International Journal of Engineering

Journal Homepage: www.ije.ir

TECHNICAL NOTE

# Shear Capacity of Reinforced Concrete Flat Slabs Made with High-strength Concrete: A Numerical Study of the Effect of Size, Location, and Shape of the Opening

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PAPER INFO

*Paper history:*
Received 11September 2016
Received in revised form 03January2017
Accepted 24January 2017

*Keywords*:
Reinforced Concrete Flat Slab
Opening
Numerical Method
High-strength Concrete
Shear Capacity

ABSTRACT

Nowadays, concrete with strength higher than 50 MPa is utilized due to the ever increasing need for higher strength and prolonged healing properties. Despite the widespread use of high-strength concrete, only a few research projects have been conducted on the punching shear strength of high-strength concrete slabs. Reinforced concrete flat slabs are widely employed in structural systems. The location of the slab-column connection is the most sensitive part of the flat slab. The present study investigates the effect of existance of opening in reinforced concrete flat slab in two groups of slab, a group with HSC concrete and the other with NSC concrete. To this end, a few examples of flat slabs with different positions, shapes, and dimensions of the opening with normal-strength concrete and, the slabs with the same geometry but high-strength concrete are compared so as to review the effect of high-strength concrete on the slabs with different openings. The results of this research show that the high-strength concrete improves the shear capacity of the slabs and leads to transferring higher forces in slab-column connection. Furthermore, the dimensions, shape, and position of the opening is effective on the percentage of load increase and ultimate deflection of samples.

***doi****: 10.5829/idosi.ije.2017.30.02b.02*

## 1. INTRODUCTION

Nowadays, concrete with strength higher than 50 MPa is utilized due to the ever-increasing need for higher strength and prolonged healing properties. Reinforced concrete flat slabs are widely employed in structural systems. Flat slab formatting is very simple and no beam or column heading is used in it. However, a disturbing failure occurs at the junction of the slab-column in this system. The location of the slab-column connection is the most sensitive part of the flat slab due to the existence of high flexural anchor and shear force. Owing to the occurrence of the punching shear failure, failure load may be considerably less than the flexural capacity of the slab. The use of high-strength concrete improves the punching shear strength of the slab and causes the transfer of higher forces in the place of slab-column connection. Despite the widespread use of high-strength concrete, only a few research projects have been conducted on the punching shear strength of high-strength concrete slabs [1]. Due to the passing of installation pipes, almost all of the slabs have an opening. The dimensions of the opening may be large (for stairs and elevators) or small (for installation pipes). The existence of the opening reduces more the punching shear capacity of slab-column connection and increases the possibility of punching shear failure of the slab. The effects of the opening on punching shear behavior and strengthening in the place of slab-column connection should be carefully reviewed because of the vulnerability of this area [2].

## 2. LITERATURE REVIEW

Among the previously conducted studies on a slab made of high-strength concrete, the research by Marzouk et al.

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[3] can be noted. In their study, the slab-column connections under the combination of gravity and lateral loads were tested in order to investigate the effect of the use of high-strength concrete on structural behavior of slab-column connections. They observed that when the concrete strength increases from 35 to 75 MPa, the shear strength of 7% and 15% for the torque loading items rises to zero shear and the highest ratio of torque to the shear, respectively. Osman's [4] experimental testing was done to verify the performance of punching shear of reinforced concrete slab made with high-strength, lightweight concrete and also with different steel percentages. Other laboratory studies have been done by De Hanai et al. [5], Abdel Hafez et al. [6], Ozden et al. [7], and Inacio [8] and some others.

Several studies have investigated the effects of openings on the punching shear strength of RC flat slabs. The pioneering work of Moe [9] was the first to propose a semi-empirical formula in order to estimate the punching shear strength of RC slabs and footings, which is proportional to the square root of the concrete compressive strength and critical section perimeter around the slab-column connection. The reduction of the critical section perimeter due to the existence of openings near columns was first considered in the work by American Concrete Institute-American Society of Civil Engineers (ACI-ASCE) Committee 326. This publication suggested that the critical section perimeter is reduced by projecting lines from the center of the column to openings and by deducting the perimeter between the lines from the original critical section perimeter. This approach was later confirmed to be conservative in a publication by ACI-ASCE Committee 426. More recently, Teng et al. [10] experimentally examined the effects of openings with relatively large aspect ratios on the punching shear capacity of RC flat slabs. Based on their results, they proposed a new method to estimate the effective critical perimeter. Borges et al. [11] compared various methods to determine the effective critical section perimeter of RC flat-plate slabs with openings and concluded that straight projection of the widths of openings onto the critical section perimeter predicts strength more consistently than any of the forms of radial projection. However, the above mentioned studies are done in laboratory, and it appears that there are few numerical models in this field.

In addition, several numerical and experimental researches have been done in the field of other concrete elements such as beams and shear walls. Hashemi et al. [12] examined the flexural testing of high-strength reinforced concrete beams strengthened with CFRP sheets. Naghipour et al. [13] presented a work about strengthening the reinforced concrete beams by post-tensioned external reinforcing bars. Alferjani et al. [14] investigated the effect of strengthening of RC pre-cracked continuous T-beam using CFRP strips research. Finally, Saghaeian et al. [15] compared different modeling techniques on the prediction of the nonlinear behavior of R/C shear walls.

The present study investigates the effect of using high-strength concrete in two groups of slab, a group with HSC concrete and the other with NSC concrete. To this end, a few examples of flat slab with different positions, shapes, and dimensions of the opening with normal-strength concrete and, the slabs with the same geometry but high-strength concrete are compared so as to review the effect of high-strength concrete on the slabs with different openings.

## 3. VERIFICATION OF MODELING

In order to verify the high-strength concrete numerical method, Inacio test (2014) [8] has been applied. In Inacio's experiment, four samples of reinforced concrete slabs that three of which had high-strength concrete (HSC) and the remaining one had normal-strength concrete (NSC), were tested. The strength of the used concrete was in the range of 35.9 MPa (NSC) to 130.1 MPa (HSC), while the average ratio of longitudinal reinforcements was between 0.94% and 1.48%.

The square slab dimensions were 1650 mm with a thickness of 125 mm. The top and bottom reinforcement grids were orthogonal and parallel to the edge of the slab. The length of the concrete cover of both high and low levels was 20 mm. The columns were simulated using a square steel plate with the length of 200 mm and the thickness of 50 mm. Figure 1 indicates the geometry of Inacio's laboratory samples.

In order to verify the slab with the normal-strength concrete and opening, Oukaili's [16] laboratory sample was employed. In Oukaili's experiment, the square slabs with the length of 1000 mm and the thickness of 70 mm, that had openings with different dimensions and placement position and made with normal-strength concrete, were compared.

In our study, to model the samples, the finite element software of ABAQUS was applied. First, for the veracity of the modeling sample with the laboratory test, a sample was modelled in the software by modifying the dimensions of the mesh, supporting the conditions,

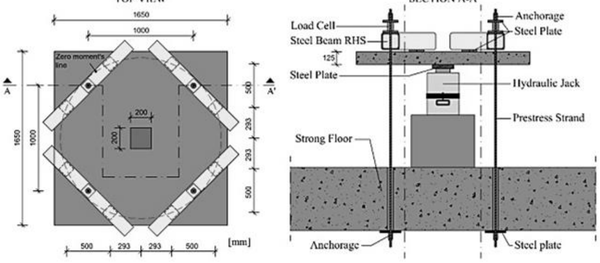


**Figure 1.** The geometry of Inacio's laboratory samples.

and entering the properties of the materials. In addition, in Figure 2 the load-deflection curve was drawn and compared with the load-deflection curve of the laboratory test. The results indicated a good agreement between the two results.

## 4. THE PROCESS OF MODELING

In the present study, the solid shape with extrusion type was used for outlining the slabs. Moreover, for modelling the slabs, an 8-noded hexahedral elements with reduced integration (C3D8R) was utilized. To mesh the slabs, the sweep technique with the medial axis algorithm of size 5 was applied. After this, the concrete damage plasticity model was used for allocation of the concrete specification. To define the stress-strain relationship for the concrete, Mander's model [17] was used to calculate the compressive strength and the ultimate strain of the concrete based on the function of enclosing steel (transverse reinforcements). In this case, using Mander's relationships and modulus of elasticity of 24 GPa for normal-strength concrete and 53.5 GPa for high-strength concrete, the values of stress-strain curve of concrete were calculated. Figure 3. A and 3. B demonstrate the stress curve for compressive section of the concrete. In this research, the wire shape with planar type was used for outlining the reinforcements.

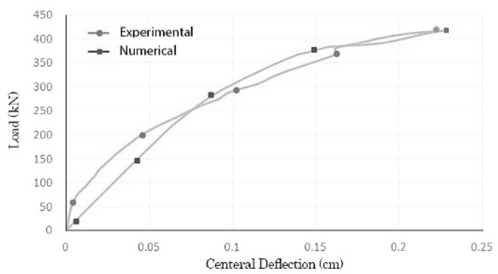


**Figure 2. A.** Comparison of load-deflection curve of Inacio's laboratory samples and analysis [8].

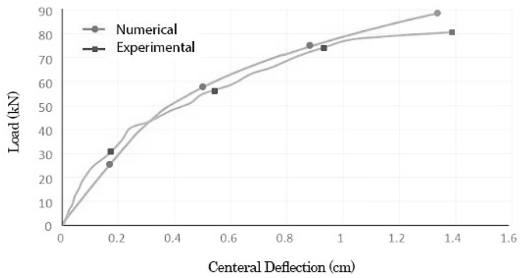


**Figure 2. B.** Comparison of load-deflection curve of Oukaili's laboratory samples and analysis [16].

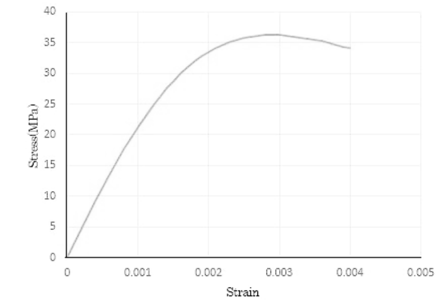


**Figure 3. A.** The stress-strain curve for compressive section of normal-strength concrete

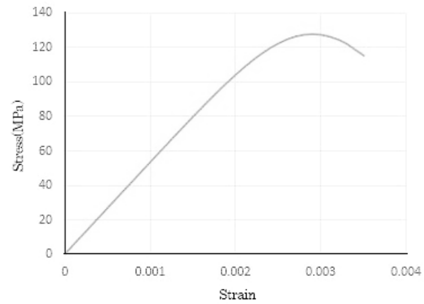


**Figure 3. B.** The stress-strain curve for compressive section of high-strength concrete

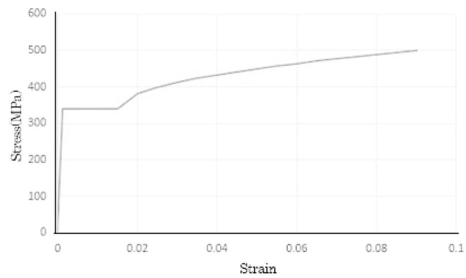


**Figure 4.** The stress-strain curve of steel

Moreover, for modelling the reinforcement, 2-noded linear truss elements (T3D2) were utilized. The embedded region method was adopted to simulate the bond between the reinforcement and the concrete. To mesh the reinforcements, size 5 was applied. Figure 4 illustrates the stress-strain curve of steel.

The dimensions of the samples were considered according to those of Oukaili's laboratory test. The concrete slab at the four directions relies on simple support at the edges. The edges of the slab as fixed support are assumed in such a way that allows no axial displacement in any direction, but rotating around the main axis is free. Loading on the square plate was applied in the center of the slab with the length side of 150 mm.

In this study, twelve reinforced concrete flat slabs made with normal-strength (NSC) and high-strength concrete (HSC), two samples without opening and ten samples with different openings were modelled in the ABAQUS software. Furthermore, their results were reviewed. The specifications of modelling samples are given in Table 1.

Figure 5 demonstrates the geometry of the model created in the software, including how to place reinforcement of the concrete slab (Figure 5. A) as well as how to model the support (Figure 5. B).
Figure 6 depicts the plan of all models which have been created in the software.

**TABLE 1.** The specifications of modeling samples

| Sample | A (mm) | P | D (mm) | $f_c^/$ (MPa) | ρ(%) |
|---|---|---|---|---|---|
| SNSC0 | - | - | - | 35.5 | 1.036 |
| SHSC0 | - | - | - | 125 | 1.036 |
| SNSC1 | 150*150 | front | 0 | 35.5 | 1.036 |
| SHSC1 | 150*150 | front | 0 | 125 | 1.036 |
| SNSC2 | 225*225 | front | 0 | 35.5 | 1.036 |
| SHSC2 | 225*225 | front | 0 | 125 | 1.036 |
| SNSC3 | 150*150 | front | 70 | 35.5 | 1.036 |
| SHSC3 | 150*150 | front | 70 | 125 | 1.036 |
| SNSC4 | 150*150 | corner | 0 | 35.5 | 1.036 |
| SHSC4 | 150*150 | corner | 0 | 125 | 1.036 |
| SNSC5 | 50*450 | front | 0 | 35.5 | 1.036 |
| SHSC5 | 50*450 | front | 0 | 125 | 1.036 |

A: **Opening dimensions, P: Opening position towards the column, D: Opening distance from the column, ρ: Reinforcement ratio**

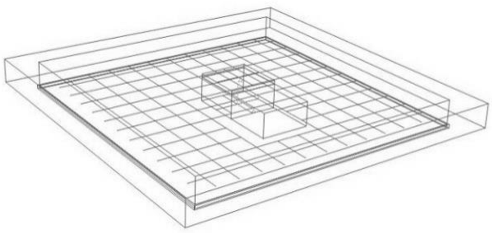

**Figure 5. A.** The geometric form of the model in software: how to place tensile reinforcement

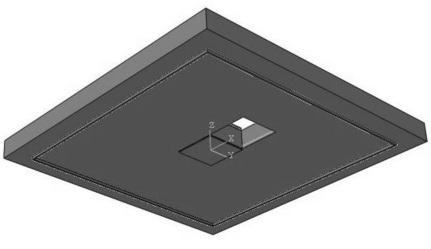

**Figure 5. B.** The geometric form of the model in software: how to model the slab support

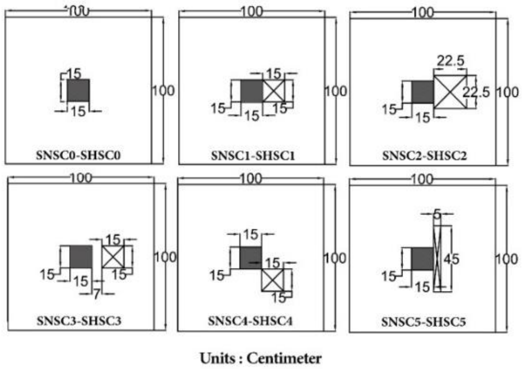


**Figure 6.** The plan of models created in the software.

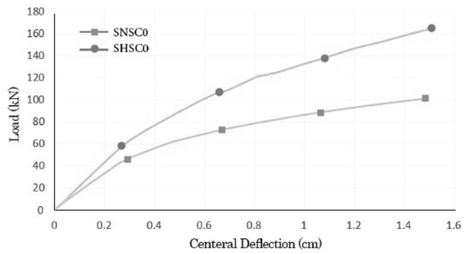


**Figure 7.** The impact of high-strength concrete on the behavior of load-deflection curve of the samples.

## 5. THE ANALYSIS OF THE MODELS

### 5 .1. The Effect of High Strength Concrete on the Sample without Opening

First, to review the impact of the high-strength concrete on the slab without opening, the load-deflection curve of the SNSC0 and the SHSC0 samples, that are both created with the same geometry but one with normal-strength concrete (SNSC0) and the other with high-strength concrete (SHSC0), are compared with each other.

As can be seen in the figure, the high-strength concrete has created a dramatic impact on the ultimate load of the SHSC0 sample. The recorded ultimate load for the SHSC0 sample, is 166.08 kN that shows 66.08% increase compared to 100 kN ultimate load of the SNSC0 sample. Additionally, the ultimate deflection created for the sample of high-strength concrete is 2 mm more than that of the normal-strength concrete sample. The comparison chart of the ultimate load and deflection of the above-mentioned two samples is shown in Figure 8.

Generally, use of HSC concrete in modelling the slab induces a dramatic increase in the ultimate load and a slight increase in the ultimate deflection and ductility of the sample at this stage.

### 5. 2. Investigation of the Effect of High-strength Concrete on the Openings with Different Dimensions

To this end, the two sample charts,

i.e. SHSC1 with square opening and a side length of 150 mm and SHSC2 with square opening and a length of 225 mm, once with the normal-strength concrete and once with high-strength concrete were analyzed and compared with each other.

According to the charts outlined, the ultimate load of the SHSC1 sample is 162.05 kN, and for the same sample with normal-strength concrete (SNSC1) is 89.80 kN which shows an 80.46% increase. The ultimate load recorded for the SHSC2 sample is 143.36 kN, and for the SNSC2 sample is 76.94 kN, which indicates an 86.33% increase in the ultimate load of the sample with high-strength concrete compared to the sample with normal-strength concrete. The ultimate deflection of the SHSC1 sample, compared to the SNSC1 sample, increased by 27.5%. The increase in the ultimate deflection of the SHSC2 sample towards the SNSC2 sample is recorded to be 34.91%. The ultimate load and deflection chart in the center of the slab for sample 1 and 2 are presented in Figure 10.

Therefore, we can conclude that the impact of the use of HSC concrete on the increase of the ultimate load and deflection in the slab with a larger opening is more than that with a smaller opening.

**5. 3. Investigation of the Effect of High-strength Concrete on the Slabs with Different Distance from the Column** In this section, the ultimate load-deflection curves of the SHSC1 sample with a square opening in the column and the SHSC3 sample

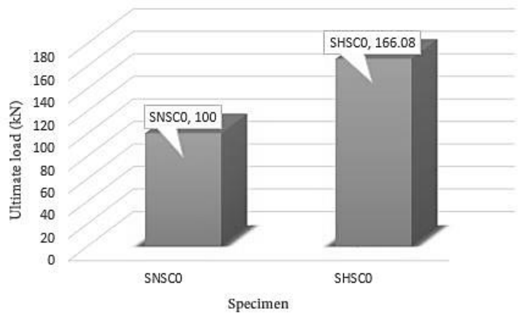


**Figure 8. A.** The impact of high-strength concrete on ultimate load of the slab without opening

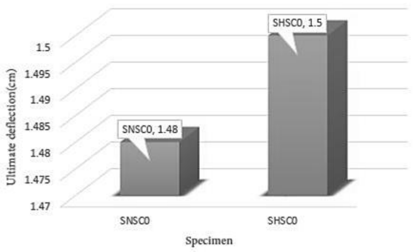


**Figure 8. B.** The impact of high-strength concrete on ultimate deflection of the slab without opening.

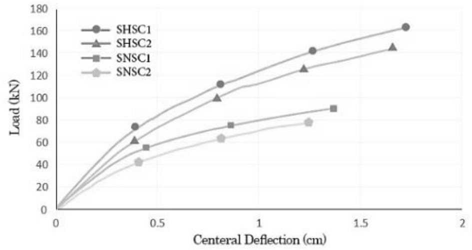


**Figure 9.** The impact of high-strength concrete on load-deflection curve of slab with openings of different dimensions.

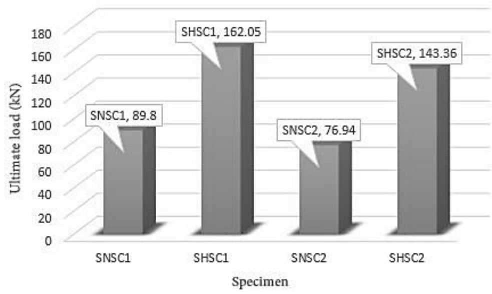


**Figure 10. A.** The impact of high-strength concrete on ultimate load of the slab with openings of different dimensions.

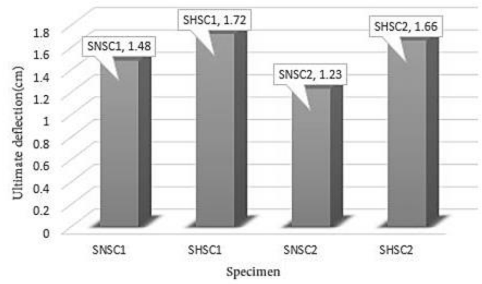


**Figure 10. B.** The impact of high-strength concrete on ultimate deflection of the slab with openings of different dimensions.

with a square opening at a distance of 70 mm from the front of the column were analyzed and compared with each other once with normal-strength concrete and once with high-strength concrete.

According to Figure 11, the ultimate load of the SHSC1 sample is 162.05 kN, and for the normal-strength concrete (SNSC1) is 89.80 kN which indicates an 80.46% increase in its ultimate load in the case of using high-strength concrete. The ultimate load recorded is 163.65 kN for the SHSC3 sample, and 92.80 kN for the SNSC3 sample, showing a 76.35% increase in the ultimate load of sample with high-strength concrete compared to the sample with normal-strength concrete. The ultimate deflection of the SHSC1 sample, compared to the SNSC1 sample, increased by 27.5%. The increase in the ultimate deflection of SHSC3 towards the SNSC3 sample is recorded to be 12.70%. In the following figure, the ultimate load and deflection of the samples can be observed.

Overally, we can conclude that the use of HSC concrete has a more significant impact on the increase of the ultimate load and deflection in the slab with an opening next to the column.

## 5. 4. Investigation of the Effect of High-strength Concrete on the Slabs with Different Locations Towards the Column

The load-deflection curves of the SHSC1 sample with square opening placed at the front of the column and the SHSC4 sample with square opening located on the corner of the column were analyzed once with normal-strength concrete and once with high-strength concrete, which are shown in Figure 13.

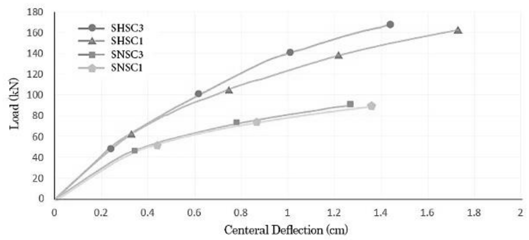


**Figure 11.** The impact of high-strength concrete on ultimate load-deflection curve of the slab with openings of different distances from the column

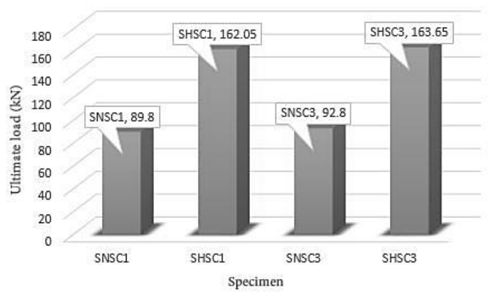


**Figure 12. A.** The impact of high-strength concrete on ultimate load of the slab with openings of different distances from the column

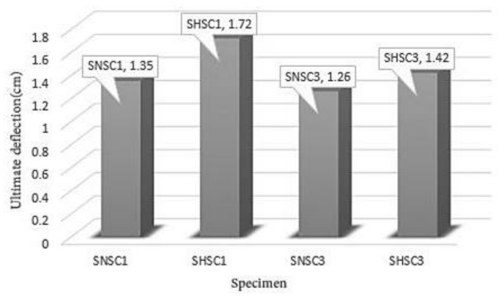


**Figure 12. B.** The impact of high-strength concrete on ultimate deflection of the slab with openings of different distances from the column

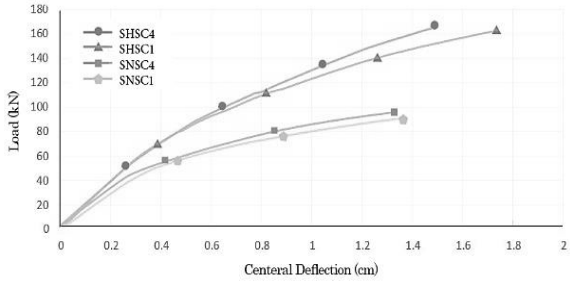


**Figure 13.** The impact of high-strength concrete on ultimate load-deflection curve of the slab with openings of different positions towards the column.

By comparing the ultimate load-deflection curves of the samples, it can be observed that the increase in the ultimate load of sample 1 in case of using high-strength concrete is 80.46%. The ultimate load of the SHSC4 sample is 163.86 kN, and it is 93.17 kN for the SNSC4 sample, representing the increase percentage of 75.87% for ultimate load of the sample with high-strength concrete compared to the sample with normal-strength concrete. The amount of the ultimate deflection of the SHSC1 sample, compared with the SNSC1 sample, is 27.5%, and it has increased by 9.01% for the SHSC4 sample, compared with the SNSC4 sample. In Figure 14, the ultimate load and deflection chart of the samples 1 and 4 are shown.

In this section, it can also be observed that the percentage of increase in the ultimate load and deflection of the samples in case of using high-strength concrete in the slab with an opening located at the front of the column is more than that of the slab with an opening placed at the corner of the column.

## 5. 5. Investigation of the Effect of Opening Shape

In the final step, to check the impact of the opening shape on the behavior of the samples, openings with same position and area were modeled. To this end, initially the load-deflection chart of the SHSC5 sample (with a rectangular opening with dimensions of 5mm * 45mm) was compared with the reference sample (with a square opening with a length of 150 mm).

Figure 15 depicts the impact of the shape of the opening on the load-deflection curve, where the behavior of the samples with a square opening with side length of 150 mm has been compared to that of samples with a rectangular opening with dimensions of 5mm * 45mm. By comparing the ultimate load-deflection chart of the samples, it can be observed that the increase in the ultimate load of the slab with a square opening in case of using high-strength concrete is 80.46%. For the slab with a rectangular opening, the ultimate load of the SHSC5 sample is 124.82 kN, and it is 66.43 kN for the SNSC5 sample demonstrating an increase of 87.93% in the ultimate load of the sample with high-strength concrete compared to the sample with ordinary strength concrete. The amount of the ultimate deflection of the SHSC1 sample is 27.5%, compared to the SNSC1 sample; in addition, it has increased by 57.14% for the SHSC5 sample, compared to the SNSC5 sample. The ultimate load and deflection curve of these two samples can be seen in Figure 16.

Accordingly, we can conclude that the percentage of increase of the ultimate load and deflection of the samples in case of using high-strength concrete in the slab with a rectangular opening is more than that of the slab with a square opening.

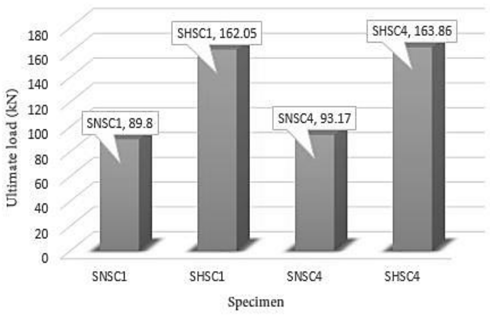


**Figure 14. A.** The impact of high-strength concrete on ultimate load of the slab with openings of different positions towards the column

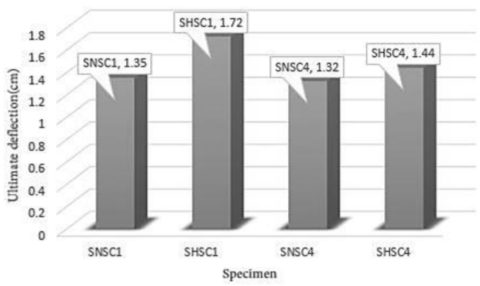


**Figure 14. B.** The impact of high-strength concrete on ultimate deflection of the slab with openings of different positions towards the column

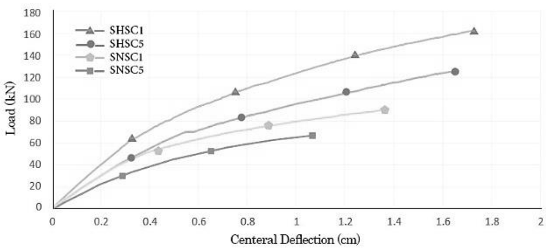


**Figure 15.** The impact of the opening shape on the behavior of the load-deflection curve of the samples

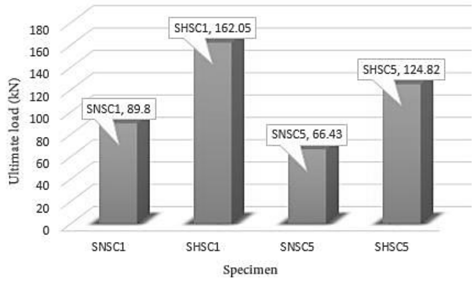


**Figure 16. A.** The impact of high-strength concrete on ultimate load and deflection of the slab with openings of different shapes

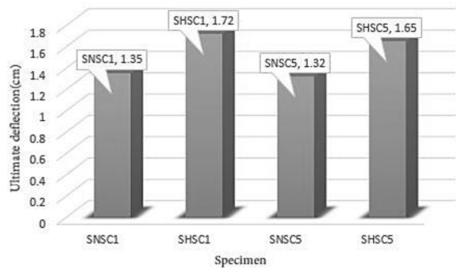


**Figure 16. B.** The impact of high-strength concrete on ultimate load and deflection of the slab with openings of different shapes

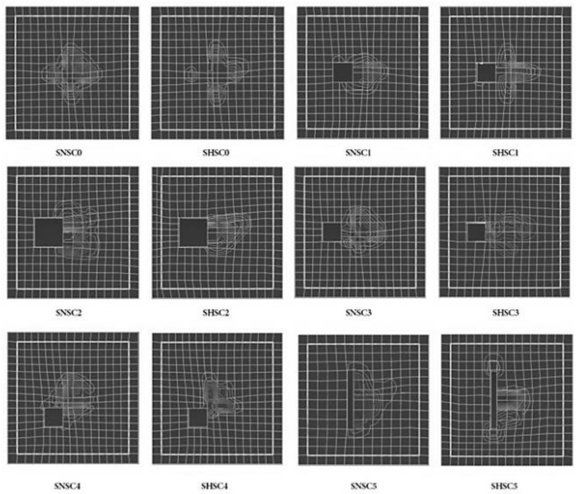

**Figure 17.** The crack pattern of samples

Figure 17 compares the crack behavior of specimens. As shown in this figure, the crack on the surface beneath the slabs started radially from the central loading area and expanded.

Furthermore, this figure indicates that use of high-strength concrete in the majority of the samples changed the pattern of the crack. In Table 2, the ultimate loads, initial cracking load and energy dissipation capacity of the samples have been shown.

**TABLE 2.** The final result of modeling samples

| Sample | First cracking load (kN) | Ultimate load (kN) | Percentage of ultimate load changes | Energy dissipation capacity (kN.mm) | Percentage of energy dissipation change |
|---|---|---|---|---|---|
| SNSC0 | 25.12 | 100 | - | 1023.90 | - |
| SHSC0 | 87.71 | 166.08 | 66.08 | 1574.14 | 53.74 |
| SNSC1 | 19.56 | 89.80 | - | 790.51 | - |
| SHSC1 | 74.92 | 162.05 | 80.46 | 1735.41 | 119.53 |
| SNSC2 | 14.23 | 76.94 | - | 592.75 | - |
| SHSC2 | 70.14 | 143.36 | 86.33 | 1459.44 | 146.21 |
| SNSC3 | 23.80 | 92.80 | - | 767.62 | - |
| SHSC3 | 84.14 | 163.65 | 76.35 | 1513.88 | 97.14 |
| SNSC4 | 22.87 | 93.17 | - | 838.33 | - |
| SHSC4 | 82.47 | 163.86 | 75.87 | 1508.31 | 79.92 |
| SNSC5 | 14.46 | 66.43 | - | 465.84 | - |
| SHSC5 | 69.83 | 124.82 | 87.90 | 1312.40 | 181.73 |

As shown in Table 2, using high-strength concrete, the energy dissipation capacity and the ultimate load of the samples have increased. The maximum energy dissipation capacity belongs to the slab with a square opening at the front of the column made of high-strength concrete; moreover, the lowest energy dissipation capacity belongs to the slab with a rectangular opening made of normal-strength concrete. It can also be observed that in case of using high-strength concrete instead of normal-strength concrete, the energy dissipation capacity and the ultimate load of the samples increased on average by 79% and 113%, respectively. The highest percentage of increase in the ultimate load and energy dissipation capacity in case of using high-strength concrete belongs to the sample with a rectangular opening, and the lowest percentage of increase in the ultimate load and energy dissipation capacity is observed in the sample without an opening. Employing high-strength concrete in the majority of samples induces an impressive increase in the first cracking load.

## 6. CONCLUSION

The present study investigates the effect of using high-strength concrete in 2 groups of slab, a group with HSC concrete and the other with NSC concrete. In each group, a slab without opening and 5 slabs with different openings existed. The general conclusions of this study are as follows:

1. The use of HSC concrete in modelling the slab induces a dramatic increase in the ultimate load and a slight increase in the ultimate deflection and ductility of the sample.
2. The use of high-strength concrete can compensate well punching shear capacity reduction resulted from the existence of openings in the slab and can even reach to much higher ultimate load than the ultimate load of slab without opening and made with normal-strength concrete.
3. The impact of use of HSC concrete on the increase in the ultimate load and deflection for the slab with a larger opening is more than that with a smaller opening. Most of the increase in the ultimate load in the study is related to the slab with square opening with a length of 225 mm on side of the column by 86.33% increase.
4. The effect of using high-strength concrete on ultimate load and deflection increase, in the slab with the opening next to the side of the column is more than the slab with opening placed at the distance from the column.
5. The percentage of increase in the ultimate load and deflection of the samples in case of using high-strength concrete in the slab with an opening located at the front of the column is more than that of the slab with an opening placed at the corner of the column.
6. In case of using high-strength concrete in the slab with rectangular opening and the slab with square opening (with the same area of the openings), the percentage of increase in ultimate load and deflection for the sample with rectangular opening is more.
7. With the use of high-strength concrete, the energy dissipation capacity and ultimate load of the samples increased. The highest percentage of increase for the

ultimate load and energy dissipation capacity in case of using high-strength concrete belongs to the sample with a rectangular opening, and the lowest percentage of increase for the ultimate load and energy dissipation capacity is observed in the sample without an opening.

8. The use of high-strength concrete in the majority of samples changed the pattern of the crack. Employing high-strength concrete in the majority of samples induces an impressive increase in the first cracking load.

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# Shear Capacity of Reinforced Concrete Flat Slabs Made with High-strength Concrete: A Numerical Study of the Effect of Size, Location, and Shape of the Opening

**TECHNICAL NOTE**

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*PAPER INFO*

*Paper history:*
Received 11September 2016
Received in revised form 03January 2017
Accepted 24January 2017

*Keywords*:
Reinforced Concrete Flat Slab
Opening
Numerical Method
High-strength Concrete
Shear Capacity

**چکیده**

امروزه بتنهای با مقاومت بالاتر از ۵۰ مگاپاسکال با توجه به نیاز روزافزون به مقاومت بالاتر و بهبود خواص طولانی مدت، استفاده می شود. با وجود استفاده گسترده از بتن مقاومت بالا، تنها چند پروژه تحقیقاتی درباره مقاومت برشی پانچ دال بتنی با مقاومت بالا انجام شده است. دال تخت بتن مسلح به طور گسترده ای در سیستم های سازه ای استفاده می شود. محل اتصال دال–ستون حساس ترین بخش دال تخت می باشد. در پژوهش حاضر اثر وجود بازشو در دو گروه دال تخت بتن مسلح، یک گروه با بتن مقاومت بالا و گروه دیگر با بتن مقاومت معمولی بررسی شد. به این منظور چند نمونه دال تخت با موقعیت، شکل و ابعاد متفاوت بازشو با بتن مقاومت معمولی، با دال هایی با همان هندسه ولی با بتن مقاومت بالا مقایسه گردیده است تا بتوان اثر بتن مقاومت بالا را در دال هایی با بازشوهای متفاوت بررسی نمود. نتایج این پژوهش نشان می دهد از بتن مقاومت بالا، مقاومت برشی دال را بهبود می بخشد و باعث انتقال نیروهای بالاتری در محل اتصال دال–ستون می گردد. همچنین ابعاد، شکل و موقعیت قرارگیری بازشو بر میزان افزایش بار و تغییر مکان نهایی نمونه ها موثر است.

***doi**: 10.5829/idosi.ije.2017.30.02b.02*