Proceedings of International Structural Engineering and Construction, 8(1), 2021
Interdisciplinary Civil and Construction Engineering Projects
Edited by El Baradei, S., Abodonya, A., Singh, A., and Yazdani, S.

ISSN: 2644-108X
www.doi.org/10.14455/ISEC.2021.8(1).STR-10

INFLUENCE OF BOND AND FRICTION ON TENSILE STRENGTH OF PERFORATED STEEL PLATE CONNECTOR UNDER CONFINEMENT

YUKA NAGAOKA[1], TAKASHI FUJINAGA[2], and TERUHISA TANAKA[3]

[1] *Graduate School of Engineering, Kobe University, Kobe, Japan*
[2] *Research Center for Urban Safety and Security, Kobe University, Kobe, Japan*
[3] *Faculty of Engineering, Fukuoka University, Fukuoka, Japan*

Concrete-filled steel tube (CFST) columns are commonly used in Japan, which utilize onsite full-strength welded splices between columns. However, onsite welding requires high technical skill and a controlled environment. Further, this type of splice is expensive and, in most cases, is not necessary for dependable building performance under severe earthquake loading conditions. Recently, new types of CFST column splices have been developed that enhance constructability and avoid the need for onsite welding. In the proposed column splice method, perforated steel plates are placed on each column half and are welded into place. To evaluate the performance of this splice, it is important to determine the pull-out strength and behavior modes of the perforated steel plates embedded into the CFSTs. In this paper, a pull-out experiment with perforated steel plates embedded into a square CFST stub is conducted. The experimental parameters are the bond between the steel plate and the concrete, the embedded length of the perforation, and the extra length of the steel plate. The effect of the bond and friction strength between the steel and concrete are discussed, and a design formula for the pull-out strength of the perforated steel plate is examined.

Keywords: Concrete-filled steel tube, Mechanical shear connector, Embedded length, Extra length.

1 INTRODUCTION

Concrete-filled steel tube (CFST) columns are widely used in Japan for their structural performance. For the CFST column splice, it is common that upper and lower column tubes are connected using onsite full-strength welding (AIJ 2008). However, full-strength welding column splices are demanding to construct and expensive. In addition, they require a high level of technical skill and a controlled environment. A new CFST column splice using perforated steel plates has been proposed (Nakajima *et al*. 2019). This splice has perforated steel plates in each column half, and they are fillet-welded into place. This splice does not need onsite welding, resulting in a reduction of the construction period. To evaluate the performance of this splice, it is important to determine the pull-out strength and behavior modes of the perforated steel plates embedded into the CFSTs. It is still not clear how the bond between the steel plate and the concrete influences the pull-out strength and behavior modes of the perforated steel plate. In this paper, the pull-out experiment of perforated steel plates embedded into square CFST stubs is conducted. The experimental parameters are the bond between the steel plate and the concrete, the embedded length of the perforation, and the extra length of the steel plate.

2 PULL-OUT EXPERIMENT

2.1 Specimens

Figure 1 and Table 1 show the dimensions of the specimens. Perforated steel plates are embedded into the center of square CFST stubs. The width of the perforated steel plates (SM490A) is 90mm, and the thickness is 22mm. One perforation (ϕ35mm) was placed at the embedded part. Concrete was placed into the stub steel tubes with the upside-down state of Figure 1 to prevent bleeding at the upper part of the perforation. The experimental parameters are the bond between the steel plate and the concrete, the embedded length of the perforation, and the extra length of the steel plate. To remove the bond between the steel and the concrete in the unbonded specimens, a concrete form release agent was applied on the surface of the perforated steel plates. All specimens have been designed so that the double shearing of concrete inside the perforation occurs prior to other parts.

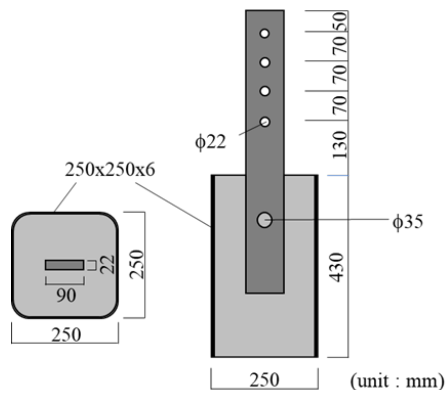


Figure 1. Dimensions of specimens.

Table 1. Dimensions of specimens.

Specimens	Embedded length of the hole	Extra length of steel plate	Bond between steel plate and concrete	Shape of steel plate
3d-3d	3*d* (105mm)	3*d* (105mm)	bonded	3*d* | 3*d*
3d-3d-U			un-bonded	
3d-5d		5*d* (175mm)	bonded	3*d* | 5*d*
3d-5d-U			un-bonded	
5d-3d	5*d* (175mm)	3*d* (105mm)	bonded	5*d* | 3*d*
5d-3d-U			un-bonded	

2.2 Loading Method and Measurements

Pull-out monotonic loading was applied using a hydraulic jack through a hinge to the embedded steel plate (see Figure 2). The CFST stub was fixed by the PC tendon and the fixing beam. The relative displacement of the steel plate and concrete was measured using displacement transducers. Figure 3 shows the position of strain gauges placed on the surface of the perforated steel plate.

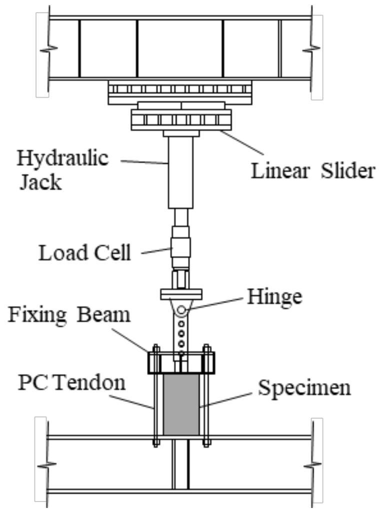


Figure 2. Experimental setup.

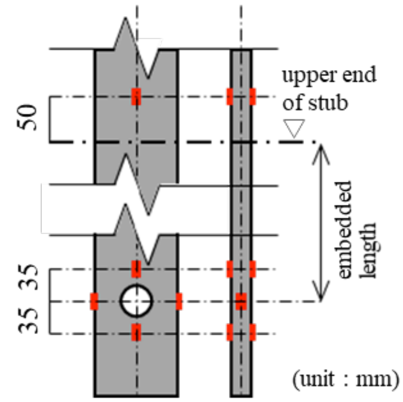


Figure 3. Position of strain gauges.

3 EXPERIMENTAL RESULTS

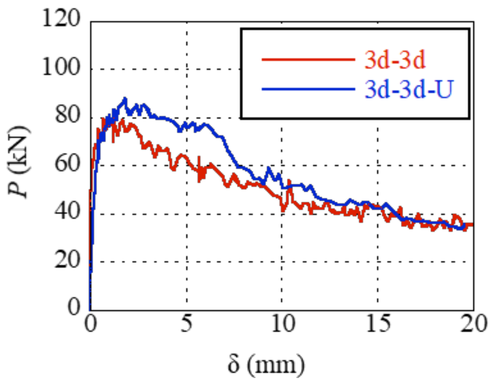
3.1 Pull-Out Strength and Behavior Modes

Figure 4 displays the relationship between pull-out strength and relative displacement of the perforated steel plate relation. The red and blue lines show the behavior of the bonded specimen and the un-bonded specimen, respectively. The maximum pull-out strength is observed at ~1.5mm of relative displacement and the failure mode is the double shear failure of filled-concrete at the perforation. The yielding of the steel plate was not observed in all specimens from the strain gauges placed beside the perforation.

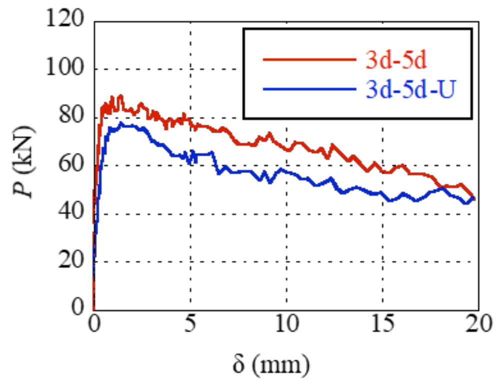
The initiation of the relative displacement of the un-bonded specimen was earlier than that of the bonded specimen. The relative displacement of the un-bonded specimen was larger than that of the bonded specimen at the very early stage. However, the gap between the bonded specimens and un-bonded ones became smaller at ~1 mm of displacement.

Although the maximum strength of the bonded specimen was greater than that of the un-bonded one for the 3d-5d series, the maximum strength of the un-bonded specimens was greater than that of the bonded ones for the 3d-3d series and the 5d-3d series. From this result, it can be said that there is almost no effect on the maximum pull-out strength from applying the surface of the steel plate with the concrete form release agent. For the specimens with embedded length 5d, the maximum strengths are greater than those of the other specimens, which shows that the embedded length influences the pull-out strength of the perforated steel plate connectors. For the case of the 5d-3d-U specimen, the maximum strength was greater than that of the bonded specimen, and the strength increased again at ~7mm of displacement after the peak. Aggregation was observed inside the perforation after the test, and it appears that the increase comes from the interlock mechanism.

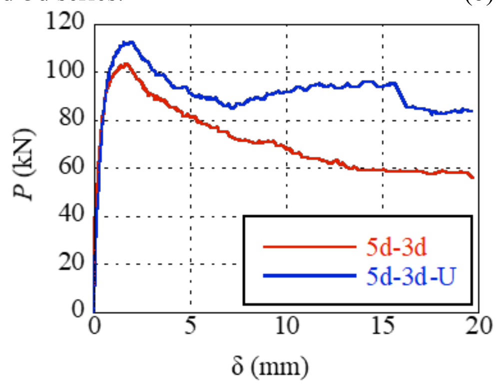
From the experimental results, significant differences in the pull-out strength and the behavior mode were not seen in comparison with the 3d-3d series and the 3d-5d series. Therefore, it can be said that the extra length does not influence the pull-out strength and behavior mode of the perforated steel plate connectors.



(a) 3d-3d series.



(b) 3d-5d series.



(c) 5d-3d series.

Figure 4. Pull-out strength; relative displacement of perforated steel plate relation.

3.2 Pull-Out Strength in Consideration of Bond and Friction Strength

From the experimental results, it is inferred that the influence of the bond between steel and concrete on the maximum pull-out strength is small. After the loss of the bond between the steel and the concrete, if frictional resistance at the same level is assumed, the resistance of the filled-concrete in the perforation becomes the strength that the frictional resistance is reduced by.

In this paper, the double shear strength of filled-concrete in the perforation was calculated by multiplying the strength proposed in (AIJ 2008), P_{ds}, and the reduction factor k. Experimental values were compared with the calculated maximum pull-out strength of the perforated steel plate, P_u, which added the double shear strength and the frictional strength in consideration of friction between the perforated steel plate and the concrete, P_f, which is expressed as

$$P_u = k\,P_{ds} + P_f \tag{1}$$

$$\tau_m = 0.600\,\sigma_n + 0.550\ \text{(MPa)} \tag{2}$$

$$P_f = A_e\,\tau_m \tag{3}$$

where P_{ds} is the double shear strength of filled-concrete inside the perforation, k is the contribution factor, A_e is the effective surface area.

In this study, the confinement to the perforated steel plate was passive, and the expansion of the concrete's volume was small in the early stage of loading. Therefore, it is assumed that the constraint stress σ_n 0 and the maximum shear stress formula in the case of the steel surface is mill scale condition (Eq. (2)) (Fukumoto and Sawamoto 2017), so the bond stress τ_m becomes 0.55MPa, which was used to calculate the frictional strength, P_f.

The effective surface area which contributed to the frictional resistance between the steel plate and the concrete was examined for the following three cases: 1) the entire surface area of the steel plate embedded into concrete; 2) the surface area of the side and above the perforation; and 3) the surface area of the side and below the perforation.

For Case 1, for k=0.6, the strength ratio exceeded 1 for all the specimens; however, the strength ratio of Specimen 5d-3d-U was 1.44, and the ratios were inconsistent and distributed unevenly. For Cases 2 and 3, for k=0.8, the calculated values predicted the experimental results relatively well, and Case 2 predicted the experimental value adequately. However, from the results of this study, it was not able to be determined whether the frictional strength above the perforation and the embedded length of the perforation greatly influenced the maximum strength of this type of connectors.

Table 2. Experimental result.

Specimen	Comp. Strength of Concrete f_c' (MPa)	Max. Tensile Strength P_{max}(kN)	d_{max} *1 (mm)	Caculated value $P_u = k\,P_{ds}{}^{*2} + P_f{}^{*3}$ (kN)			P_{max} / P_u		
				case 1	case 2	case 3	case 1	case 2	case 3
3d-3d	37.1	80.3	1.24	67.7	71.9	71.9	1.186	1.116	1.116
3d-3d-U		88.3	1.79	67.8	72.0	72.0	1.302	1.226	1.226
3d-5d		89.3	1.38	76.4	73.6	80.6	1.169	1.213	1.108
3d-5d-U		78.3	1.39	76.4	73.6	80.6	1.024	1.063	0.970
5d-3d	39.8	105.3	1.66	79.6	84.8	77.8	1.323	1.241	1.354
5d-3d-U		114.5	1.57	79.5	84.7	77.7	1.440	1.351	1.474

*1: the relative displacement at the maximum pull-out strength, *2: the effective double shear strength of filled-concrete inside the perforation, *3: the bond strength between steel and concrete using the bond stress of 0.55MPa

4 CONCLUSION

From the experimental results obtained from the six specimens in this study, the following conclusions can be made.

1) The influence on the maximum pull-out strength of applying the surface of the steel plate with the concrete form release agent was not observed.
2) The embedded length influences the pull-out strength of the perforated steel plate connectors.
3) Applying the surface of the steel plate with the concrete form release agent affects both the initiation of relative displacement and the relative displacement in the very early stage.

Acknowledgments

This research was funded by the Ministry of Education, Culture, Sport, Science and Technology (MEXT), Grant-in-Aid for Scientific Research (C), grant number 20K04771.

References

Architectural Institute of Japan, *Recommendations for Design and Construction of Concrete Filled Steel Tubular Structures,* 2nd Edition, 2008.

Fukumoto, T., and Sawamoto, Y., *Friction and Bonding Behavior Between Steel and Concrete Under Restriction Stress*, Journal of Structural and Construction Engineering (Transactions of AIJ), 82(736), 941–948, June, 2017.

Nakajima, K., Sadamoto, N., and Fujinaga, T., *Tensile Strength of Perforated Steel Plate Under Lateral Confinement*, Proceedings of the Japan Concrete Institute, 41(2), July, 2019.