Punching Shear Behavior under Sustained Load

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***Abstract*—This paper presents an experimental research program focused on the punching strength of flat-plate test specimens under the effect of sustained load. Two identical 2/3 scaled test specimens were loaded up to different sustained load levels for 270 days and the change in the crack width and propagation were monitored. After 270 days, these two specimens were loaded up to failure. The punching strengths of those specimens were compared with the identical control specimen that kept unloaded in the same environment.**

***Index Terms*—Flat plate, punching shear, sustained load**

I. Introduction

Several reasons such as improper design and detailing, poor construction quality or change in structural use may result in unintentional increase in service loads on existing flat-plate type of structures. In addition, time dependent effects such as concrete deterioration and corrosion of steel, drying shrinkage and creep can also cause reduction in the performance of those structures. One of the vital deficiencies of flat plate type of structures is the possibility of punching failure in the slab-connection region due to excessive vertical shear.

Punching shear strength of flat-plates has been studied since the 1930s [1]-[5]. Moe [5] performed one of the pioneering study that focused on the several parameters that may possibly effect the shearing strength of reinforced concrete flat-plates under concentrated loads. Moe tested total of 43 flat-plate specimens, one of which was subjected to sustained load for three months and unloaded and loaded again up to failure to determine the long-term loading effect on punching strength of flat plates. There are also other studies [6]-[8] that mainly focused on the long-term cracking and deflection behavior of flat-plate structures.

In this study it was aimed to investigate the effect of long term (9 months) sustained loading on the punching strength of flat-plates. Contrary to traditional methods in which the load applied by a hydraulic jack, the sustained load was applied by mechanical post-tensioning method that may eliminate the possible errors caused by the hydraulic jack or load measuring device.

II. Experimental Program

A. Design of Test Specimens

Three reinforced concrete flat-plate specimens with identical dimensions and reinforcement ratios were constructed. The geometrical details and reinforcement layout of the specimens were illustrated in Fig. 1.

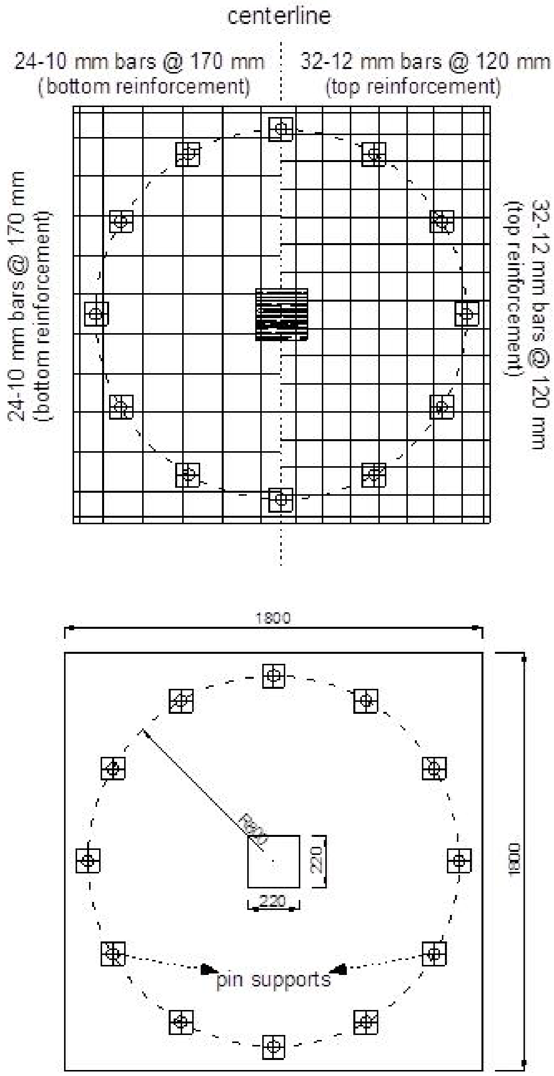

Fig. 1. Test specimen details and reinforcement layout

The specimens were designed to represent the 2/3 scaled slab-column connection portion of a prototype flat-plate type of structure. The thickness and the effective depth of the specimens were equal to 130 mm and 100 mm respectively. The testing region was bounded by the slab contraflexure points where the theoretical moment assumed to be zero under vertical loading which is a commonly preferred testing method to minimize the specimen size.

B. Test Setup and Loading History

A commonly used testing setup in the literature was adopted in the experimental program. First, two circular steel tubes were placed on a prismatic rigid concrete block with depth of 500 mm to provide sufficient resistance for

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application of the load. Then, a rigid steel beam was set on the circular tubes as shown in Fig. 2. Finally, the specimen was seated on the spreader beam and connected to the rigid concrete block at the bottom via total of 12 high strength 18 mm rods positioned in a circular boundary of the slab. Contrary to general load application schemes by using hydraulic jack and measuring the applied load by a strain gauge induced load cell, the load was applied by post-tensioning in order to minimize the possible errors due to unexpected time-dependent pressure changes in hydraulic jack and deformation of the strain gage in the load-cell. A calibrated torque wrench was used for equally post-tensioning of 12 high-strength connection rods around the specimen boundary.

Fig. 2. General view of test setup and sustained load application

ACI 318-11 [9] defines the punching load of flat plates without any shear reinforcement as the smallest of three expressions given in Equation 1;

$$V_c=\frac{1}{3}\sqrt{f_c'}b_o d \;;\; V_c=\left(\frac{1}{6}+\frac{1}{3\beta}\right)\sqrt{f_c'}b_o d \;;\; V_c=\left(\frac{\alpha_s d}{12.b_o}+\frac{1}{6}\right)\sqrt{f_c'}b_o d \qquad (1)$$

where f_c' is the compressive strength of concrete, b_o is the critical punching perimeter (located $d/2$ away from the column face), d is the effective depth, β is the column aspect ratio , α is a coefficient depending on the column location (40 for interior columns).

Two identical test setups were prepared. At the age of 14 days after casting two identical specimens, PT01 and PT02, were loaded up to 50% and 85% of their capacities calculated by ACI provisions respectively. The high-strength connection rods were checked three times in a week and the loss in sustained load due to cracking of the specimens was restored by tightening the rods, it was aimed to keep the applied load constant in this way. Since, the load was applied mechanically without using any data acquisition system, no deflection is measured during long-term loading.

At the end of 270 days, a hydraulic jack with a capacity of 600 kN and load cell of 1000 kN was placed between the two circular steel tubes as shown in Fig. 3 to load the specimens up to failure. Additionally, the center-deflection of the specimens was also measured in order to determine the flexural rigidity of the specimens after application of sustained loading.

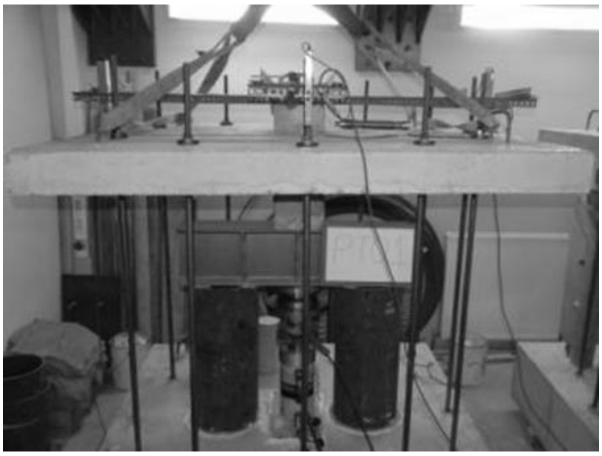


Fig. 3. Loading up to failure after 270 days

C. Materials

The concrete mixture was designed to have compressive strength of 30 MPa at the age of 28 days. The results of cylinder test at different ages of concrete were given in Table I. The hot-rolled deformed reinforcing steel bars (having 10 and 12 mm diameters) were used to construct the top and bottom reinforcement mats of the test specimens. The yield strength of the steel bars was 465 and 481 MPa respectively,

TABLE I: VARIATION OF CONCRETE STRENGTH BY TIME

Age of Concrete (days)	7	14	28	270
Compressive Strength (f_c' - MPa)	21.3	26.5	28.1	29.84

III. TEST RESULTS AND DISCUSSIONS

A. Crack Patterns and Measurements

The variation of crack widths over time is displayed in Fig. 4. It is obvious from the graph that the maximum crack width measured on top face of the specimens has a tendency to increase up to 120th day of loading. The remainder of the test, the change in maximum crack width is relatively small compared to rapid increase in first 120 days. Similar behavior was reported in the literature [6]. Fig. 5 shows the crack pattern on top face of the specimens under sustained load at the age of 270 days, just before loading up to failure.

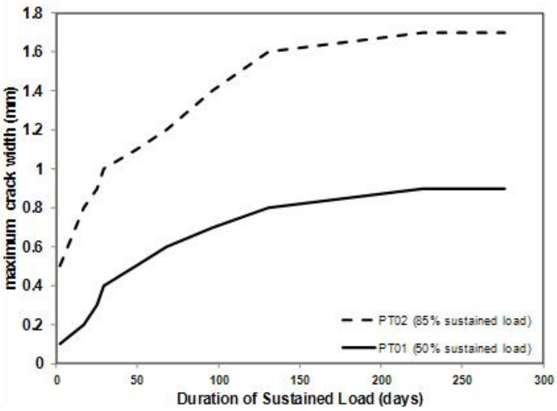
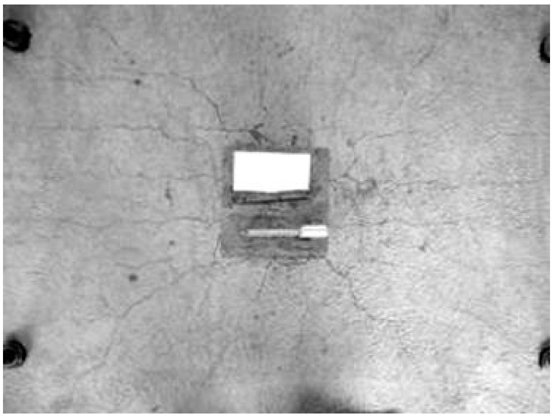


Fig. 4. Variation of maximum crack width with time

a) Specimen PT01 (top view)



b) Specimen PT02 (top view)

Fig. 5. Crack patterns of specimens after 270 days under sustained load, just before loading to failure

B. Load-Deflection Curves

The load versus center deflection curves of the specimens (PT01 and PT02) recorded during post-loading stage (considering the end of sustained loading period till failure) is illustrated in Fig. 6 together with the load-center deflection curve of companion control specimen (CNT) without any sustained load. In Fig. 6, the load values are normalized with respect to punching design capacity computed by Eq. (1) which clearly indicates that the mechanical application of sustained load is satisfactory with negligible errors. Fig. 6 also indicates that application of sustained load has no significant effect on the punching strength of both specimens PT01 and PT02. The comparison of experimental capacities of specimens PT01 and PT02 with respect to design capacity of ACI 318-11 and capacity of control specimen CNT are given in Table II.

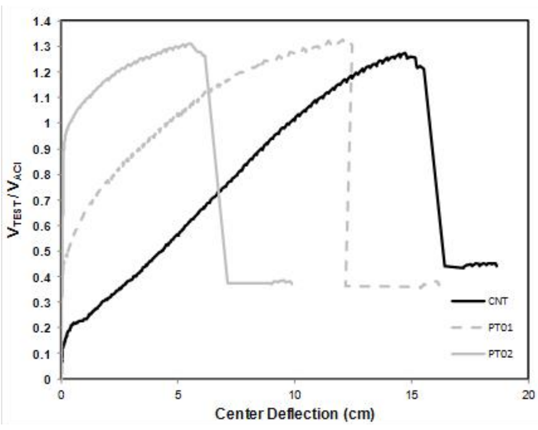


Fig. 6. Load-deflection curves

TABLE II: COMPARISON OF TEST RESULTS

Specimen	V_{ACI} (kN)	V_{TEST} (kN)	V_{SUS} (kN)	V_{SUS} / V_{TEST}	V_{TEST} / V_{ACI}	V_{TEST} / V_{CNT}
CNT		294.8	0	0	1.27	1.00
PT01	231.4	307.9	106.4	0.35	1.33	1.04
PT02		303.5	204.5	0.65	1.31	1.03

V_{SUS} = sustained load; V_{ACI} = ACI 318-11 prediction; V_{TEST} = failure load

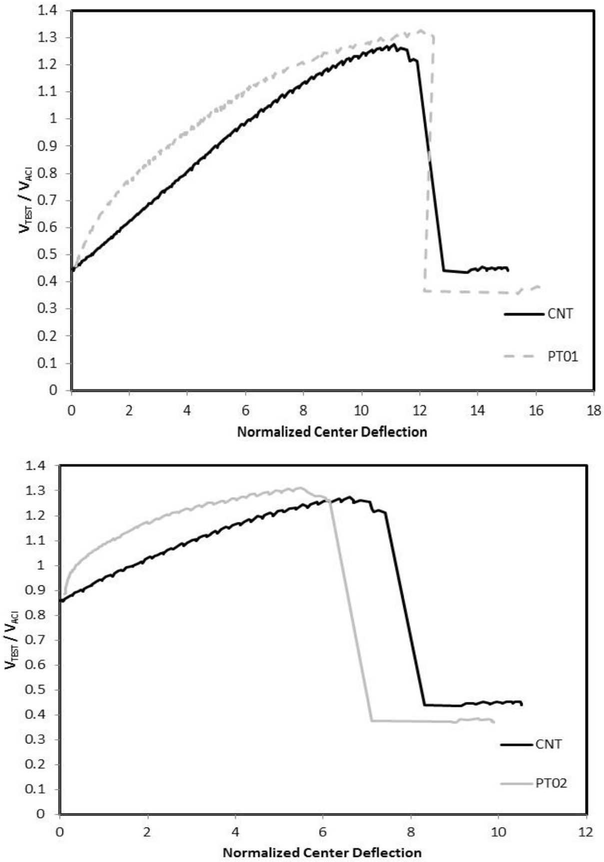


Fig. 7. Load vs normalized deflection curves for comparison of stiffness after sustained loading.

On the other hand, the center deflection values at failure load decreased significantly with increasing sustained load level for post-loading stage. This may be attributed to the cracking observed during sustained loading stage that reduced the deformability of the specimen when it is loaded to failure.

For comparison purposes and better understanding the effect of sustained load on post-loading stiffness of the specimens PT01 and PT02, the load-center deflection curve of control specimen CNT is shifted by equating the deflection values to zero that corresponding to the sustained load level for both specimens PT01 and PT02 separately as shown in Fig. 7. It is apparent from Fig. 7 that sustained loading and existence of cracks has no detrimental effect on the post-loading stiffness of the specimens. However, it should be noted that excessive cracking of the specimens under the effect of long-term sustain loading may lead to significant reduction in initial flexural rigidity of the specimens.

IV. CONCLUSION

The sustained load and its variation had no significant effect on the punching load and post-loading stiffness of the identical test specimens. However, the deformation capacity of the connection at the time of failure load decreases with increasing sustained load level. The proposed mechanical load application scheme by post-tensioning the connection ties of the test setup appear to be applicable for sustained load testing of reinforced concrete structures.

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