PUNCHING SHEAR BEHAVIOR OF RC FLAT PLATES REINFORCED WITH HIGH STRENGTH STEEL

A. Aljasar¹ and D. Naish²

ABSTRACT

Reinforced concrete flat plate or slab-column framed system is a popular type of construction in high rise buildings throughout the U.S. and around the world. Studies of using high strength steel as flexural and shear reinforcement in RC flat plates are limited in the literature. Thus, current ACI 318 provisions are not permitted using reinforcement steel with a strength higher than 80 ksi as flexural or shear reinforcement. This research has two main objectives. First, the effect of using high strength steel as a flexural reinforcement in RC flat plates on punching shear resistance is examined. Second, the feasibility of using the HSS as shear reinforcement to increase the punching shear capacity of RC flat plates is investigated. To accomplish these objectives, five half-scale RC flat plates were tested under monotonic loading. The experimental program consisted of one flat plate reinforced with 60 ksi main reinforcement and 60 ksi shear reinforcement, and four flat plates reinforced with 100 ksi main reinforcement and no, 60, 80, and 100 ksi shear reinforcement in the form of stirrups. All flat plates were designed per ACI 318-14 provisions. The experimental results show that replacement of conventional reinforcement steel (Grade 60) with high-strength steel for the flexural reinforcement increased the punching shear capacity by 6%. Also providing shear reinforcement with higher yield strength 60, 80 and 100 ksi increased the punching shear resistance by 7%, 11%, and 16% respectively. Conclusions were drawn based on the load-deflection relation and the strain distributions between the RC flat plates.

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Reinforced concrete flat plate or slab-column framed system is a popular type of construction in high rise buildings throughout the U.S. and around the world. Studies of using high strength steel as flexural and shear reinforcement in RC flat plates are limited in the literature. Thus, current ACI 318 provisions are not permitted using reinforcement steel with a strength higher than 80 ksi as flexural or shear reinforcement. This research has two main objectives. First, the effect of using high strength steel as a flexural reinforcement in RC flat plates on punching shear resistance is examined. Second, the feasibility of using the HSS as shear reinforcement to increase the punching shear capacity of RC flat plates is investigated. To accomplish these objectives, five half-scale RC flat plates were tested under monotonic loading. The experimental program consisted of one flat plate reinforced with 60 ksi main reinforcement and 60 ksi shear reinforcement, and four flat plates reinforced with 100 ksi main reinforcement and no, 60, 80, and 100 ksi shear reinforcement in the form of stirrups. All flat plates were designed per ACI 318-14 provisions. The experimental results show that replacement of conventional reinforcement steel (Grade 60) with high-strength steel for the flexural reinforcement increased the punching shear capacity by 6%. Also providing shear reinforcement with higher yield strength 60, 80 and 100 ksi increased the punching shear resistance by 7%, 11%, and 16% respectively. Conclusions were drawn based on the load-deflection relation and the strain distributions between the RC flat plates.

Introduction

In 1971, ACI 318-71 [1] changed the limitation of the yield strength of the reinforcement steel bars from 60 ksi to 80 ksi for non-seismic system except for shear reinforcement which is limited to a maximum of 60 ksi. To date, the limitation is still the same. Indeed, the last version of the ACI Code 318-14 [2] allowed for using reinforcement steel with a yield strength of 100 ksi for confinement. In recent years, population and social demand had been increased calling for larger and more complex structures with higher performance and durability, opening the door to many innovations to increase the capacity (strength) of the construction materials like concrete and reinforcement steel. Recently it has become more common to produce steel reinforcement with yield strength not only higher 80 ksi but also higher than 100 ksi. In this study, high-strength

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steel is defined as reinforcing steel having a yield strength of 80 ksi or more. High strength steel provides beneficial aspects: higher corrosion resistance compared to the conventional steel; reduction in the amount of reinforcement in members, which can reduce congestion in joint regions and allow for better placement of concrete. [3, 4, 5].

Some work has been completed on slabs with HSS in the past. Yang [6] conducted a test to investigate the punching shear behavior of two-way slabs reinforced with HSS as a flexural reinforcement and the influence of the flexural reinforcement ratio and the concentration of reinforcement. Results indicate that replacing of conventional steel with the HSS increased the punching shear capacity. The purpose of this current research is to investigate the effectiveness of using the high strength steel in the form of shear reinforcement (stirrups) to increase the punching shear capacity of the RC flat plates and to examine the effect on the punching shear resistance of using high strength steel for the flexural reinforcement of RC flat plates.

**Research Significance**

This research compares the punching shear resistance of RC flat plate reinforced with HSS as a flexural reinforcement with conventional steel, and the punching shear capacity of RC flat plates reinforced with HSS as flexural and shear reinforcement.

**Details of the Test Specimens**

Five half scale RC flat plates specimens were designed per ACI 318-14 provisions, constructed and tested under monotonically axial loading. The specimens represent isolated interior slab-column connections. The five slabs all had the same dimensions, 5x5x0.5 ft. The slab specimen and the test setup is shown in Fig. 1. The primary variable was the yield strength of the flexural and the shear reinforcement. No. 4 size (1/2 in. diameter) reinforcing bars were used for the flexural and the shear reinforcement in all slabs. Flexural reinforcement was spaced at 5 in. with a reinforcement ratio of 0.92% in each principal direction. Shear reinforcement in the form of stirrups with dimensions of 7 x 4.25 in. were spaced at 4 in. Specimen M60-S60 was reinforced with conventional steel reinforcement for its flexural and shear reinforcement. Other specimens were constructed with high strength steel with Grade of 100 ksi as the main reinforcement, and each of these slabs was reinforced with shear reinforcement (stirrups) of no, 60, 80, 100 ksi labeled M100-None, M100-S60, M100-S80, and M100-S100 respectively. Figure 2 shows the reinforcement and the strain gauge layout.
Figure 1. Slab specimen and the test setup.

Figure 2. Specimen details.

Figure 3. Locations of LVDTs and the string potentiometers. (All dimensions in in.).
Test Setup and Instrumentation

All specimens were tested upside down and simply supported on all four sides. Twelve high strength threaded rods were used to connect the specimens to the laboratory floor. The test specimens were supported along their perimeter with twelve support locations spaced at 18 in. to simulate a simply supported end condition. The load was applied monotonically by a vertically oriented hydraulic jack through a steel column fabricated to represent an 8 x 8 x12 in. column. The tests terminated when a significant loss of load capacity was observed. The test setup is shown in Fig. 1. A load cell under the hydraulic jack was used to measure applied vertical force. Strain gauges were attached to the reinforcement bars of each specimen at locations of interest, Strain gauge distribution in the specimen is shown in Fig. 2. Three Linear Variable Differential Transducers (LVDTs) and six string potentiometers were used to measure the vertical displacement. The locations of the LVDTs and the string potentiometers are shown in Fig. 3.

Material Properties

Reinforcing Steel Properties

Three tension coupons representative of each grade were tested according to ASTM A370 [7] to evaluate the reinforcement bars. Table 1 summarizes the mechanical properties of the tested bars. Stress-strain relations show rounded curves for the high strength steel without a distinct yield point led to use the 0.2% offset strain method to find the yield stress for grade 80, 100 according to ASTM A370. Grade 60 and 80 steel satisfied ASTM A706 [8] requirements as well as Grade 100 steel satisfied ASTM A1035 [9] requirements.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Yield Stress (ksi) Fy</th>
<th>Strain at Yielding εy</th>
<th>Peak Stress (ksi) Fu</th>
<th>T/Y Ratio</th>
<th>Total Elongation %</th>
<th>Modulus of Elasticity (ksi) E</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>69.91</td>
<td>0.00241</td>
<td>107.96</td>
<td>1.54</td>
<td>17.5</td>
<td>29000</td>
</tr>
<tr>
<td>80</td>
<td>92</td>
<td>0.00307</td>
<td>116.67</td>
<td>1.27</td>
<td>13.38</td>
<td>30000</td>
</tr>
<tr>
<td>100</td>
<td>134</td>
<td>0.00447</td>
<td>158.53</td>
<td>1.18</td>
<td>10.3</td>
<td>30000</td>
</tr>
<tr>
<td>100</td>
<td>135</td>
<td>0.0045</td>
<td>165.7</td>
<td>1.23</td>
<td>10.23</td>
<td>30000</td>
</tr>
</tbody>
</table>

Concrete Properties

The flat plates were constructed with a normal weight ready-mixed concrete with a compressive strength of approximately 4,000 psi at 28th day age, a 3/8 in. maximum aggregate size, and specified slump of 4 in. To evaluate the concrete compressive strength a total of 12 standard 6 x 12 in. cylinders were cast, cured, and stored under the same conditions as the test specimens. Table 2 summarizes the average concrete compressive strength and modulus of elasticity at 28th day and testing day age of all specimens.
Table 2. Concrete properties.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>28th Day Age</th>
<th>Testing Day Age</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>f'c (ksi)</td>
<td>E_c (ksi)</td>
</tr>
<tr>
<td>M60-S60</td>
<td>4.22</td>
<td>3702</td>
</tr>
<tr>
<td>M100-None</td>
<td>4.22</td>
<td>3702</td>
</tr>
<tr>
<td>M100-S60</td>
<td>4.22</td>
<td>3702</td>
</tr>
<tr>
<td>M100-S80</td>
<td>4.22</td>
<td>3702</td>
</tr>
<tr>
<td>M100-S100</td>
<td>4.22</td>
<td>3702</td>
</tr>
</tbody>
</table>

Test Results

Failure Modes

The crack pattern at failure on the tension side of each specimen is shown in Fig. 4. In all the tests, the column was observed to punch the slab. In all slabs cracking started with a noticeable diagonal flexural crack followed by inclined punching cracking. The observed failure pattern was a punching cone as expected. The punching cone initiated from the column face on the top surface of the slabs all the way to the perimeter of the slab.

Figure 4. Cracking pattern.
Load-Deflection response

Table 3 summarizes the measured peak load, the normalized shear stress, and the deflection at the center of the flat plate at the peak. Figure 5 shows the applied load versus the deflection.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Failure Mode</th>
<th>Peak Load, Pmax (Kips)</th>
<th>Normalized Shear Stress Pmax / b₀d√f’c</th>
<th>Deflection at Peak Load (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M60-S60</td>
<td>Punching</td>
<td>84.43</td>
<td>5.74</td>
<td>1.08</td>
</tr>
<tr>
<td>M100-None</td>
<td>Punching</td>
<td>83.75</td>
<td>5.70</td>
<td>0.76</td>
</tr>
<tr>
<td>M100-S60</td>
<td>Punching</td>
<td>89.55</td>
<td>6.09</td>
<td>0.94</td>
</tr>
<tr>
<td>M100-S80</td>
<td>Punching</td>
<td>92.70</td>
<td>6.34</td>
<td>0.90</td>
</tr>
<tr>
<td>M100-S100</td>
<td>Punching</td>
<td>96.83</td>
<td>6.59</td>
<td>0.93</td>
</tr>
</tbody>
</table>

Figure 5. Load versus deflection response.

For comparison purposes, normalized punching shear stress \((P/b₀d\sqrt{f’c})\) versus deflection response is shown in Fig. 6 and 7. The normalization is meant to reduce the effect of different concrete cylinder strength. The critical perimeter, \(b₀\), was calculated according to the ACI 318-14 and was equal to 49 in. All specimens exhibited abrupt punching shear failures with a sudden drop in load. Figure 6 shows the influence of yield strength of the flexural reinforcement on the normalized punching shear stress-deflection response. Specimens M60-S60 and M100-S60 showed a similar initial stiffness because they have the same reinforcement ratio. However, the stiffness after cracking was higher for M100-S60 than M60-S60. Because of this higher stiffness, members with higher strength steel may draw more force in the system.
However, specimen M100-S60 had a 6% greater punching shear resistance than specimen M60-S60, indicating that members reinforced with higher strength steel may be able to take that increase in demand due to higher post-cracking stiffness. See Table 3. Strain gauges readings show that the flexural reinforcement in specimen M60-S60 had been yield at 44.60 kips loading. However, specimen M100-S60 yielded at 57.51 kips. Also, the shear reinforcement of the M60-S60 yielded at 56.5 kips, while it did not yield in M100-S60 specimen at that load. Replacement of the conventional steel with HSS of the flexural reinforcement of RC flat plates had increased the punching shear capacity. Figure 7 shows the influence of yield strength of the shear reinforcement on the normalized punching shear stress-deflection response of slabs reinforced with a 100 ksi flexural reinforcement. In general, all RC flat plates with a 100 ksi flexural reinforcement showed a similar initial stiffness as all reinforced with the same reinforcement ratio. Yet, stiffness after cracking was higher as a result of using shear reinforcement with higher strength. Furthermore, slabs with higher shear reinforcement displayed higher peak load, and less deflection at failure compared to the specimen M100-None which has no shear reinforcement. Strain gauges records indicate that at a load of 57.52 kips. The flexural reinforcement in specimen M100-S60 starts yielding, however, yielding starts at a load of 69.43 kips in specimen M100-S80 with no yielding at all in specimen M100-S100 at that load. Also, no yielding occurred in the shear reinforcement of the all 100 ksi flexural reinforcement flat plates. In sum, providing a shear reinforcement with higher yield strength 60, 80 and 100 ksi increased the punching shear resistance by 7%, 11%, and 16% respectively.

![Figure 6. Effect of different flexural reinforcement grades.](image-url)
Conclusions

Test results presented herein showed that direct replacement of the conventional reinforcement steel bars grade 60 with high strength steel resulted in a 6% increased in the punching shear capacity. Also using a high strength steel as a shear reinforcement in RC flat plates reinforced with high strength steel was effective method to increase the punching shear capacity as a flat plate with 60, 80 and 100 ksi shear reinforcement increased the punching shear resistance by 7%, 11%, and 16% respectively. Using reinforcement steel with higher strength leads to increase the stiffness after the cracking stage as RC flat plates with HSS showed less deflection with a higher load capacity compared to RC flat plate with the conventional reinforcement. Furthermore, all RC flat plates reinforced with high strength steel exhibited a punching shear stress higher than $6\sqrt{f'c}$ which is the limit in ACI 318-14. More investigations are needed in future in this area to confirm this work especially under a different type of loading as this study was under monotonic loading only.

Acknowledgments

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References


