3). The effective area of the perforated steel plate inside the exterior column can be assumed to be the same with or without stud, and using Park's equation for the specimen without stud, the ratio of the experimental strength divided by the strength using the proposed equation is accurately predicted to be between 0.92 and 1.02, as shown in column (8) of Table 3. Therefore, when calculating the strength in the presence of stud that transmit only shear forces, applying Eq. (4) assuming no stud will give a more accurate value, as shown in column (7) of Table 3.

Principal stress direction

To confirm the principal stress direction of the perforated steel plate, the deformation results of strain rosettes attached to 10 points of Unit 1 at story drift ratios of 0.35%, 0.5%, and 1.0% are shown in Table 4 and Figure 11. The experimental results showed that the principal stress direction of the perforated steel plate is closer to 45° than 34°, which is the diagonal direction of the steel plate.

Table 4. Principal stress angle

Loc. No. \ Story drift(%)	0.35	0.5	1.0
1	54.99	62.72	32.99
2	54.99	43.14	54.91
3	40.92	42.40	41.50
4	41.28	48.13	45.48
5	45.51	46.86	53.23
6	44.03	42.79	45.92
7	44.33	42.66	41.61
8	44.39	44.00	45.91
9	48.69	49.73	47.68
10	42.12	42.86	44.87

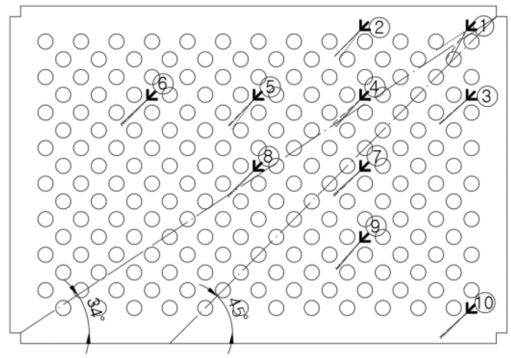


Figure 11. Principal stress direction

Horizontal stiffness of perforated steel plate

When the steel plate is converted to a strip model as shown in Figure 12, the effective stiffness for horizontal forces is equal to the horizontal force divided by the horizontal displacement. Converting the stiffness of a steel plate to a strip to the stiffness for a perforated steel plate can be expressed as Eq. (5).

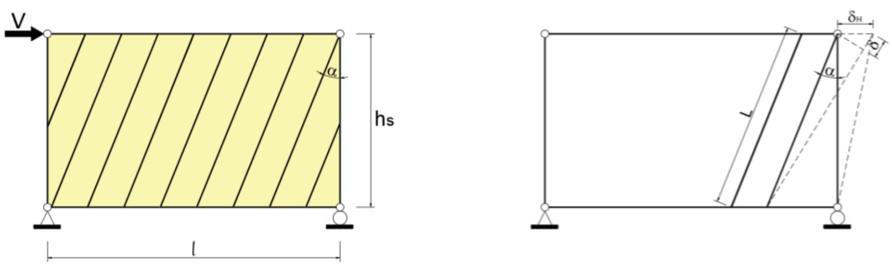


Figure 12. Strip model

$$k_0 = \lambda \frac{Etl(cos\alpha)^2}{h_s} \tag{5}$$

In Figure 12, the horizontal stiffness of a perforated steel plate based on the relationship between the horizontal displacement and the displacement in the diagonal direction and the strength of the strip due to the relationship between the horizontal strength and the tensile strength of the strip can be obtained as shown in Eq. (6). Assuming the angle of the strip to be 45°, the horizontal stiffness of the perforated steel plate can be simplified as shown in Eq. (7).

$$k_s = \lambda \frac{Etl(cos\alpha)^2(sin\alpha)^2}{h_s} = \lambda \frac{Etl(sin2\alpha)^2}{4h_s} \tag{6}$$

$$k_H = \lambda \frac{E}{4}\left(\frac{l}{h_s}\right)t \tag{7}$$

Table 5. Horizontal stiffness

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit S1	Unit S2	Unit S3	Unit S4	Unit S5
(1)	29.5	26.5	24.3	25.9	20.6	13.5	13.8	7.9	7.2	6.8
(2)	31.1	24.5	24.5	24.5	21.2	31.1	24.5	24.5	24.5	21.2
(1)/(2)	0.95	1.08	0.99	1.06	0.97	0.43	0.56	0.32	0.29	0.32

(1) Effective stiffness at yield point from experiment, (2) Horizontal stiffness by Eq. 6

In Table 5, the effective stiffness of the perforated steel plate is obtained by dividing the yielding force by yielding story drift ratio. Comparing the stiffness for the specimens without stud with the suggested equation (Park), the equation predicted with an accuracy of 0.95~1.06, while the stiffness with stud is less than 0.5. The reason why the initial stiffness of the specimen with stud is somewhat lower than the specimen without stud (see Figure 10) is estimated to be an error caused by the different column inclination angles due to the height difference between the exterior columns and the stud.

CONCLUSION

An experiment was conducted on the lateral load resistance characteristics of perforated steel plates with studs for seismic retrofit of RC frames. The experiment was conducted with the ratio of the diameter to the diagonal distance between each perforation lines (D/S_{diag}) of 60% or more, and the experimental parameters were perforation ratio (D/S_{diag}) and perforation diameter, and the results were as follows.

(1) It was found that the specimens without stud yielded at 0.4% or less, while the specimens with stud yielded at 0.6-1.1%, and the yielding strength was almost the same regardless of the with and without of stud.
(2) The strength at the yield point of each specimen was more than 85% of the maximum strength of the specimen, and the strength was maintained after yielding until to story drift 3.5%.
(3) Park's equation (2020) was suggested to predict the strength of perforated steel plates without studs when the perforation ratio is greater than 60%. Park's equation predicted the strength of perforated steel plates without studs more accurately than Pruba's equation (2006). However, the strength of perforated steel plates with stud was somewhat underestimated compared to Pruba's equation.

Further research is needed to understand why the yield displacement ratio is larger in specimens with stud than in specimens without stud. Also, due to the different methods of jointing stud to exterior columns, further research is needed on the strength evaluation equation based on the jointing method.

ACKNOWLEDGMENTS

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