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Reliability Study of Punching Shear Design of Column-Slab Connection according to the Saudi Building Code (SBC-304)

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Abstract - *The punching shear in column slab connection is a common studied problem that every building code tries to eliminate. The Saudi building code, as derived from the American building code, uses the minimum of triple-formula combination to predict the expected strength of the connection. However, it is experimentally proven that these predictions may predict higher value than the slab can actually bear on the connection without shear which results in failure events and decreases the reliability of the code. In this study, 618 experimental results collected from previous researches are used measure the reliability of the Saudi building code punching shear design column slab connection without shear reinforcement. Also, comparison with EC-2 reliability is performed in the work. The study shows that the reliability of SBC-304 design approach is higher than the EC-2. The reliability equal 80.11% for all samples, 83.16% for circular, 89.53% for rectangular and 77.67% for square.*

Key Words: reliability, punching shear, column slab connection, Column shape, reliability index

1. INTRODUCTION

Shear is a common failure event in structural design. Researchers has studied and analyzed it thoroughly in order to gain control over its factors and eliminate its failure probability. Punching shear, precisely, is a more dangerous shear failure event as its minimum consequence would not be less than fall of ceiling. Its effect might extend to cause a failure for the whole structure.

Due to this importance, every project should conform to some regulations and standards to avoid punching shear in the structure. Globally, national councils investigate the building health factors and forms building control rules called building code to maintain satisfactory status suitable for the regional parameters. Thus, the building code involves many aspects from civil engineering, architecture engineering, safety, material manufacturing, and insurance to guarantee quality control over the projects [1]. The concept of the building code is known as a set of requirements, standards, and rules considering building and construction process [2]. Currently, many organizations are responsible for forming the building code internationally and locally.

The Saudi Building Code (SBC-304) [3] is a set of rules and standards regarding legal, administrative, and technical regulations and requirements to specify the minimum standards of construction projects that ensure public health and safety. It was formed by the national committee composed of representatives of Saudi universities and governmental and private sectors starting after getting approved in September 2001 by the Council of Ministers to develop a national building code for the Kingdom of Saudi Arabia.

The code involves multiple important aspects. It is built based on the most recent results of contemporary experiences and updated and upgraded frequently based on evaluations and modifications. The building code is not evaluated as a whole. It is evaluated based on the objectives to determine any new types, methods, or standards are more suitable. One of the most evaluation methods is to calculate the reliability [4], [5].

Slabs are the basic structure for floor construction. Slabs can be supported on beams, columns with drop panels, or column heads. One of the most used types is the simple flat slab which means to carry the slab directly on the column. This has many advantages including easiness in construction, fewer time consumption, freer design, and more empty space control. However, this also come with some disadvantages. One of the worst disadvantages is the possibility of punching shear failure. The punching shear is characterized as a disappointment instrument by shear under the activity of concentrated load. These concentrated loads create punching shear in the critical area near the connection point and can prompt an unexpected disappointment of the structure without prior notification. This sort of disappointment can be a cataclysmic circumstance in the construction and development projects since it doesn't permit the experts or the client to anticipate the unavoidable upcoming breakdown of the structure, causing incredible financial and human misfortunes. Consequently, the assessment of well-being in plans including level chunks is of crucial significance for the productive and dependable utilization of sections [6].

The SBC-304 code provisions recommends that the punching shear strength Vc in reinforced concrete flat slabs without shear reinforcement can be determined through the analysis of the shear stresses at a critical perimeter taken at distance d/2 from the column face or loaded area using the equation (1).

$$V_c \leq \begin{cases} 0.33\,\lambda\sqrt{f_c'}\,b_o\,d \\ 0.17\left(1+\frac{2}{\beta}\right)\lambda\sqrt{f_c'}\,b_o\,d \\ 0.038\left(\frac{\alpha_s d}{b_0}+2\right)\lambda\sqrt{f_c'}\,b_0\,d \end{cases} \quad (1)$$

According to the EC2, the following expression can be used to calculate the punching shear resistance $V_{Rd,c}$ of a slab without shear reinforcement at the basic control perimeter u1 that is taken at 2d from the column face using the equation (2). In square columns, the corners of the critical perimeter are rounded.

$$V_{Rd,c} = 0.18\,k\,(100\,\rho\,f_{ck}')^{1/3}\,u_1\,d \quad (2)$$

2. Literature review

Silva et al (2018)[7] Studied the reliability of internal column-slab connection under punching according to the Brazilian Standard NBR 6118:2014. The evaluation of reliability was carried out by comparing the reliability index β with the target reliability index provided by the fib Model Code 2010. The reliability indices were determined through statistical analysis of the data obtained with numerical simulations using the Monte Carlo method with Latin Hypercube sample using ANSYS software. The results indicated for most slabs the indices of reliability β presented acceptable results. However, some of the slabs tested showed results below the expected limits. Therefore, this research suggests that the Brazilian Standard NBR 6118:2014 is suitable for most flat slabs without shear reinforcement.

Nassim et al (2015)[8] studied the Reliability and punching shear resistance of slabs in nonlinear domain. The punching shear resistance of slabs is numerically evaluated and compared with predictions specified in ACI-318, the Canadian code (CSA), and The British Standard code (BS-8110) punching design codes. Also studied is the interaction of major parameters which affect the punching shear behavior and failure mode of slabs. The results of the reliability study are described in terms of the reliability index for different levels of P_u/P_{flex}. In addition to the analysis of reliability, the sensitivity analysis is performed in terms of various load levels in order to evaluate the influence of the major variables on the results.

Huang et al (2016)[9] reviewed the Comparative analysis of punching shear strength for reinforced concrete slabs based on database. Although various studies and hundreds of experimental investigations have been published and performed about the punching shear strength of reinforced concrete (RC) slabs, code provisions were improved based on a limited subset of the available test results and the specifics of test slabs and experiments were neglected in those studies. Through the present analysis, a database of 678 specimens was categorized and organized according to the test set-up type. In this analysis, eight equations were evaluated for the punching shear strength prescribed in parameters based on the database and also proposed a simplified strength equation. The calculation results of the current 8 design codes have significant deviations in which Japan Society of Civil Engineering (JSCE) code has the best results in comparison. The method proposed in the paper considers the impact of size effect, strength of concrete, reinforcement ratio and perimeter thickness ratio of critical section on punching strength and further considers the impact of punching span ratio.

Halvoník et al (2019)[10] studied the Reliability of methods aimed at evaluating the punching resistance of flat slabs without transverse reinforcement. Several models were developed and calibrated for determining punching capacity using experimental results from laboratory testing. Some methods are entirely empirical such as EC2, whereas other methods represent the physical nature of the phenomenon, however, their safety level was tested using experimental results such as the method described in Model Code 2010 or the Critical Shear Crack Theory (CSCT) based model, which is represented in a closed form. This article deals with a statistical analysis of the safety level of the previously punching resistance methods without shear reinforcement. A database was used which includes the results of over 600 experimental tests of flat slab specimens. Using advanced statistical techniques, relations between the safety of the method and the performance of the concrete used, the amount of bending reinforcement, and the effective depth were established.

3. METHODOLOGY

The methodology used in this study is hybrid quantitative methodology implementing descriptive and analytical methodologies. First, Code results will be compared with approved experimental results. Then, it evaluates the safety margin, beta-index, and the reliability of punching shear design in column-slab connection in SBC-304. finally, it compares the reliability of SBC-304 with the reliability of other international building codes, namely, the European building code EC2. The methodology of the study is illustrated in
Fig- **1**.

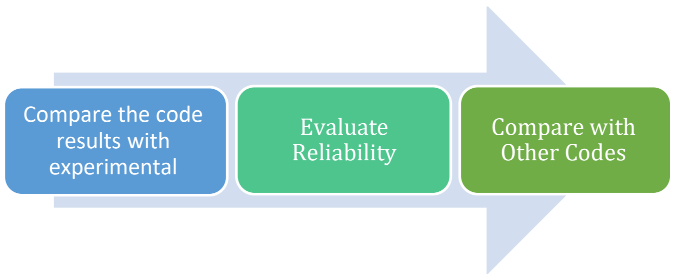

Fig- 1 methodology of the study

The study starts by calculating the safety margin M for the samples using experimental values V_{exp} as resistance and the code value V_C as load. The reliability of the code is derived from the safety margin. A safety margin of zero or below indicates to a failure event. The safety margin M is defined as:

$$M = V_{exp} - V_c \quad (3)$$

Given that the resistance V_{exp} and the load V_c are independent and normally distributed, the mean of the safety margin is obtained by subtracting the mean of V_c from the mean of V_{exp}.

The standard deviation of the safety margin can be obtained using the square root of the sum of variance of V_{exp} and variance of V_c. Based on that, the reliability index β is defined as:

$$\beta = \frac{\mu_M}{\sigma_M} = \frac{\mu_{V_{exp}} - \mu_{V_c}}{\sqrt{\sigma^2{}_{V_{exp}} + \sigma^2{}_{V_c}}} \quad (4)$$

This beta index represents the z-score for the reliability probability. The reliability R equals:

$$R = \Phi(\beta) = \int_{\beta}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{(\beta)^2}{2}} d\beta \quad (5)$$

The experimental data are extracted from a list of literature work. The details of experimental samples and list of literature are shown in Ref [11]. Then, the data is re-organized into a unified form. After that, the punching shear design value is calculated based on SBC-304 equation. Finally, the code values have been compared with the experimental ones and the reliability is calculated using equation (5). The total number of the considered experimental results is 618.

4. RESULTS AND DISCUSSION

Starting with comparing the code results and experimental values, the distribution of the code results and experimental results after removing the outliers is reveled in
Fig- **2**.

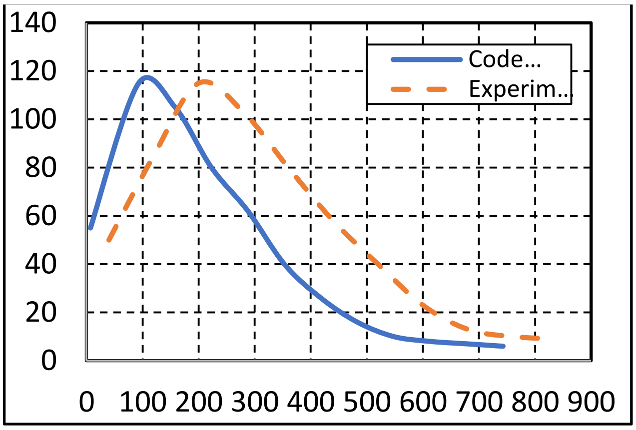

Fig- 2 The frequency curve of the experiments and the code values

Using the equation (3) on the data produces the following insights over the safety margin of SBC-304. The safety margin is going in range between -666.70 and 679.24 KN representing relative punching resistance between 0.68 to 2.52. The mean is 78.67 KN with standard deviation of 93.01 KN and variance of 8650 KN. With a range of about 1345.94 KN and such relatively high standard deviation considering the mean, it is better to analyze the data using the median and quartiles to understand the distribution. The first quartile is 27.90 KN and the third one is 120.26 KN with median of 71.90 KN including 57 cases with negative safety margin. The major difference in the results appears in the Fig- 3 in range between -3 KN and 149 KN.

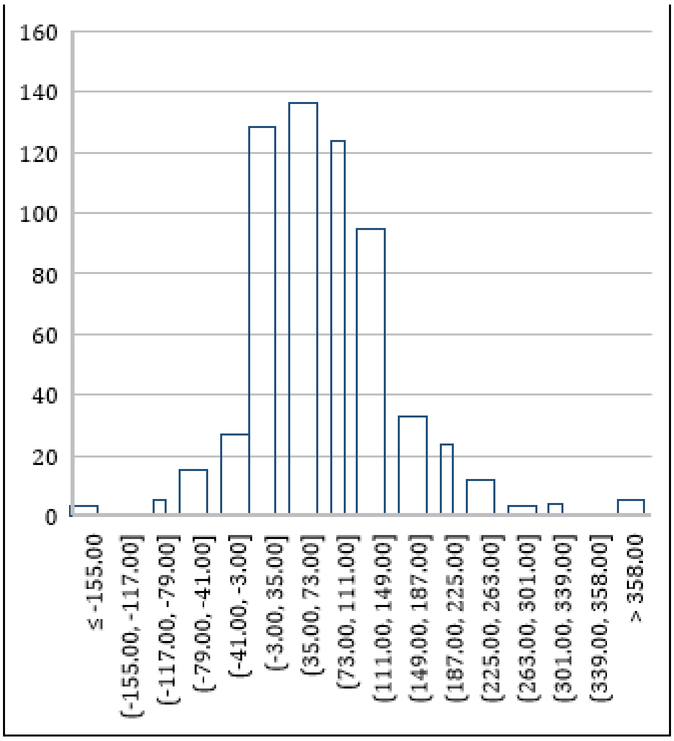

Fig- 3 safety margin distribution for SBC-304

There are 57 test results out of 618 have negative safety margin that indicates to failure event where the punching shear will take place before the pressure reaches the predicted code value. This failure event occurred with rate 9.22% of the total experiments.

Using the equation (4) and the mean of the safety margin μ_M = 78.67 with standard deviation σ_M = 93.01, the reliability index equals:

$$\beta = \frac{78.67}{93.01} \approx 0.8458$$

Evaluating the reliability based on this index provides the reliability R using equation (5) as:

$$R = \Phi(0.8458)$$

$$R = \int_{0.8458}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{(0.8458)^2}{2}} d\beta$$

$$\approx 0.8011 \approx 80.11\%$$

This concludes that the reliability of punching shear of column-slab connection using SBC-304 formula is 80.11%.
On the other hand, EC2 produces the following insights. Using the equation (3) the safety margin is going in range between -730.37 and 405.15 KN representing relative punching resistance between 0.64 to 2.59. The mean is 33.38 KN with standard deviation of 71.32 KN and variance of 5087 KN. With a range of about 1135.52 KN and such significantly high standard deviation that goes more than double considering the mean, The first quartile is 6.34 KN and the third one is 63.28 KN with median of 30.38 KN including 115 cases with negative safety margin. The major difference in the results appears in the

Fig- **4** in range between -5 KN and 82 KN.

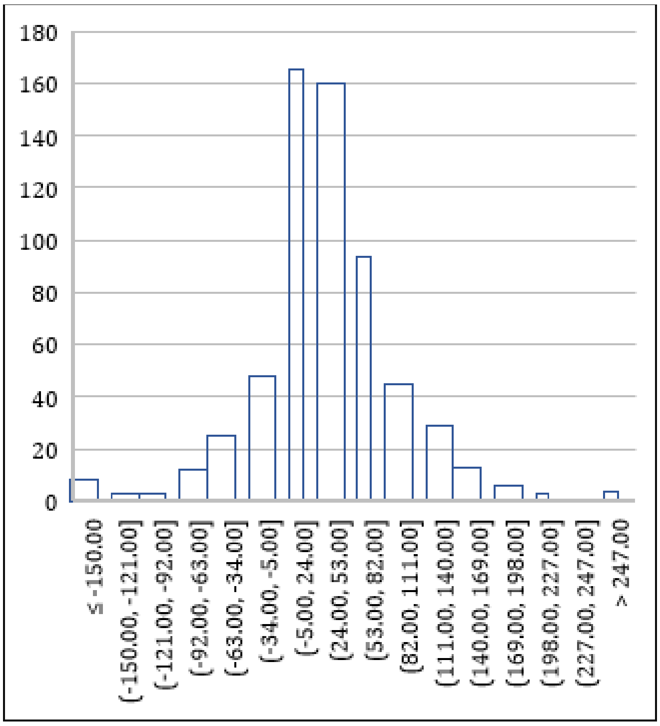

Fig- 4 safety margin distribution of EC2

There are 115 of 618 have negative safety margin that indicates to failure event where the punching shear will take place before the pressure reaches the predicted code value. This failure event occurred with rate 18.61% of the total experiments.

Using the equation (4) and the mean of the safety margin μ_M = 33.38 with standard deviation σ_M = 71.32, the reliability index equals:

$$\beta = \frac{33.38}{71.32} \approx 0.4680$$

Evaluating the reliability based on this index provides the reliability R using equation (5) as:

$$R = \Phi(0.4680)$$

$$= \int_{0.4680}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{(0.4680)^2}{2}} d\beta$$

$$\approx 0.68011 \approx 68.01\%$$

This concludes that the reliability of punching shear of column-slab connection using EC2 formula is 68.01%.

Based on the statistical analysis above, the reliability of punching shear of column-slab connection in the European building code is 68.01%. Comparing with the reliability of the Saudi building code 80.12%, it is notable that it is lower. The comparison between the SBC-304 and the EC2 through the margin of safety is shown in the Fig- 5.

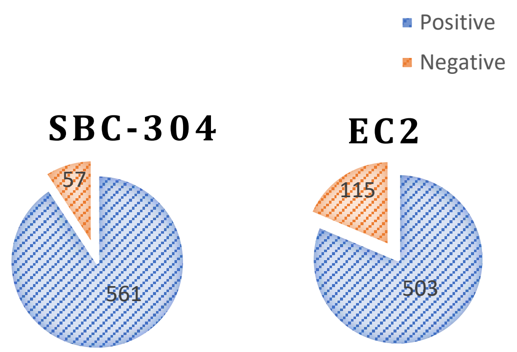

Fig- 5 Negative and positive safety margin of SBC-304 & EC2 using pie chart

The detailed comparison between the SBC-304 and the EC2 formula is revealed in the Table- 1.

Table- 1 Comparison between SBC-304 and EC2 formula

Type	SBC-304	EC2
Min	-666.70	-730.37
Max	679.24	405.15
Mean	78.67	33.38
Std. Deviation	93.01	71.32
Beta index	0.8458	0.4680
Reliability	80.11%	68.01%

Segregating the experimental results according to column shape, it is encountered that the reliability is affected by the shape of the column. For circle-shaped column the reliability R is 83.16%; for the rectangular-shaped column R is 89.53% and finally, for the square-shaped column R=77.67%. These results are shown in the Table- 2. It is also noted that the number of test samples has an affect on the reliability.

Table- 2 Column cross section shape with reliability for SBC-304

Shape	No.	β	R
Circular	127	0.96	83.16%
Rectangular	80	1.26	89.53%
Square	411	0.76	77.67%

On the other hand, it appears that the reliability of EC2 obtained by using circle-shaped column with reliability R=66.77%. Next, come the rectangular-shaped column R=67.70%. Finally, square-shaped column has R=68.66% as shown in the Table- 3.

Table- 3 Column cross section shape with reliability for EC-2

Shape	No.	β	R
Circular	127	0.43	66.77%
Rectangular	80	0.46	67.70%
Square	411	0.49	68.66%

5. CONCLUSIONS

618 test samples from previous research works have been considered to study the reliability of SBC-304 punching shear design of column flat slab connection. The investigation of the safety margin provides the mean of the margins μ_M = 78.67and the standard deviation σ_M = 93.01 for overall samples. Accordingly, the reliability index equals 0.8458. Evaluating the reliability based on this index provides the reliability R as: = 0.8011≈ 80.11%. Analyzing considering column shape gives reliability 83.16% for circular, 89.53% for rectangular and 77.67% for square. This difference ensures that the formulae of SBC-304, needs to be revised to consider the effect of some important parameters, such as steel ratio.

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