Punching shear strength of steel fibre reinforced concrete flat slabs: a literature review and design codes evaluation

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Abstract: The design of reinforced concrete flat slabs is usually governed by their punching shear strength, and various methods have thus been suggested to increase the punching shear strength of flat slabs. Of these methods, the addition of steel fibre has proven to be among the most effective, not only in terms of enhancing punching shear capacity but also with regard to improving the ductility of flat slabs. This paper presents a comprehensive literature review of experimental investigations conducted to study the behaviour of steel fibre reinforced concrete (SFRC) flat slabs. In addition, the punching shear calculations of the ACI-318-19, the EC2, and the BS8110 codes were evaluated using the test results for SFRC flat slabs reported in the literature to determine their applicability in practice. These codes do not consider the strength contribution of steel fibres, and thus these comparisons with the test results revealed that the punching shear calculations of the above codes consistently underestimate the shear capacity of SFRC flat slabs.

1. Introduction
Flat slabs are popular floor systems due to their architectural and economic benefits, and the design of flat slabs is usually controlled by their deflection at midspan or their punching shear at the slab-column connections [1], as punching shear creates a local brittle failure that might lead to a progressive collapse of the entire structure [2]. Drop panels and column capitals are not cost-efficient solutions, and thus various methods have been proposed to increase the ductility and punching shear strength of flat slabs, including bent-up bars, closed stirrups, and shear stud fixings [3]. Recently, experimental studies have also shown that the application of steel fibres to the concrete mix increases the punching shear strength [4], an increment attributed to the fact that steel fibres bridge the cracking in concrete mixes [5]. Several design methods have thus been proposed to estimate the contribution of steel fibres and to calculate the punching shear strength of SFRC flat slabs [6]. To date, however, the relevant design codes have not begun to consider the shear strength enhancement provided by steel fibres; the punching shear design provisions adopted by these codes were developed using test results for flat slabs without steel fibres, and it is not clear how to use these design codes for SFRC flat slabs while accounting for the shear strength enhancement created by the presence of steel fibres.
This paper thus reviews previous experimental investigations on the punching shear behaviour of SFRC flat slabs at internal columns to allow the punching shear calculations of the ACI-318-19 [7,], the EC2 [8,], and the BS8110[9,] codes to be evaluated in terms of their applicability for the design of SFRC flat slabs to resist punching shear.

1. Literature Review
Due to its brittle nature and complex behaviours, the punching shear failure of SFRC flat slabs has attracted the attention of many researchers. This section reviews the main previous experimental investigations on the punching-shear failure behaviours of steel fibre reinforced concrete (SFRC) flat slabs at internal column connections.

2.1 Punching shear in the absence of unbalanced moment transfer
Alexander and Simmonds [10,] tested six slab specimens to study the punching shear behaviours of SFRC slabs. Four of these were constructed with steel fibres and the remaining two were control specimens constructed without steel. The variables considered were the steel fibre content (0, 31, 34, 66, or 69 Kg/m$^3$), the concentration of steel fibres (11 or 38 mm) and the thickness of the concrete cover. Corrugated steel fibre was used with lengths of 50 mm, and the test results showed that the addition of steel fibre increased the punching shear strength by 20 to 30%. The researchers attributed this increment to the increase of flexural resistance provided by steel fibres in the region outside of the contraflexure lines.

Theodorakopoulos and Swamy [11,] carried out an experimental investigation in 1993 to study the effect of steel fibres on punching shear strength. Their experimental programme consisted of testing twenty slab specimens, three of which were constructed without steel fibres; the remaining seventeen specimens were constructed with steel fibres. The variables considered were the proportion of steel fibres in concrete mix (0.0, 0.5, or 1.0%) the tension and compression reinforcements, the size of the column, the type of steel fibres (crimped, hooked, or paddle) and the concrete compressive strength (17.75 to 58.56 N/mm$^2$). The three types of steel fibre used had diameters ranging from 0.418 to 0.760 mm and lengths ranging from 25.0 to 53.0 mm. The researchers found that the presence of steel fibres increased the ultimate punching shear strength by 30 to 45% based on various parameters. The addition of steel fibre to plain concrete slabs also increased the service load by 15 to 40%, as well as delaying the formation of punching shear cracks.

In 1994, Tan and Paramasivam [12,] reviewed the previous tests reported in the literature and carried out an experimental investigation to study the effect of steel fibres on the punching shear behaviours of SFRC flat slabs. Their experimental investigation involved testing fourteen slab specimens with various proportions of corrugated steel fibres with lengths of 25 mm and diameters of 0.711 mm, ranging from 0 to 6.4%. All slab specimens failed by punching shear, and...
the results showed that the presence of steel fibres increased the punching shear strength of slab specimens by 15%. The researchers thus used these test results and previous literature to propose a design equation to calculate the punching shear of SFRC flat slabs.

In 1995, Harajli et al. [14,] reviewed the previous tests reported in the literature and carried out an experimental investigation to study the effect of steel fibres on the punching shear behaviours of SFRC flat slabs. The experimental worked included testing twelve slab specimens of thickness 55 mm or 75 mm with various proportions of steel fibre (0.45 to 2.0%). Hooked steel fibres were used in the construction of these specimens, with diameters of 0.5 mm and lengths of 30 mm. The test results showed that the punching shear failure mechanism was more brittle and sudden in slabs without fibres as compared to that seen in slabs containing fibres. Moreover, the crack width smaller with higher amounts of steel fibre, suggesting that steel fibre can be used to improve slab integrity in the critical zone of slab column connections.

Hanai and Holanda [15,] conducted analytical and experimental studies to examine the influence of steel fibres on the punching shear strength of flat slabs. The experimental study involved testing eighteen slab specimens with various proportions of steel fibre (0 to 2%) and various concrete compressive strengths (25, 40, and 56 MPa). Hooked-end steel fibres were used in the construction of specimens, and the test results showed that the ductility and punching shear strength were increased as the steel fibre amount in the concrete mix increased, by up to 20 to 35%. In addition, they observed that presence steel fibre in slabs reduced crack widths.

In 2009, Wang et al. [16,] tested five slab specimens to study the punching shear behaviours of SFRC flat slabs at internal column connections. Specimens were constructed with various proportions of hooked-end steel fibres (0, 1.0, or 1.5%). The test results showed that the punching shear capacity and ductility of SFRC slabs were thus enhanced, and crack formation was delayed.

In 2011 and 2012, Nguyen et al. [17,] and Nguyen et al. [18,] reviewed the tests conducted by previous researchers and carried out experimental investigation on twelve slab specimens constructed with various proportions of steel fibre (30, 45, or 60 Kg/m³). Hooked steel fibres with diameters of 0.75 mm and lengths of 60 mm were used, and the test results showed that the ductility of punching shear was increased as the steel fibre proportion increased as shown in Figure 1. The crack width was also reduced by about 70% as the steel fibre amount increased, while the punching shear resistance was increased by 9 to 39.8 % as the amount of steel fibre increased from 30 to 60 Kg/m³.
Grimaldi et al. [19] tested seven slab specimens to examine the influence of steel fibres on their punching shear strength. Slab specimens were constructed with two proportions of hooked steel fibres of diameter 0.75 mm and length 50 mm, 0 and 0.5%. The test results showed that the presence of steel fibre increased the punching shear capacity of slab specimens by 30 to 35%.

In 2015, Barros et al. [20] conducted experimental work testing eight slab specimens. Two of these served as control specimens, being constructed without steel fibres, while the remaining six specimens were constructed with steel fibres. The variables considered were the proportion of hooked steel fibres (0, 60, 75, or 90 Kg/m³), and the concrete compressive strength (50 or 70 MPa). The researchers found that the punching shear capacity and ductility of slabs containing steel fibre were higher than those of the control specimens. In addition, they observed that the crack width was smaller as the proportion of steel fibre increased.

Sermet and Ozdemir [21] analysed previous tests in 2016 and carried out their own experimental investigation to study the punching shear behaviours of SFRC flat slabs and the effects of steel fibres on punching shear capacity. Test variables were the shear span effective depth ratio (a/d), and the amount of hooked steel fibres in the mix. The latter was ranged from (0.5-2.5) %. Test results showed that punching capacity and deflection for concrete slab containing steel fibre were increased from by (12-21) %. In addition, they observed that the shear crack width was reduced when steel fibres were added.

2.2 Punching shear in the presence of unbalanced moment transfer

Ozden et al. [22] tested sixteen slab specimens in 2006 to study the punching shear behaviours of SFRC flat slabs at internal column connections in the presence of unbalanced moment transfer. The variables considered were the proportion of steel fibres (0 or 1.0%), the amount of unbalanced transferred moment, and the concrete compressive strength (18.5 to 81.3 MPa). Hooked-end steel fibres were used,
and the test results showed that the addition of steel fibre increased punching shear capacity and ductility, as well as increasing the number of cracks yet reduced their width.

**In 2008, Smadi and Bani** [23,] tested ten slab specimens constructed with various proportions of steel fibres and concrete compressive strengths subjected to various levels of unbalanced transferred moment. Hooked steel fibres were used in the construction of specimens at 0, 0.5, or 1%; these were 30 mm long, with diameters of 0.5 mm. Specimens were constructed with compressive strengths ranging from 21 to 51 MPa. The test results showed that the presence of steel fibres increased the punching shear strength of slab specimens with normal concrete compressive strength by up to 8 to 57%, depending on the proportion of steel fibres used, and increased the punching shear strength of slabs constructed with high concrete compressive strength by up to 5 to 35%, again depending on the steel fibre ratio. In addition, the presence of steel fibres increased the stiffness and the ductility of slab specimens.

**Abdel-Rahman et al.** [24,] carried out experimental work in 2018 based on testing fourteen slab specimens. The slab specimens were tested to failure in two phases: the first phase included ten slab specimens subjected to concentric punching shear and the second phase included four slab specimens subjected to eccentric punching shear. The test variables included the proportion of steel fibre in the concrete mix (0.5, 1.0, or 1.5%) near the column zone. Twelve of slab specimens were constructed with steel fibres and the remaining two were control specimens. In phase 1, the presence steel fibre increased the punching shear capacity (as indicated in Figure 1) and ductility and reduced crack widths; the researchers also observed that increasing the concentration of steel fibre near the column increased the punching shear capacity.

### 3. Current design codes

Current design codes have adopted the control surface approach for the design of flat slabs against punching shear failure. In accordance with this approach, the punching shear capacity of a flat slab is estimated by the algebraic sum of the shear stresses distributed on a vertical shear surface (critical section) located a specific distance from the column faces. Design codes differ from each other in terms of concrete punching shear strength equations, the location of the critical section with respect to the column, and the calculation of additional shear stresses induced from unbalanced moment transfer, however. In this section, the punching shear calculations of the ACI-318-19 [7,] (American concrete institute), the EC2 [8,] (The European Standard), and the BS8110 [9,] (British Standard) are presented, though it is important to note that these codes do not consider any punching shear contribution provided by the presence of steel fibre.

#### 3.1 ACI-318-19 [7,]

The ACI-318-19 [7,] positions the critical section at 0.5d from the column faces, as shown in Figure 4 (a). The concrete punching shear strength is a function of concrete compressive strength and the effective depth of a slab. In the absence of unbalanced moment transfer, the ultimate punching shear capacity of a flat slab at internal column connections is thus given by

\[ V_{ACI} = v_c b_o d \]

Eq. (1)

where:  
\( V_{ACI} \): Ultimate punching shear load.  
\( b_o \): Perimeter of critical section,  
\( b_o = 2(c_1 + d) + 2(c_2 + d) \)
\(d\): Effective depth of a slab.

\(c_1, c_2\): Column dimensions.

\(\nu_c\): Concrete punching shear strength, taken as the minimum value from equations 2 to 4:

\[
\nu_c = \left(0.17 + \frac{0.33}{\beta}\right) \lambda_s \sqrt{f_c} \tag{Eq. (2)}
\]

\[
\nu_c = \left(0.17 + \frac{0.03\alpha s d}{b_0}\right) \lambda_s \sqrt{f_c} \tag{Eq. (3)}
\]

\[
\nu_c = 0.33\lambda_s \sqrt{f_c} \tag{Eq. (4)}
\]

where: \(\beta_c\): Ratio of long side to short side of the column.

\(f_c\): Cylinder concrete compressive strength.

\(\alpha_s\): Factors for internal, edge, and corner, taken as 40, 30, and 20, respectively.

\(\lambda_s\): Size effect factor, \(\lambda_s = \sqrt{\frac{2}{1+0.004d}} \leq 1\)

In the presence of moment transfer, the ACI-318-19 [7,] assumes part of unbalanced transferred moment, \(\gamma_f M_{\text{test}}\), is resisted by the flexural capacity at the column connection. The rest of the transferred moment, \(1 - \gamma_f M_{\text{test}}\), is assumed to be transformed into unbalanced shear stresses. The induced shear stresses from the unbalanced are then assumed to combine with those induced by shear force. The distribution of the resultant shear stresses is thus assumed to vary linearly, as shown in figure 4(b). In the presence of moment transfer, the ultimate punching shear load of a flat slab at internal column connections is thus given by

\[
\min \nu = \frac{V_{\text{ACI}} b_{od}}{b_1 d} \pm \frac{\nu_0 M_{\text{Sc}} c_{AB}}{f} \tag{Eq. (5)}
\]

where: \(\nu_0\): Factor used to determine the fraction of \(M_{\text{Sc}}\) transferred by eccentricity of shear at slab-column connections, \(\nu_0 = 1 - \gamma_f\).

\(\gamma_f\): Factor used to determine the fraction of \(M_{\text{Sc}}\) transferred by slab flexure at slab-column connections, \(\gamma_f = \frac{1}{1+(\frac{2}{3}) \frac{b_1}{b_2}}\).

\(b_1\): Critical section’s side which is parallel to direction related to transferred moment,
\(b_1 = c_1 + d\).

\(b_2\): Critical section’s side which is perpendicular to direction of the transferred moment,
\(b_2 = c_2 + d\).

\(M_{\text{Sc}}\): Factored slab moment.
$J_c$: Representing polar moment of the inertia related to critical section, 

$$J_c = \frac{d(c_1+d)^3}{6} + \frac{d(c_2+d)(c_1+d)^2}{2}.$$ 

(a) Critical section  

(b) Distribution of shear stresses induced from unbalanced moment transfer

Figure 2. Punching shear calculations from ACI-318-19 [7,] at internal column.

3.2 EC2 [8,]

The EC2 [8,] positions the critical section at 2d from the column faces (figure 5(a)). The concrete punching shear strength is a function of concrete compressive strength and effective depth of a slab, and the ultimate punching shear capacity of a flat slab at internal column connections is given by

$$V_{EC2} = v_c \ u \ d$$

Eq. (6)

where: $V_{EC2}$: Ultimate punching shear load.

$u$: Perimeter of critical section’s, $u = 2c_1 + 2c_2 + 4\pi d$

$d$: Effective depth of a slab.

$c$: Column dimensions.

$v_c$: Concrete punching shear strength,

$$v_c = 0.18 \ k(100\rho f_c)^{1/3}$$

Eq. (7)

where $k$: Size effect factor, $k = 1 + \left(\frac{200}{d}\right)^{0.5}$, where $k \leq 2$

$\rho$: Ratio of tension steel reinforcement, where $\rho \leq 2\%$

$f_c$: Cylinder concrete compressive strength.
Figure 3. Punching shear calculations of EC2 [8,] at internal column.

EC2 [8,] assumes that the transferred moment is transmitted by the unbalanced shear stresses. The shear stresses induced from the unbalanced shear stresses are then assumed to combine with the shear stress induced by concentric shear, as shown in figure 5(b). The moment transfer factor, $\beta$ can then be computed from the following equation:

$$\beta = 1 + k \frac{M_u}{V_u} + \frac{u}{w_1}$$

Eq. (8)

where: $\beta$: Moment transfer factor

$k$: Factor accounts for the effect of the column’s rectangularity, to be determined from Table 6.1 in EC2 [8,].

$M_u$: Factored slab moment.

$V_u$: Ultimate punching shear load.

$u$: Perimeter of critical section, $u = 2c_1 + 2c_2 + 4\pi d$

$c_1, c_2$: Column dimensions.

$d$: Effective depth of a slab.

$w_1$: Corresponds to distribution related to shear stress, for a rectangular column, so that $w_1 = \frac{c_1^2}{2} + c_1 c_2 + 4 c_2 d + 16d^2 + 2\pi c_3$

The punching shear strength is computed using equation 9:
\[ v_c = \beta \frac{V_u}{u d} \]  

**Eq. (9)**

3.3 **BS8110 [9,]**

The BS8110 [9,] positions the critical section at 1.5d from the column faces (see figure 6). The concrete punching shear strength is a function of concrete compressive strength and effective depth of a slab. The ultimate punching shear capacity of a flat slab at internal column connections is given by

\[ V_{BS8110} = v_c u d \]  

**Eq. (10)**

where \( V_{BS8110} \): Ultimate punching shear load.

\( u \): Perimeter of critical section, \( = 2(c_1 + 3d) + 2(c_2 + 3d) \).

\( d \): Effective depth of a slab.

\( c \): Column dimensions.

\( v_c \): Concrete punching shear strength, \( v_c = 0.79 \sqrt{\frac{f_{cu}}{d}} \)  

**Eq. (11)**

where \( \rho \): The ratio of the tension steel reinforcement, where \( \rho \leq 3\% \)

\( f_{cu} \): Cube concrete compressive strength, \( f_{cu} \leq 40 \text{ MPa} \)

![Critical section of BS8110 [9,]](image)

**Figure 4.** Critical section of BS8110 [9,]

BS8110\(^9\) assumes that the transferred moment is transmitted by the vertical shear stresses. These shear stresses are then assumed to combine with the shear stress induced by concentric shear. The moment transfer factor, \( \beta \) can thus be computed using equation 12:

\[ \beta = \left( 1 + \frac{1.5 M_u}{V_u x} \right) \]  

**Eq. (12)**

where: \( \beta \): Moment transfer factor
$M_u$: Factored transferred moment.

$x$: Side of the critical section parallel to the applied moment, $x = c_1 + 3d$

The punching shear strength can then be computed from equation 13:

$$v_c = \beta \frac{V_u}{u}$$  \hspace{1cm} \text{Eq. (13)}

4. Test data

Relevant test results from previous experimental studies were collected to evaluate the accuracy of the punching shear design procedure of ACI-318-19 [7,], EC2 [8,], and BS8110 [9,]. A total 135 tests from the literature on slabs constructed with steel fibre subjected to internal punching shear failure in both the absence and the presence of moment transfer were used in this study. The specimens thus covered a wide range of test variables. The test data is divided into two groups: the first group consists of 118 SFRC flat slabs failed by internal punching shear in the absence of moment transfer, as presented in table 1. The second group consists of 17 SFRC flat slabs failed by internal punching shear in the presence of moment transfer, as presented in table 2.

**Table 1.** SFRC flat slabs subjected to punching shear in the absence moment transfer

| Source                          | No. of slabs | $V_{test}$ (KN) | $d$ (mm) | $f_c$ (MPa) | $\rho$ (%) | $\rho_f$ (%) |
|---------------------------------|-------------|-----------------|---------|-------------|----------|-------------|
| Cheng & Parra [5,]              | 8           | 386-530         | 127     | 25.4-59.3   | 0.66-0.98| 1.0-1.5     |
| Theod. & Swamy [11,]            | 16          | 166-259.8       | 100     | 14.2-46.8   | 0.37-0.56| 0.5-1.0     |
| Alexander & Simond [10,]        | 4           | 308-345         | 105.7-132.7 | 35 -38.5 | 0.5-0.63 | 0.39-0.88  |
| De Hanai & Holanda [15,]         | 6           | 139.6 -236.2    | 80      | 24.4 -59.7  | 1.56     | 0.75 -2.0   |
| Swamy & Ali [25,]               | 12          | 179.3-267.2     | 100     | 36.8-41.1   | 0.37-0.74| 0.6-1.2     |
| McHarg [26,]                    | 2           | 422-438         | 109     | 41.5        | 1.12-2.18| 0.5         |
| Suter & Moreillon [27,]          | 8           | 286-402         | 88-92   | 103-108     | 0.55-1.29| 0.25-1.02   |
| Source                        | No. of slabs | $V_{test}$ (kN) | $M_{test}$ (kN.m) | $d$ (mm) | $f_c$ (MPa) | $\rho$ (%) | $\rho_f$ (%) |
|-------------------------------|--------------|-----------------|-------------------|--------|-------------|----------|-------------|
| Ozden & Ersoy & Ozturan [22,] | 8            | 142-528         | 82.2-19.2         | 100    | 19.3-81.3   | 0.73-2.25 | 1.0         |
| Abdel-Rahman & Hassan & Soliman [24,] | 3            | 225-250         | 45-50             | 115    | 30          | 1.2      | 0.5-1.5     |

Table 2. SFRC flat slabs subjected to punching shear in the presence moment transfer
5. Evaluation of codes

Previous experimental work has indicated that the punching shear strength of flat slabs is enhanced by steel fibres. So far, however, the punching shear design provisions in the major design codes still ignore the strength contribution of steel fibres. The major design codes presented in section three were thus applied to predict the punching shear failure load of the 118 slab specimens found in the literature in order to evaluate the applicability of these codes to designing SFRC flat slabs against punching shear. All material safety factors in these codes are set to unity.

Figure 5 presents comparisons between the test results for 118 SFRC flat slabs failed by internal punching shear in the absence the moment transfer and the punching shear design predicted in the current building codes (ACI-318-19 [7], EC2 [8], and BS8110 [9]). The means of punching shear strength to tests of the ACI-318-19, EC2 2, and BS8110 3 were 0.67, 0.69, and 0.76, respectively. The standard deviations of punching shear strength to tests in ACI-318-19 [7], EC2 [8], and BS8110 [9] were 0.17, 0.11, and 0.14, respectively. A comparison reveals that the current codes provide very conservative predictions of punching shear strength in SFRC flat slabs subjected to punching shear in the absence of unbalanced moment transfer. This is to be expected, as these current codes do not consider the strength enhancement provided by steel fibres detected in previous experimental work.
Figure 5. Comparisons between the punching shear strength predictions of current building codes (ACI-318-19 [7,], EC2 [8,], and BS8110 [9,]) of 118 SFRC flat slabs in the absence the moment transfer.

Figure 6 compares the internal punching shear failure loads of 17 SFRC flat slabs subjected to moment transfer and the punching shear predicted by the current design codes ACI-318-19 [7,], EC2 [8,], and BS8110 [9,]. The means of predicted punching shear failure loads to tests of ACI-318-19 [7,], EC2 [8,], and BS8110 [9,] were 0.31, 0.52, and 0.51, respectively, and the standard deviations of punching shear strength to tests of the ACI-318-19 [7,], EC2 [8,], and BS8110 [9,] were 0.13, 0.29, and 0.39, respectively. Comparison with the test results for SFRC flat slabs shows that the punching shear calculations in current design codes are both conservative and widely scattered, which is again attributable to the codes’ neglect of the shear strength contribution provided by steel fibres.
6. Conclusion

The followings conclusions can be drawn from this study:

1. The addition of steel fibre to the concrete mix increases the punching shear capacity with moment transfer by up to 57%, depending upon various parameters.
2. The addition of steel fibre reduces the crack width by up to 70% in some cases and delays the formation of shear cracks.
3. As the punching shear design provisions in (ACI-318-19 [7,], EC2 [8,], and BS8110 [9,]) do not consider the strength contribution of steel fibres, they provide conservative and scattered predictions of the punching shear capacity of SFRC slabs at internal columns.

Figure 6. Comparisons between the punching shear strength predictions of current building codes (ACI-318-19 [7,], EC2 [8,], and BS8110 [9,]) of 17 SFRC flat slabs in the presence of moment transfer.
NOTATION

\( d \)       Effective depth of a slab.

\( \rho f \)  The steel fibre percentage.

\( f_c \)  Concrete compressive strength

\( \rho \)  Flexural reinforcement ratio.

\( V_{test} \)  Punching shear failure load.

\( V_{ACI} \)  Predicted punching shear load by ACI-318-19 [7,].

\( b_o \)  Perimeter of critical section in ACI-318-19 [7,].

\( c_1, c_2 \)  Column dimensions.

\( \beta_c \)  Ratio of long side to short side of the column as per ACI-318-19 [7,].

\( \alpha_s \)  Factor for internal, edge, and corner is taken 40 as per ACI-318-19 [7,].

\( \lambda_s \)  Size effect factor in ACI-318-19 [7,].

\( \gamma_v \)  Factor used to determine the fraction of \( M_{sc} \) transferred by eccentricity of shear at slab-column in ACI-318-19 [7,].

\( \gamma_f \)  Factor used to determine the fraction of \( M_{sc} \) transferred by slab flexure at slab-column in ACI-318-19 [7,].

\( M_{Sc} \)  Factored slab moment in ACI-318-19 [7,].

\( J_c \)  Representing polar moment of the inertia related to critical section in ACI-318-19 [7,].
$V_{EC2}$ Predicted punching shear load by EC2 [8].

$u$ Perimeter of critical section in EC2 [8] and BS8110 [9].

$v_c$ Concrete punching shear strength.

$k$ Size effect factor in EC2 [8].

$\beta$ Moment transfer factor in [8].

$k$ Factor accounts for the effect of the column’s rectangularity in EC2 [8].

$V_{BS8110}$ Ultimate punching shear load.

$f_{cu}$ Cube concrete compressive strength.

$M_u$ Factored transferred moment, BS8110[9].

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