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The Effect of Beam Attachment to Slab-Column Connections on The Punching Shear Perimeter

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الملخص:تعتبر البلاطات المسطحة من أشهر أنظمة البلاطات الخرسانية المسلحة لما لها من مميزات مثل امكانية تقليل الإرتفاع الصافى للأدوار وسهولة وضع الشدة الخاصة بها والمظهر الجيد للبلاطة. وعلى الرغم من هذه المميزات إلا أن هناك بعض المشاكل التى قد تصاحب إستخدام هذا النوع من البلاطات مثل إنهيار القص الثاقب لوصلة العمود مع البلاطة نتيجة زيادة إجهادات القص عند هذه الوصلة. في هذا البحث، تمت دراسة سلوك القص الثاقب للبلاطة المسطحة المرتبطة بكمرة أو كمرتين من جانب واحد فقط، ومقارنتها بالبلاطة التي لا تحتوي على كمرات. في هذه الدراسة تم إجراء اختبارات عملية و كذلك تم عمل نموذج تحليلي من العناصر المحدودة غير الخطية ثلاثية الأبعاد. أظهرت الدراسة أنه في حالة البلاطة بدون كمرات فإن شكل محيط إنهيار وصلة العمود مع البلاطة تكون عبارة عن مسار مغلق موازى لحدود العمود على مسافة تتراوح بين نصف وضعف السمك الفعال للبلاطة. عندما تتواجد كمرة بوصلة البلاطة مع العمود وجد أن محيط القص لا يشكل مسار مغلق حول العمود ولكن يتحول الى مسار مفتوح موازيا لحدود الكمرة. في كلتا الحالتين تم التنبؤ بأحمال الإنهيار ومحيط الإنهيار والسلوك العام بإستخدام نموذج العناصر المحدودة اللاخطي بدقة مقبولة

الكلمات المفتاحية : الخرسانة المسلحة, البلاطات, البلاطات المسطحة, القص الثاقب, وصلة البلاطة مع الكمرة مع العمود.

ABSTRACT : Due to some advantages, the flat slab system is prevalent among many RC slab systems. These advantages are the ability to reduce story heights, easy setting up of the formwork and good slab appearance. A major drawback, however, of the flat slab system is the brittle punching shear failure due to the concentration of shear stresses at slab-column connections. In this research, the punching behavior of a flat slab attached to one or two beams from only one side is studied, and compared to the slab with no beams. Both an experimental program and a 3D non-linear finite element analysis were conducted in this study. The study showed that in case of a slab with no beams, the shape of the punching failure perimeter is a closed loop around the column perimeter, this loop is offset from the column edge by a distance ranging from 0.5d to 2d. When a beam was attatched to the slab-Column connections the shape of the failure perimeter didn't make a close loop around the column, but was diverged at the beams and propagated parallel to the beam. The failure perimeter in this case was formed of an open loop. In both cases the failure loads, the failure perimeter and the general behavior were predicted by the finite element model with acceptable accuracy.

KEYWORDS: Reinforced concrete, Slabs, Flat slabs, Punching shear, slab-beam-column connections.

1. Introduction

Among many types of RC slab systems, the flat slab system is viral. Although, it has some advantages, there are also disadvantages in using that system, such as its low resistance to punching shear. The main parameters affecting behavior and capacity of punching shear in flat slabs were widely studied such as concrete compressive strength and flexural reinforcement of slabs [1],[2]. Hawkins [3], Oliveira [4] and Milligan et. al [5] studied the effect of column dimensions on the punching behavior of flat slabs. Hawkins [3] studied the ratio between the largest and the smallest sides of the column (c_{max}/c_{min}) and concluded that for ratios greater than two, the nominal shear strength decreased with increasing ratios between the largest and the smallest sides of the column. While, Oliveira [4] believed that the ratio affecting the punching shear capacity is (c_{max}/d) following the Model code CEB-FIP MC90 [6]. Oliveira [4] and Milligan et. al [5] concluded that the relationship (c_{max}/d) may be a better parameter for determining the punching strength of slabs supported on rectangular columns and proposed a correction factor (λ) to refine the recommendations for codes such as ACI 318 [7] and CEB-FIP MC90 [6]. The punching shear behavior of slab-column connections for L-shape column was studied by Zhang et. al [8], it was found that shear stress magnitudes along the inner sides of the L-shaped column were typically lower than those along the outer sides of the column. It was also concluded that the diagonal portion of the critical perimeter was inactive and should be neglected. The effective control perimeter for walls and wall corners was addressed by CEB-FIP MC90 [6] as illustrated in **fig. (1).** Elongated supports of slabs could be caused by rectangular columns, shear walls, cores and dropped beams. For flat slabs supported on rectangular columns with an elongated cross-section in one direction, punching shear around such columns is generally the governing design criterion in flat slabs for the ultimate limit states. Shear stress distribution along the control perimeter is non-uniform [9][10]. Dropped beams on one or two sides of the column can increase the stiffness of the slab on one side of the column, which in turn will affect the punching behavior and perimeter of the slab. This situation, slab-beam-column connections that have beams connected only on one or two sides, was not covered in the literature and will be investigated in this research. The objective of the research is to study the effect of beam existence on the punching shear perimeter.

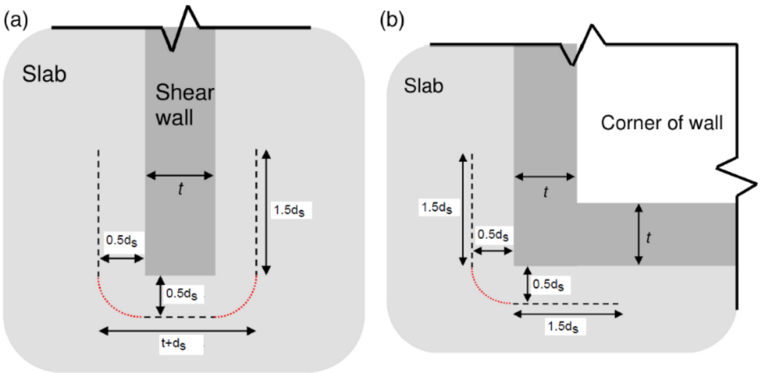


Fig. (1)-Perimeter of failure for (a) wall edge and (b) wall corner [6].

2. Experimental Program

To study the effect of beam attachment to the connection of slab-column, nine interior slab-column connections were prepared. The test specimens consisted of square slabs with dimensions of (1500x1500x100mm) supported on columns with cross sectional dimensions of (200x200mm). Test specimens were divided into three groups: the first group was used to investigate the general punching behavior and perimeter of failure for slabs with columns connecting with beams (connection without beams, with one beam and with two beams), the second group was used to study the effect of beam width on the punching perimeter and behavior of the slab in punching and the third group was used to study the effect of beam depth on the punching behavior and punching perimeter of the slab. Slabs, beams and columns reinforcement were constant in all groups. Specimen's dimensions and reinforcement were presented in **table 1.** The specimens of groups 1,2 and 3 were presented in **figs. (2,3, 4)**, respectively. The average concrete compressive strength for the tested cubes at 28 days was 33 N/mm^2. Two different types of steel reinforcement were used in this research. Plain reinforcement steel with yield strength of 367MPa, and deformed reinforcement steel with yield strength of 486MPa. The slab was tested upside down by applying the load on the column as shown in **fig. (5).** The isolated test specimens investigated in this experimental program represented an interior slab-column connection bounded by the lines of moment inflection (zero moment lines where rotation is not restrained) around the column as shown in **fig. (6)** [12]. The supports in the test setup represent the perimeter of moment inflection in the interior slab column connection.

Table 1: Specimens dimensions and reinforcement

Group-No.		Dimension of slab (Lxbxt)	No. of beams	Beam dimensions		Beam RFT. (TOP+BOTT.)	Beam Stirrups	Slab RFT.
				Width	Depth			
Group 1	S11	1500x1500x100	None	None	None	None	None	7T12/m` B.D*
	S12		1	100	300	2T12+2T12	Y6@200	
	S13		2	100	300			
Group 2	S21		1	100 (tc/2)	300			
	S22		1	150 (3tc/4)	300			
	S23		1	200 (tc)	300			

Group 3	S31		1	100	200 (2ts)			
	S32		1	100	300 (3ts)			
	S33		1	100	400 (4ts)			

*Both Directions

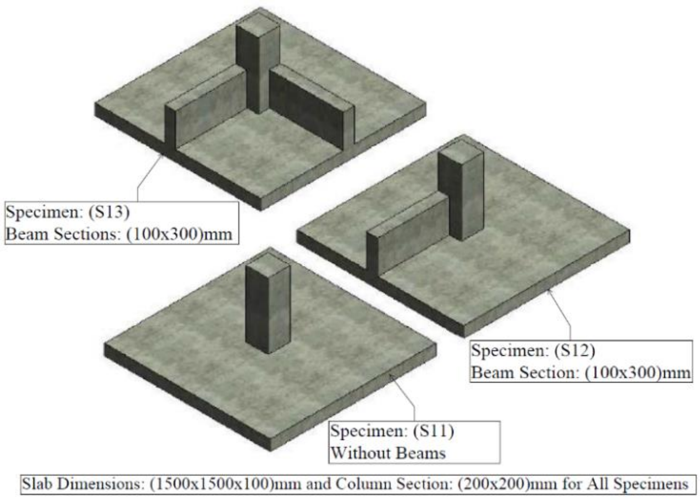


Fig. (2)-Specimens of group 1

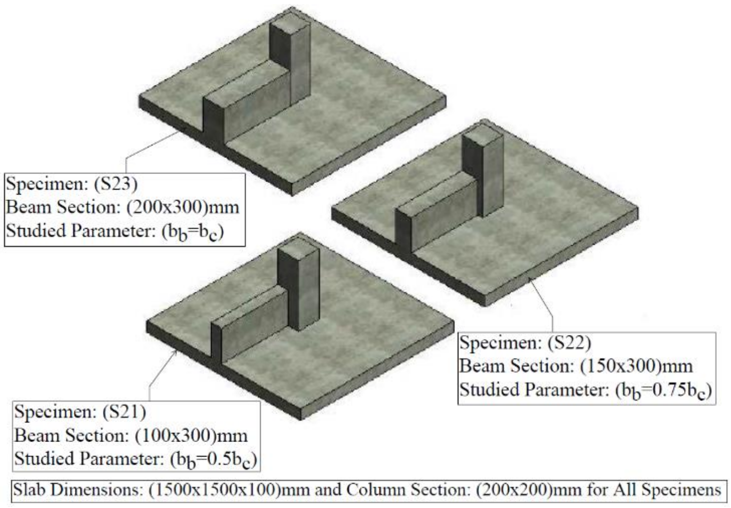


Fig. (3)- Specimens of group 2

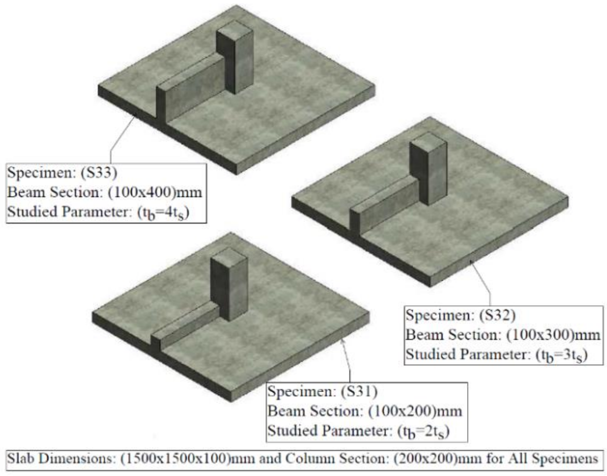


Fig. (4)-Specimens of group 3

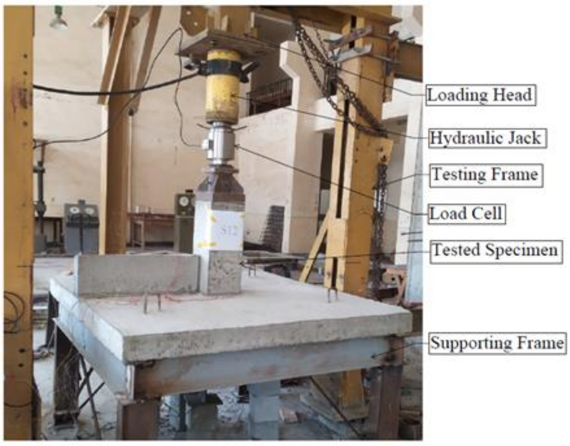


Fig. (5)- Testing frame and setup of specimens

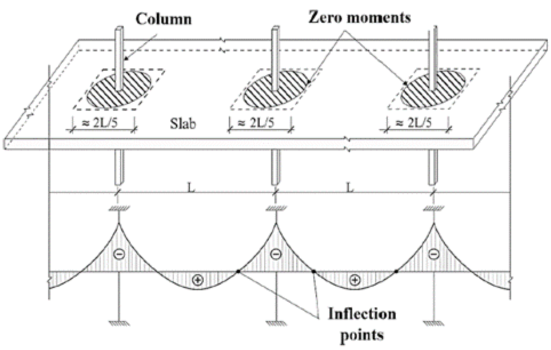


Fig. (6)- Point of inflection in flat slabs

3. Numerical Modeling

The Finite Element Method (FEM) is used to analyze the tested specimens to reinforce the experimental results and gain more insight into the structural behavior of the test specimens. The program used in this study is the ANSYS program. Tested specimens were modeled as shown in **figs. (7,8)** and loaded up to failure.

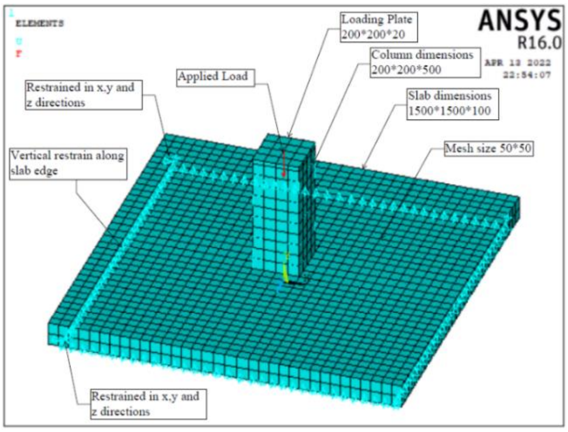


Fig. (7)- FE model of slab without beam (S11)

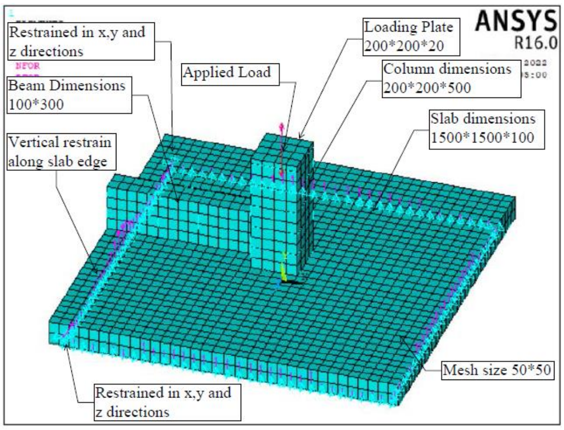


Fig. (8)- FE model of slab with beam

The obtained results, such as crack pattern, failure load, slab deflection and steel strain of longitudinal RFT of the slab, were compared with the results obtained from the experiments. The failure load obtained from the ANSYS model was compared with that obtained from experiments and presented in **figs. (9,10,11)** for groups 1,2 and 3, respectively.

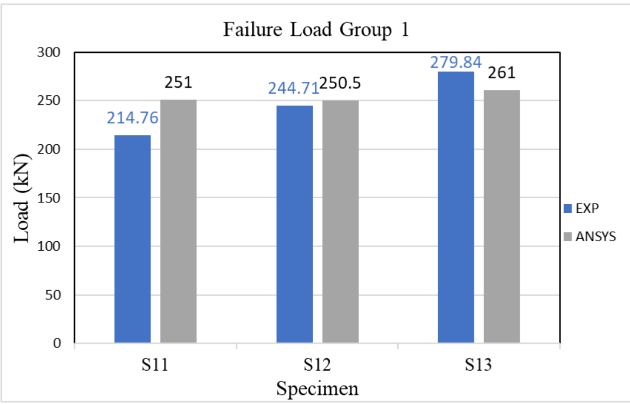


Fig. (9)- Failure loads for group 1

ANSYS vs Experimental

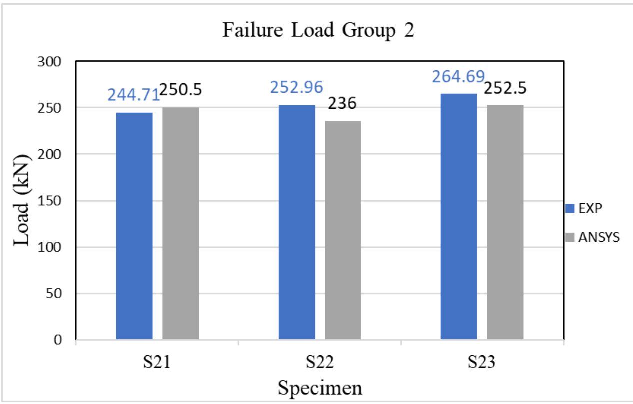


Fig. (10)- Failure loads for group 2

ANSYS vs Experimental

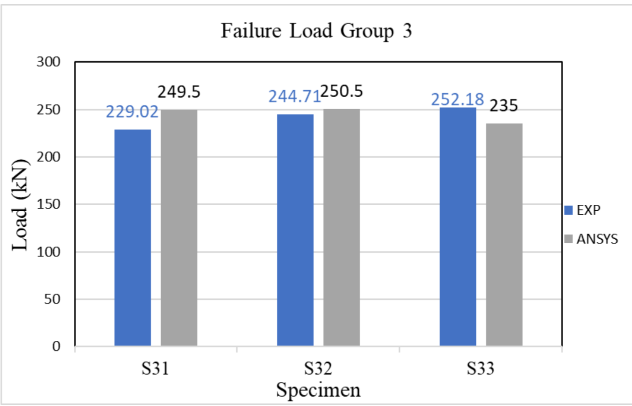


Fig. (11)- Failure loads for group 3 (ANSYS vs Experimental)

The failure load comparison is presented for all specimens in **table (2)** along with the ratio between the values obtained from the experiments to that obtained from the ANSYS model. These ratios changed from 85.56% to 107.31% with an average of all specimens of 99.66% and this is an indication that there is a good agreement between the two results.

Table 2: Failure load comparison for all specimens

Group	specimen	beam section (bxt) (mmxmm)	Failure load (Experimental)	Failure load (ANSYS)	EXP /ANSYS	Average
Group1	S11	None	214.76	251.00	85.56%	96.82%
	S12	100x300	244.71	250.50	97.69%	
	S13	100x300	279.84	261.00	107.22%	
Group2 (Beam width)	S21	100x300	244.71	250.50	97.69%	103.23%
	S22	150x300	252.96	236.00	107.19%	
	S23	200x300	264.69	252.50	104.83%	
Group3 (Beam depth)	S31	100x200	229.02	249.50	91.79%	98.93%
	S32	100x300	244.71	250.50	97.69%	
	S33	100x400	252.18	235.00	107.31%	
						99.66%

The cracking patterns in the experiments were compared with those obtained from the ANSYS program. The cracking patterns were similar in both cases as shown in **figs. (12,13,14).** The crack pattern of the specimen without beam made a close loop around the column tracing the column perimeter as shown in **fig. (12).** On the other hand, the failure perimeter of the specimen with one or two beams didn't make a close loop around the column but in this case the perimeter was formed of an open loop tracing the perimeter of the columns and the edge of the beam. When the column was attached to one beam the final perimeter made a U-shape while an L-shape occurred when the column was attached to two beams as shown in **figs. (13,14).** In the ANSYS model, the cracks propagated on the bottom face of the slabs in the same locations that appeared in the experiments. It is clear from **fig. (13)** that the cracks were limited at the beam's location and were dense on the other side of the column where the beam didn't exist. This also means that the beam is working as a rigid support to the slab and governing the perimeter of failure. The cracked zone on the bottom face of the slab in the ANSYS model representing the top area of the cone of failure in the experiments. In **fig. (14)**, a quarter of the specimen in the ANSYS model located between beams had a limited number of cracks and the cracks were very dense on the other sides of the specimen (identical to the crack pattern of the specimen from the experiments).

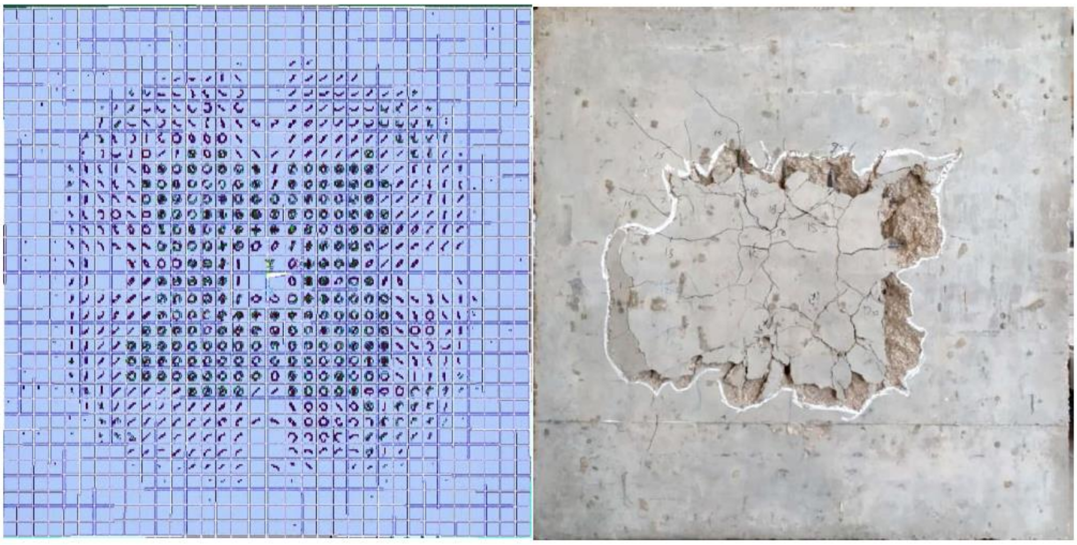


Fig. (12)- Crack pattern of slab specimen without beam (S11), ANSYS program vs. Experimental

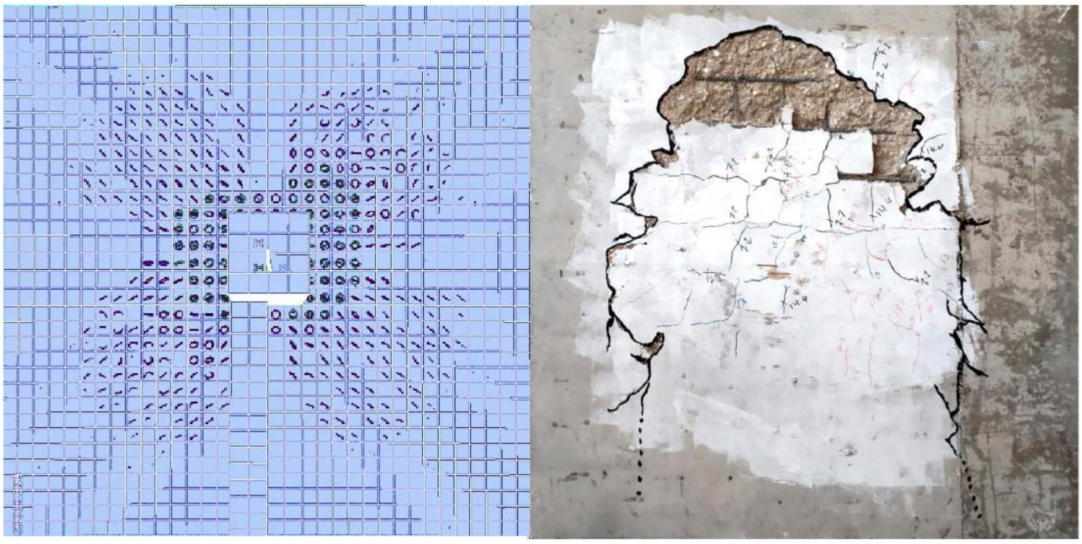


Fig. (13)- Crack pattern of slab specimen with beam, ANSYS program vs. Experimental

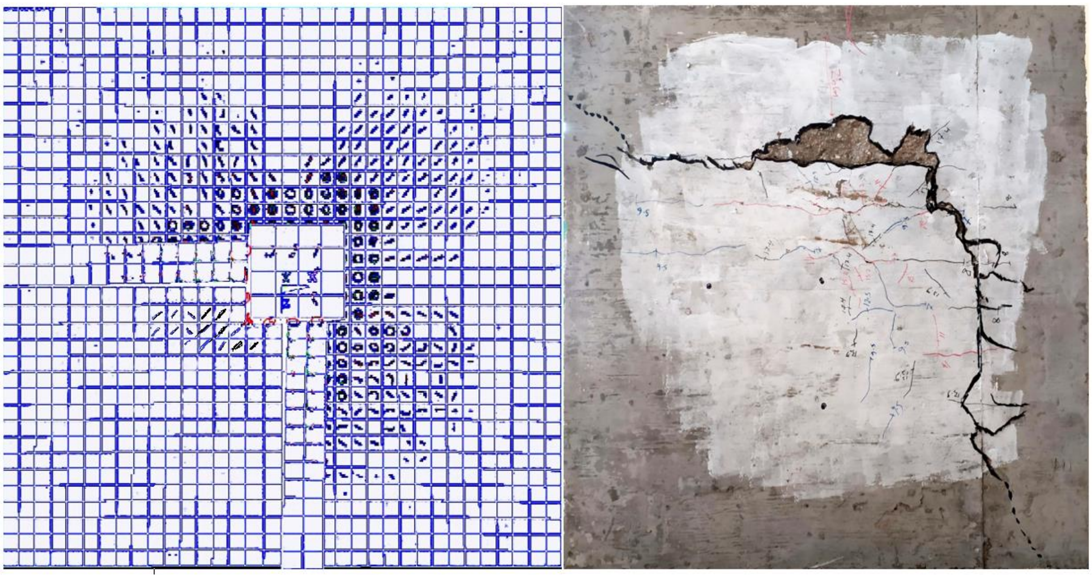


Fig. (14)- Crack pattern of slab specimen with two beams, ANSYS program vs. Experimental

The locations of failure can also be deducted from the values of strain in the slab as shown in **figs. (15,16).** In these figures, the strain in the concrete is shown at a vertical cross section located in the center of the slab. **fig. (15)** shows the strain at a cross section that is parallel to the beam, while **fig. (16)** shows the strain at a cross section orthogonal to the beam. In the direction parallel to the beam, the strain values were largest at the column edge opposite to the beam as shown in Fig. (15). The strain values along the beam were less than the assumed maximum concrete strain capacity (0.002). For the perpendicular direction, the high strain values were concentrated on both sides of the column as shown in **fig. (16)** (identical to the shape of failure obtained from the experiments). **Fig. (17)** shows the concrete strain at a vertical cross section located in the center of the slab with two beams in both directions. The strain values were largest at the column edge opposite to the beam in both sections, while along the beams the strain values were less than the assumed concrete strain capacity (0.002).

These figures indicated that when a beam is present, the failure perimeter doesn't make a close loop around the column as in the case of a specimen without beams. In the presence of a beam, the crack perimeter diverged at the beam and propagated parallel to it. The failure perimeter in this case was formed of an open loop U-shape. If the column was attached to two perpendicular beams the final shape of failure formed of an open loop with an L-shape.

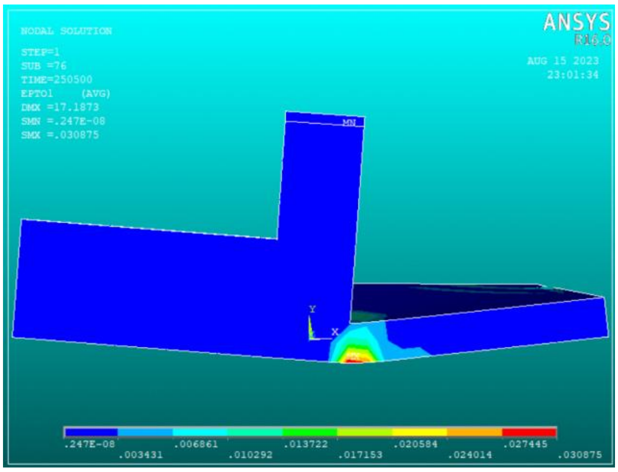


Fig. (15) Concrete strain- beam direction (S12)

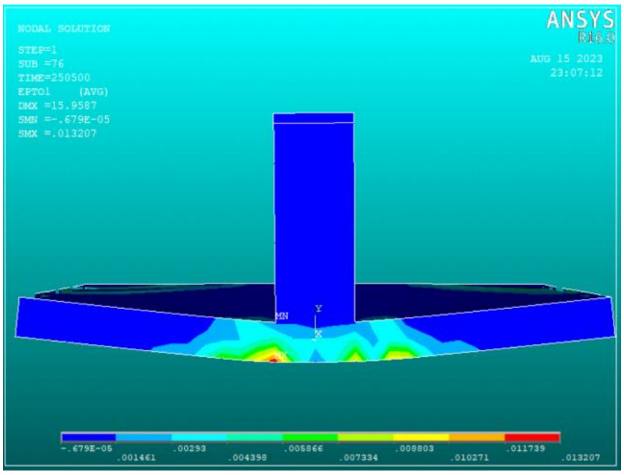
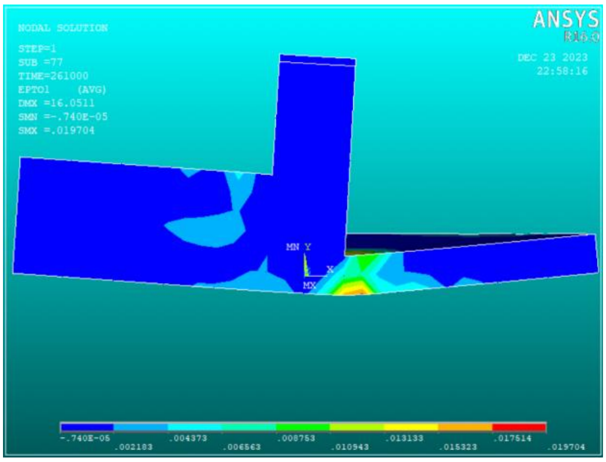
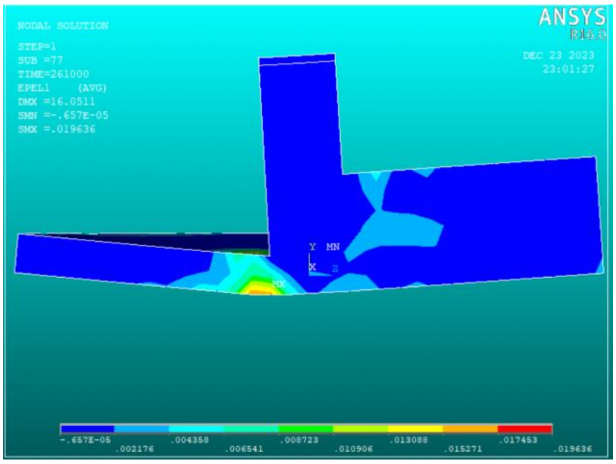


Fig. (16) Concrete strain - perpendicular to beam direction (S12)



Concrete strain- XY- direction (a)



Concrete strain- YZ- direction (b)

Fig. (17) Concrete strain - slab specimen with two beams (S13)

The strain in the longitudinal slab reinforcement was also examined and compared to the experimental results. Load vs reinforcement strain relations for a slab without a beam, a slab with one beam and a slab with two beams are presented in **figs. (18,19,20),** respectively. These figures showed a good agreement between the experiments and the finite element results. The load deflection curve at the point under the column was also compared and showed a good agreement between the experiments and the finite element results. **Figs. (21,22,23)** show examples for such a comparison of a slab without a beam, a slab with one beam and a slab with two beams, respectively.

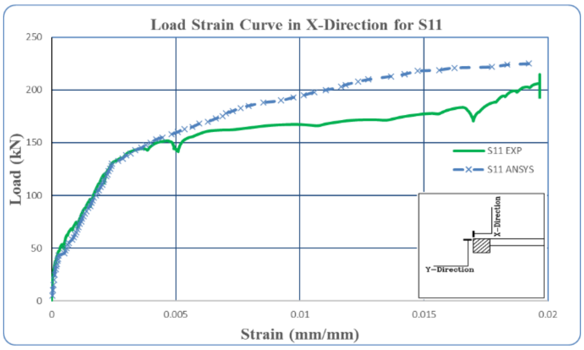


Fig. (18) Load vs. Reinforcement Strain

ANSYS vs. Exp. (Slab with No Beams)

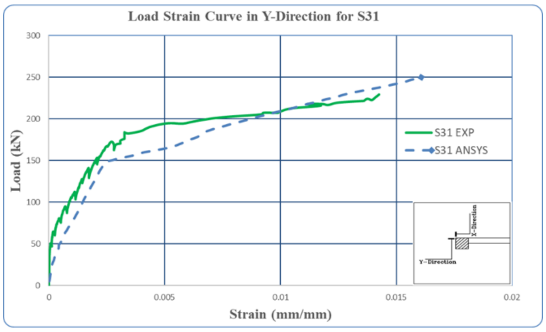


Fig. (19) Load vs. Reinforcement Strain

ANSYS vs. Exp. (Slab with one Beam)

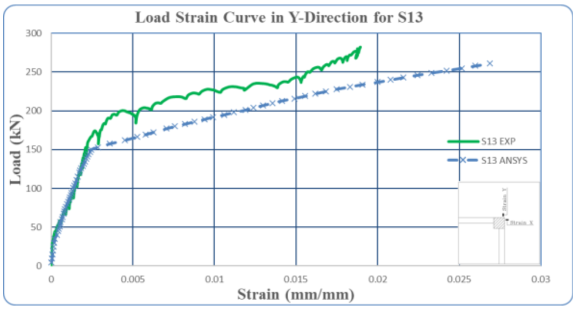


Fig. (20) Load vs. Reinforcement Strain

ANSYS vs. Exp. (Slab with two Beams)

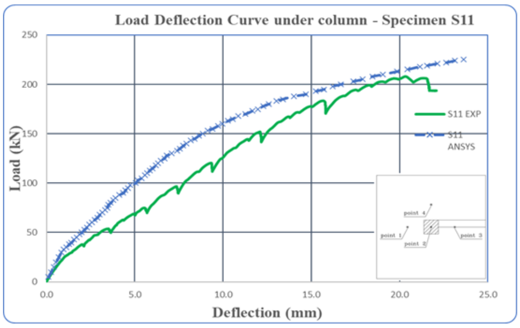


Fig. (21) Load deflection curve,

ANSYS vs. Exp. (Slab with No Beams)

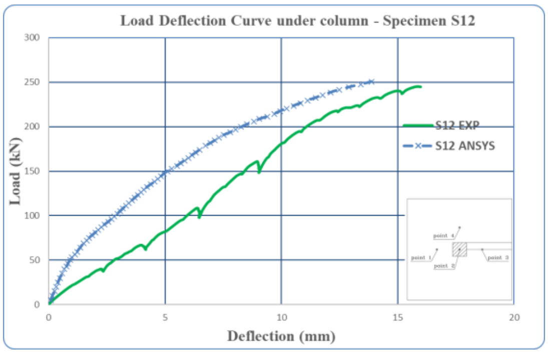


Fig. (22) Load deflection curve,

ANSYS vs. Exp. (Slab with one Beam)

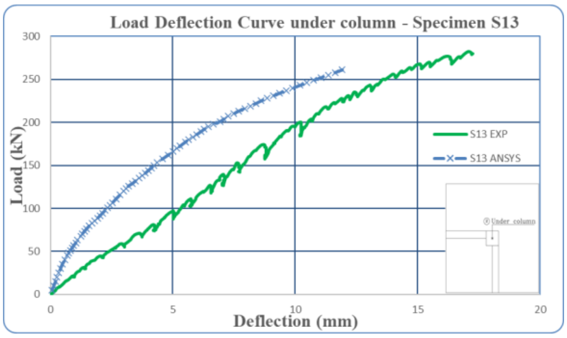


Fig. (23) Load deflection curve,

ANSYS vs. Exp. (Slab with two Beams)

Based on the results presented here, it can be deduced that there is a good agreement between the experiments and the finite element results obtained from the ANSYS model and that the observed differences in the results can be considered acceptable. These results lead us to believe that the ANSYS model can simulate the punching behavior of the slab specimen with acceptable accuracy and can be relied upon to conduct a more comprehensive analysis.

4. Conclusion

Based on the results of the experimental and finite element analysis, the following conclusions are drawn:

1- Punching shear failure could occur when the column is attached to one or two beams.
2- The shape of the failure perimeter is affected by beam attachment to the slab-column connections as follow:
   a. In the case of a specimen without beams, the failure perimeter is making a closed loop around the column.
   b. In the presence of a beam, the crack perimeter diverged at the beam and propagated parallel to it. The failure perimeter in this case was formed of an open loop U-shape.
   c. If the column was attached to two perpendicular beams the final shape of failure formed of an open loop with an L-shape.
3- A finite element model using ANSYS program could effectively be used to conduct a comprehensive study on the punching analysis of slabs with and without beams.
4- There is a good agreement between the finite element results and the experimental results in the slab punching analysis for example the ratios between the failure loads obtained from the experiments to that obtained from the ANSYS model with an average of all specimens of 99.66%.

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