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Experimentally and Numerical Investigation on Behavior of Annular RC Slabs under Ring Loading

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ABSTRACT

This research presents the experimentally measured displacement and strain at specified locations of the concrete of tested annular reinforced concrete slabs subjected to lateral load with three different ratios of inner to outer radii and simply supported at the outer circumference. Performed 3D model of annular RC slabs under the axisymmetric ring load applied, as close as at the inner edge, and investigated their stress-strain state in the elastic stage. This study contains different approaches based on classical thin-plate (CTP) theory and performed a 3D finite-element (FE) model to predict the fields of radial and circumferential stresses and deflection of the slab. Experimentally investigated the crack widths and crack pattern of the two groups of slabs-group A- radially reinforced and group M–orthogonally reinforced.

added a correction factor to the CTP equations, which used to determine both radial and circumferential stresses. Also, investigated the appearance of the first cracks, deflection, failure

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mode, and the maximum value of the failure load for both cases of the reinforcement.

I. INTRODUCTION

The key role of the modern RC buildings is designing the diverse configuration of floor slabs. Currently, circular and annular plates are an integral part of many buildings. Based on this, one of the main tasks of this work is to supply architects to use different configurations of the RC slabs in civil and industrial buildings. If square and rectangular plates have been extensively studied over the past decades, then it can be surely asserted that the methods for the analysis of circular and annular slabs are still in the process of improvement (Azizian & Dawe, 1985; Ladevèze, 2002; Jarak & Soric, 2008; K. Vijayakumar, 2009; Balasubramanian, 2011; Matešan et al., 2013; Takabatake, 2019).

Investigation of the out of plane displacement occupied the most extensive aspect of the study of stress-strain state of the annular concrete slab. The other important part of this work was the selection of suitable finite elements, followed by an adequate model, which will be covered all details of the conducted experiment, such as the type of reinforcement, loading, supporting, etc. (Skibeli, 2017; Juárez-Luna & Caballero-Garatachea, 2019; Mohammed, 2019).

Although there were several approaches and solutions for annular planform plates which can be expressed in cartesian or polar coordinates (Timoshenko & Woinowsky-Krieger, 1959; Ventsel & Krauthammer, 2001; Young et al., 2002; Gujar & Ladhane, 2015), all previous works, without exception, were based on the premise that the classical theory of plates, the theories of Kirchhoff–Love and Reissner–Mindlin, remains an approximation which can be satisfactory only if the thickness is relatively small and the plate is, absolutely, homogeneous and isotropic (Ventsel & Krauthammer, 2001; Ladevèze, 2002; Kaza Vijayakumar, 2014).

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Much research has been devoted to the validation of the 2D modeling and simulation of the plates. This work presents an initial and very important attempt focused on the development of a posteriori modelings and search of the more exact model, adequate to the stress-strain state of the annular concrete slabs (Lebée & Brisard, 2017; Hamad & Abdal, 2019). The numerical and analytical investigations were supported by experimental tests of the annular RC slabs.

On the other hand, this research showed that the type of reinforcement plays a significant role in the bearing capacity of the slabs and the time of the first cracks' appearance on the bottom surface of the plate, besides, observed two completely different crack patterns.

Considering the above mentioned, the primary purpose of this study is to compare the experimental results with the analytical results based on the CTP and obtained from FE analysis. The experimentally investigated strain and deflection of the annular RC slabs and created a 3D FE model in the ABAQUS environment than compared results, taking into account the recent approaches based on the classical theories of the plate. Comparative analysis of the results using different methods became the basis for adding a correcting factor to the equation of the classical theory for both investigated stresses, which give fairly precise results, close to experimental and FEA results.

II. MATERIALS AND METHODS

i. Materials and Specimens

Agapov (2016) reported that the plate is called thin if there is a ratio of $1/5 > t/b > 1/80$. b- smallest dimension of the plate in plan and t- is its thickness. Given the different classification of plates, the presented work considers thin plates with small deflection and ratio of thickness to the radius of $0.2 \geq t/a \geq 0.025$.

This study attempted to compare two types of steel reinforcing of annular slabs with three different diameters of the central hole. For theoretical and experimental

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investigation considered two groups of circular reinforced concrete slabs with central positioned annular opening. The first group (group A) consisted of 3 specimens with 20, 30, 40cm in diameter central hole, 8cm thick, and reinforced by 8mm deformed steel bars in radial and circumferential directions and an outer diameter of 110cm as shown in Figure 1. The second group (group M) differed from the first only in the type of reinforcement mesh, as can be seen from Figure 1, the orthogonal reinforcement was used with square meshing. All six specimens tested under an interior edge ring load, uniformly distributed around the inner circumference.

Schematic Figure 1 is presented to illustrate the geometry, supporting, and loading of specimens, including the arrangement of reinforcement at the bottom of slabs. Only the outer edge of slabs was constrained against Z-directed displacement. The tested slabs specimens have values of the ratio of ζ=d/D equal to 0.2, 0.3, and 0.4 respectively, where d- is the diameter of central hole and D- is the diameter of supporting ring having a constant value of 1m for all specimens.

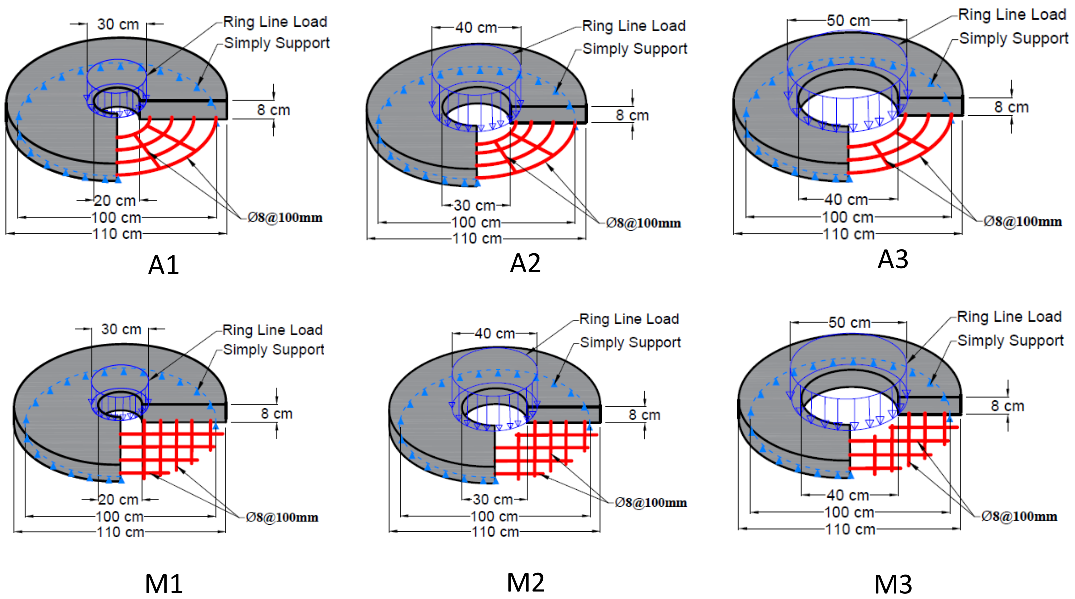

Figure 1 Geometry, reinforcement, supporting, and loading of the radially and orthogonally reinforced annular slab.

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The mechanical properties of concrete and steel bars are presented in Table 1:

Table 1 Mechanical properties of concrete and steel bars

Concrete		Steel	
Modulus of elasticity, E_c, GPa	31.2	Modulus of elasticity, E_s, GPa	200
Ultimate Compressive strength, $f'c$, MPa	39	Yield strength, fy, MPa	420
Poisson's ratio, v	0.18	Poisson's ratio, v	0.3

ii. Preparation of Specimens

In this research, circular molds with different opening sizes were used to prepare samples with predetermined sizes. Using a computerized universal machine of 2000kN capacity, all specimens were subjected to the ring load applied as close as possible to their inner edge (Figure 2).

Figure 2 Specimens preparation and testing.

iii. Analysis Methods

a) Analytical Method

For geometric reasons, it was convenient to formulate this problem in the polar coordinate r and θ for 2D, and z in the 3D investigation.

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Several plate theories that have been developed since the late 19th century, two are widely accepted and used in engineering (Reismann, 1988; Taylor & Govindjee, 2004; Balasubramanian, 2011):

- the Kirchhoff–Love theory of plates (classical plate theory)
- The Mindlin–Reissner theory of plates (first-order shear plate theory)

In those cases, when the deflection- w is small compared with its thickness- t, it is possible to construct a completely satisfactory approximate engineering theory of plate bending under transverse loads, based on the general Kirchhoff hypotheses.

The process of formation of various methods and approaches for analysis of plates in general, and annular ones in particular, in the CTP formulation, cannot be considered complete, since its development continues to this day. In this study, the linear theory of bending of isotropic circular plates under the Kirchhoff-Love hypotheses applied for analyzing annular RC slabs.

Considering the fact, that applied lateral load acts on the middle surface, the shape of the annular slab is adequately defined by describing the geometry of this surface that bisects the slab thickness at each point. Young and et al. (2002) proposed universal approaches for analysis of different plates, particularly for annular plates. This research is an attempt to check the ability of this approach, analyzing reinforced concrete annular slabs.

Annular plate with a uniform annular line load w at the inner edge and schematic illustration of the stresses and deflection are shown in Figure 3.

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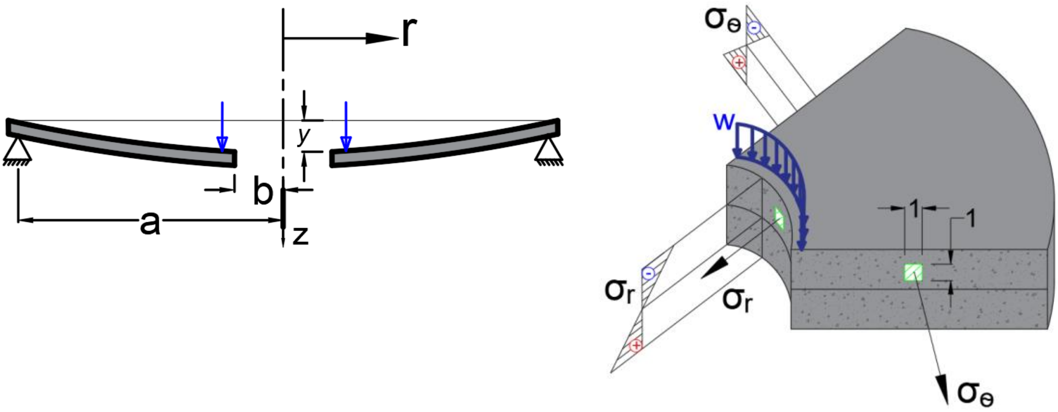

Figure 3 Schematic illustration of the stress-deflection state of the annular RC plate.

General expressions for deflection and moments in radial and circumferential directions can be determined by Roark's formulas (Young et al., 2002)

$$y = \frac{-q\,a^3}{D}\left(\frac{C_1 L_9}{C_7} - L_3\right) + \frac{qa^2}{DC_7} L_9\, r\, F_1 - \mathrm{q}\frac{r^3}{D} G_3$$

$$M_r = \frac{qa^2}{DC_7} L_9 * \frac{D}{r} F_7 - q\, r\, G_9$$

$$M_\theta = \frac{\left(\frac{q\,a^2\,L_9\,F_4}{C_7} - q\,r^2\,G_6\right)(1 - v^2)}{r} + \left(\frac{q\,a^2\,L_9\;F_7\,v}{C_7\,r}\right) - q\,r\,G_9\,v$$

Using expression $\sigma = {}^{6\,M}\!/_{h^2}$ the corresponding bending stresses can be found from the moments M_r and M_Θ for the above equations.

Where:

q = Unit line load (force per unit of circumferential length).
y = Vertical deflection of plate (length).
M_r = Unit radial bending moment.
M_Θ = Unit tangential bending moment.
E = Modulus of elasticity (force per unit area).

ν = Poisson's ratio.
a = Outer radius.
b = Inner radius for annular plate.
t = Plate thickness.
r = Radial location of quantity being evaluated.
r_o = Radial location of unit line loading or start of a distributed load.
D = $Et^3/12(1-\nu^2)$ plate constant.
F & G-Functions of the radial location r.
C- Plate constants dependent upon the ratio a/b.
L- Loading constants dependent upon the ratio a/r_o.

b) Finite Element Modelling

The adopted physical and geometrical parameters of modeled samples for the FE analysis were the same as experimentally tested specimens. The created FE model allowed presenting the displacement field, which experimentally was measured. Simultaneously, using this model, it was easy to identify and demonstrate the entire stress fields and compare them with analytical results. Regardless of the strategy, the accuracy of analysis methods depends on modeling and used approaches in this work; thus, the widely used FEM was implemented for tested specimens.

The main purpose of 3D modeling was the complex study of the stress-strain state of the tested annular slabs. Numerical simulation instruments such as ABAQUS can be used to create an adequate model representing the tested specimens. This computer simulation made it possible to visualize the real state of the annular slab under the ring load. Known, that ABAQUS provides advanced reinforcement concrete modeling and analysis features compared to the other FE computer programs. On the other hand, several element types are available in ABAQUS library that enables simulation with high accuracy (Hibbitt, 1984; Giner et al., 2009; Chaudhari & Chakrabarti, 2012; Khennane, 2013). The ABAQUS is widely used to calculate and analyze such studies and its validation base on FEM to analyze annular RC slab undeniably (Mohammed, 2019; da Silva et al., 2020; Kartheek & Das, 2020).

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All slab domains and subdomains were modeled with finite plate elements with three degrees of freedom in each node: one linear and two angular displacements. After cracks in concrete reached a certain width, which defined by using “Smeared cracking” feature, ABAQUS released the strain energy to steel rebars until fracture of RC slab. Using this feature allowed us to perform adequate models and realistic analysis of them.

Recent studies recommend C3D8R linear brick 3D finite element and T3D2 two-node 3D linear truss element for concrete and steel bars modeling, respectively (*Abaqus 2016 Documentation*, 2016; Hamad & Abdal, 2019). It is worth noting that the mechanical properties of the materials obtained during the experimental testing became the input data for numerical analysis by ABAQUS.

Figure 4 illustrates the most optimal option of the 3D model's discretization representing the approximate number of elements ranging from 3400 to 3900 depending on the size of the central opening.

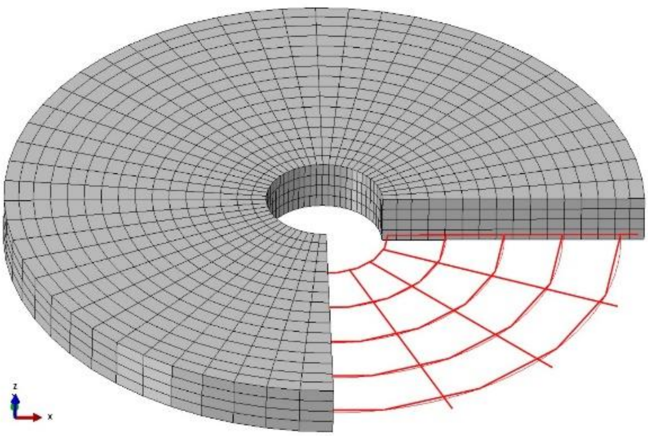

Figure 4 RC annular slab meshing

III. RESULTS AND DISCUSSION

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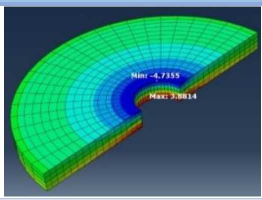
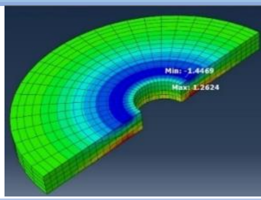
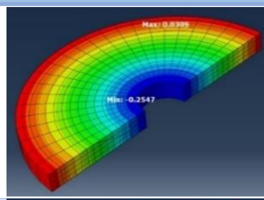
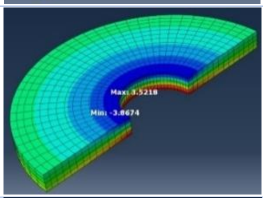
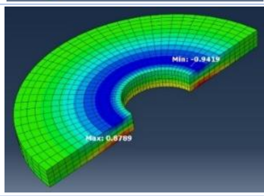
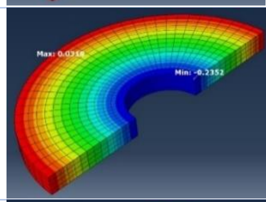
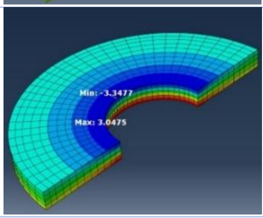
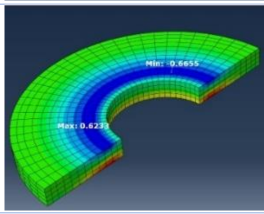
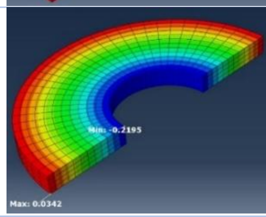
i. Stresses

For the general illustration of the distribution of the stress and deflection, corresponding fields are presented in Figure 5. The finite element model allowed to clearly identify the location of the maximum compressive and tensile stresses on the top and bottom surfaces of the slab, as well as the location of the maximum deflection.

Results of FE simulation and experimental results have proved that circumferential stresses play the dominant role in the slab's failure under annular loading. The location of these maximum stresses coincided with the ring load location, which is applied 5cm far from the inner edge of the slab. It is worth noting that these results for all samples presented under a load of 25kN, converted to the uniformly distributed ring load, depending on the diameter of the opening, i.e., in the elastic stage of operation of the slab.

Specimen	Ring Load kN/m	σ_θ, MPa	σ_r, MPa	w, mm
A1	27			
A2	20			
A3	16			

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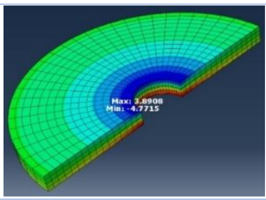
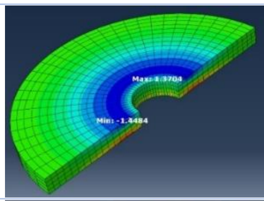
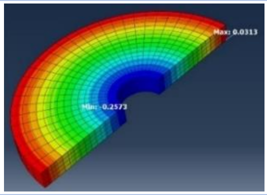
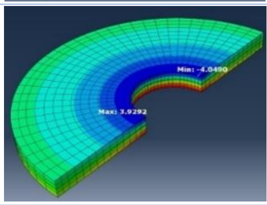
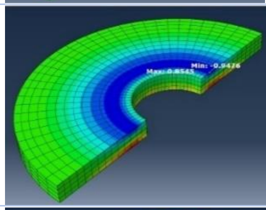
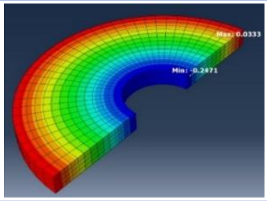
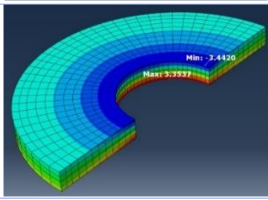
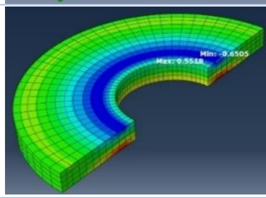
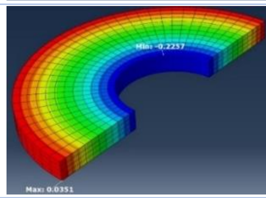
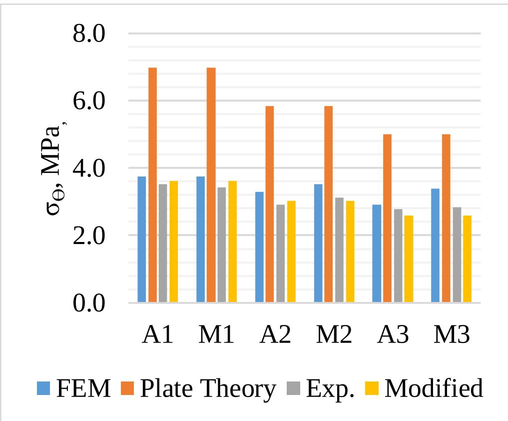
M1	27			
M2	20			
M3	16			

Figure 5 Maximum value and location of the radial and circumferential stresses and z-directed component of the deflection.

Figure 6 shows the value of the circumferential and radial stresses calculated by four different methods and equations, including the proposed modified equations of the classical theory.



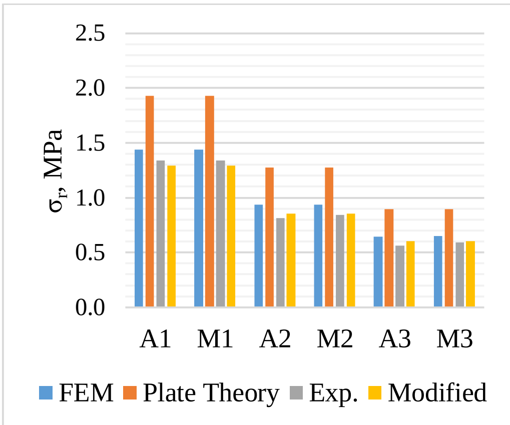


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Figure 6 Comparative illustration of the σ_θ and σ_r at the first crack loading stage using different analysis methods.

As can be seen from the above diagrams, the application of the classical plate theory's formulas for annular reinforced concrete slabs gave a large error in the results compared with the experimental and finite element analysis. In some cases, the difference was 50%, indicating the unacceptability of the adoption of the classical theory approaches proposed in recent studies related to the annular plates for reinforced concrete slabs.

Based on a statistical analysis of all samples at different loading levels, determined the means, standard deviation, and coefficient of variation. As a result, a factor for the classical equations of plate theory was revealed; in other words, the classical theory of plates for reinforced concrete annular slabs was modified.

Thus, this research proposes the following equation for finding the stresses in both radial and circumferential directions.

$$M_r = K_r\left[\frac{qa^2}{DC_7}L_9 * \frac{D}{r}F_7 - \mathrm{q}\,r\,G_9\right]$$

$$M_\theta = K_\theta\left[\frac{\left(\frac{q\,a^2\,L_9\,\mathrm{F}_4}{\mathrm{C}_7} - \mathrm{q\,r^2\,G_6}\right)(1-\mathrm{v}^2)}{\mathrm{r}} + \left(\frac{q\,\mathrm{a}^2\,\mathrm{L}_9\;\mathrm{F}_7\,\mathrm{v}}{\mathrm{C}_7\,\mathrm{r}}\right) - \mathrm{q\,r\,G_9\,v}\right]$$

where K_r=0.67 and K_Θ=0.52 are the proposed factors to classical equations for radial and circumferential stresses, respectively.

The addition of these factors in classical equations gives good agreement of the results to the experimental and finite element analysis results.

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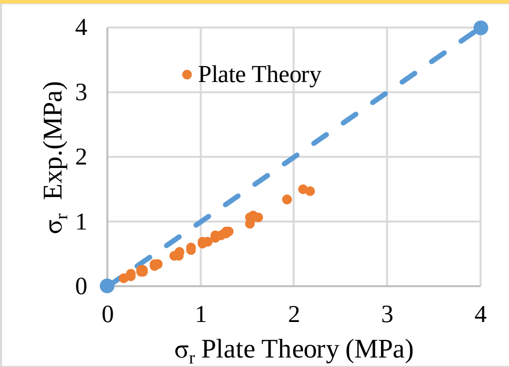
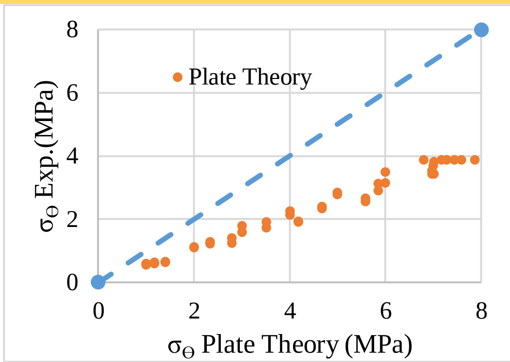
Convergence and discrepancy between the values of the stresses, obtained from the experimental investigation, in the radial and circumferential directions with the results obtained by calculating the slabs using classical, finite element methods, and modified equations are presented in Figure 7.

Analyzing slabs with modified equations, i.e., adding to them new factors-K_r and K_Θ showed that these results most of all others are in agreement with the results obtained experimentally.

σ_r	σ_Θ
	

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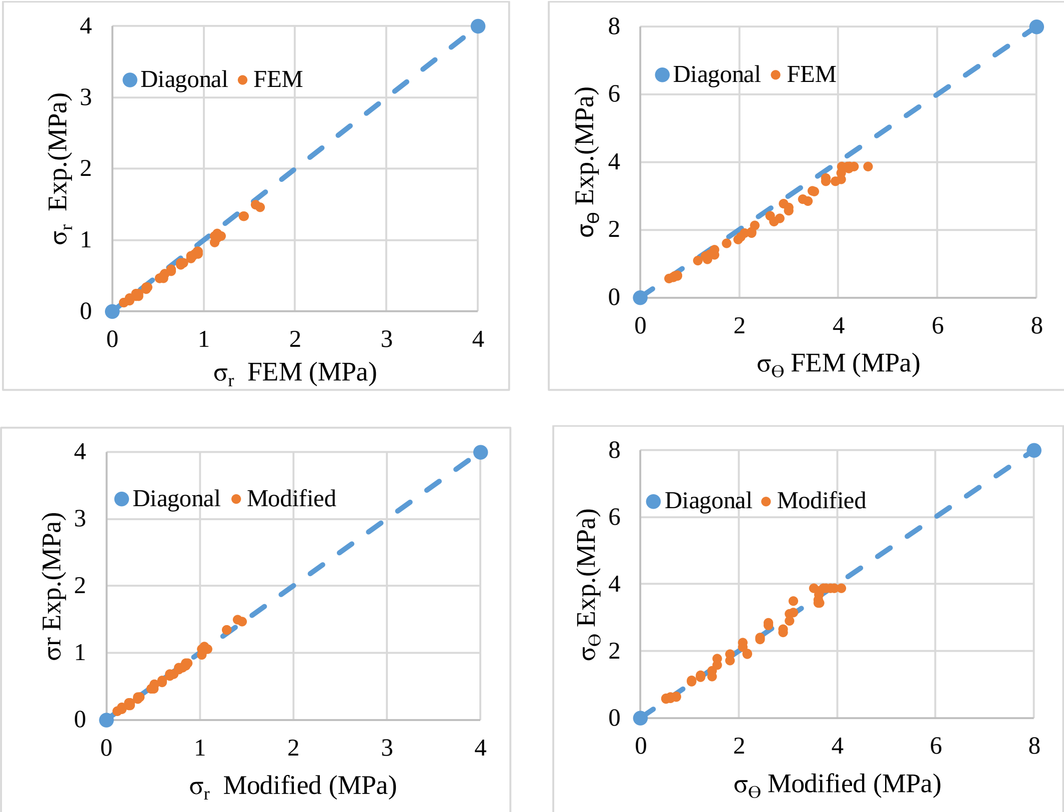

Figure 7 Convergence and discrepancy of the experimental results with the results obtained by plate theory, FEM, and proposed modified equations for σ_r and σ_Θ.

ii. Load vs. Deflection

Another necessary and critical evaluation was the determination of the deflection at the most vulnerable points of the annular RC slabs, performed by using dial gauges and optical continuous deflection monitoring. Figures 8 shows dependence diagrams of plate deflection on the value of the applied load for all six tested specimens and illustrates a comparison of deflections of paired specimens from both groups A and M, depending on the type of reinforcement.

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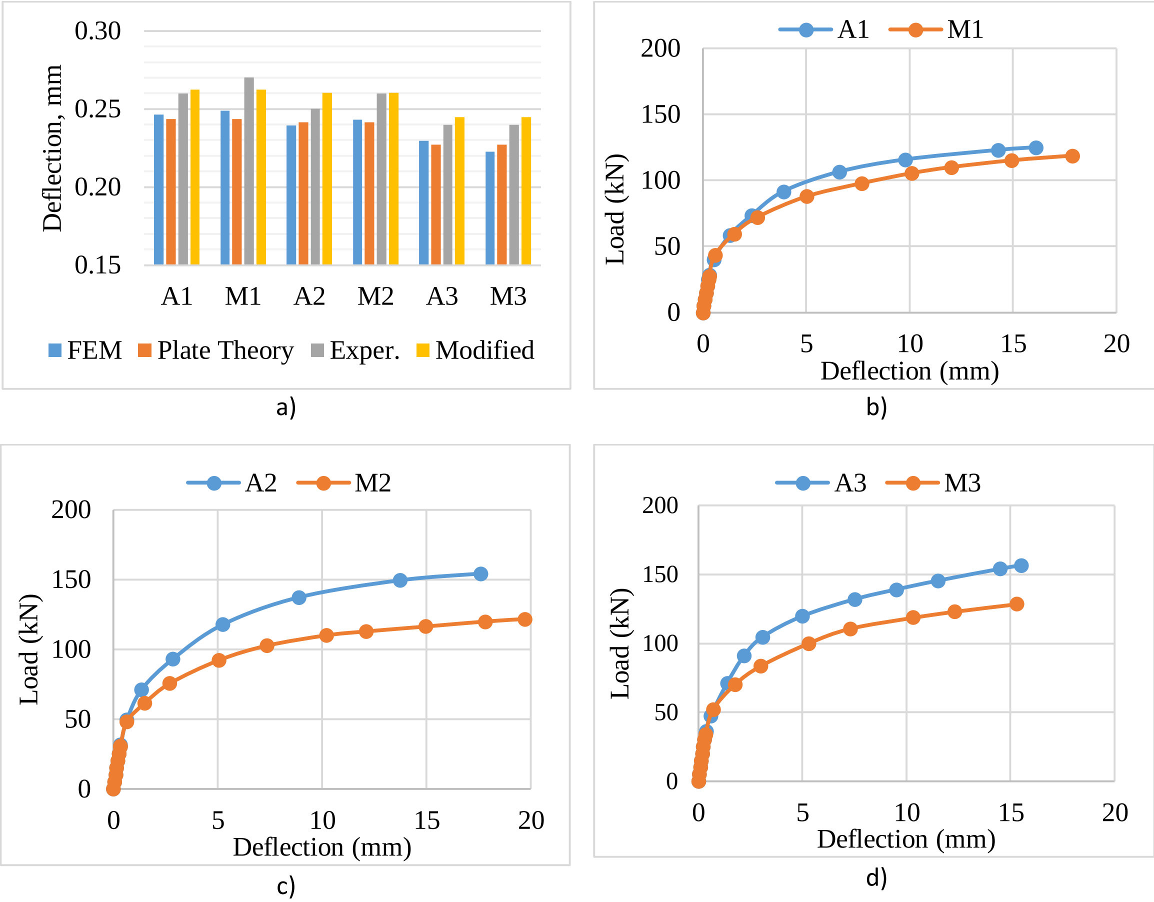

Figure 8 a) deflection calculated by different methods in the elastic stage of loading due to applied load of 25 kN; b-d) load-deflection of the RC annular slabs with 20cm, 30cm and 40cm diameter of the central opening for radially and orthogonal reinforcing.

During the experiment it was established that the value of the deflection within the elastic zone calculated by the FEM and theoretical approach coincides with the experimental results with sufficient accuracy, i.e., it is possible to easily use the classical method plate theory to determine the deflection. However, adding a coefficient and receiving a modified equation increases the accuracy of the conventional approach. Simultaneously, the type of reinforcement in both cases does

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not significantly affect the deflection value, for example, at specific load values -25kN, before the appearance of first cracks (Figure 8-a).

As the load increases and cracks appear on the slab's bottom surface, the discrepancy of the deflection value for the case of radial and orthogonal reinforcing becomes more noticeable. On the other hand, as can be seen from Figure 8-b, c, d, an increase in the central hole's diameter contributes to this discrepancy.

As the diameter of the plate opening increases, the role of the reinforcement type becomes more pronounced. The diagram shown in Figure 8-b shows that for small diameters of the central opening, the values of failure loads are not very different for radial and orthogonal reinforcement, while as can be seen from the diagrams in Figure 8-c, d, when the diameter of the hole increased, it is preferable to use radial reinforcement.

Taking into account the maximum deflection at failure, recorded the difference between deflection of specimens A1 and M1 and also, A2 and M2 was about 11%, whereas between A3 and M3 it decreased to 1%. It’s worth noting that in radial reinforcement, the value of the failure load exceeds that with orthogonal. The experimental results show a significant discrepancy in the plastic stage of the work of slabs. The effect of the type of reinforcing is more significant when the diameter of the inner hole increases.

As can be seen from the results presented in Figures 8, and according to even the most pessimistic estimates, with great certainty, classical approaches can be applied to determine the deflection of the annular RC slabs. The experimental results were very close to the result obtained from the FEM and satisfied the plate theory equation.

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iii. Failure Mode

One of the most important factors influencing the configuration of reinforcing is the pattern of distribution of the cracks throughout the slabs' bottom surface, which was monitored with high definition cameras during their testing.

This work showed that the type of reinforcement did not significantly affect the samples' elastic strength, while it had a sufficient effect on the types of cracks and the place of occurrence of the first cracks on the bottom surface of the plate.

It was not possible to predict the location of occurrence of the first cracks in the case of radial reinforcement, while in the case of orthogonal reinforcement, the location of the first cracks was predictable and coincided with the radial direction with the smallest reinforcement. On the other hand, the distribution and width of cracks in the first case are uniforms along the central hole's circumference, while in the second case, cracks width in the directions of minimal reinforcement has a sufficiently large width. Figure 9 shows that crack patterns on the bottom surface of the plate in both cases is very different.

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Figure 9 Crack pattern on the bottom surface of two groups of the tested specimens.

IV. CONCLUSION

Experimental and modified theoretical investigation of the stress state verified an ABAQUS finite element model that proposed to simulate the bending strength of annular reinforced concrete slabs. It was found that all tested slabs collapsed due to the loss of bearing capacity of concrete in the circumferential direction, i.e., failure under maximum hoop-directed tensile stress.

The FEA confirms the experimental results, and this contributed to the addition of new factors in the equation of theories of plates of K_r=0.67 and K_Θ=0.52 for radial and circumferential stresses, respectively. The discrepancy between the achieved results by classical methods and experimental reaches 50%. In contrast, in the worst case, the difference between the experimental results and the finite element method and the modified method is only 1%, which supports the acceptability of the proposed factors to the classical equations. This study revealed a strong correlation between modified equations, experimental and FE analysis methods for all tested specimens with orthogonal or radial reinforcement, and different sizes of central opening and diameter of ring load.

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As the ratio ζ=d/D increased, the reinforcement's influence becomes significantly noticeable, i.e., with the small size of the central opening the value of the failure load for radially and orthogonally reinforced annular slab changed slightly.

The pattern of cracks and their paths on the bottom surface of slabs is a hallmark between the two types of reinforcement. Cracking tracks are essential to identify the location of the maximum tensile value of circumferential stresses, which qualitatively indicates the zone where the steel reinforcement must be placed in the hoop direction. Therefore, large displacements are observed where the concrete is cracked.

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پوختە:

ئەم توێژینەوەیە پێوانی سترێس و دابەزین و لادانی سلابی کۆنکریتی شێشداری ناوەراست کون لە خۆ دەگرێت. پشکنینی تاقیگەیی بۆ شەش نمونە کراوە کە رێژەی ئەندازەی تێرەی کونی ناوەراستیان لەسەر تیرەی خودی سلاب سێ پری جیاوازن. سلابەکان لە چێوەی دەرەوە بە شێوەی راگری لولەکی جێگیرکراون و بار بە شێوەی بازنەیی خراوەتە سەر چێوەی بازنەی ناوەراست. وێرای ئەوە کە ئەم نمونانە بە تیۆرییەکانی کلاسیکی تایبەت بە پلێت شێکاریان بۆ کراوە، لە هەمان کات بە شێوەی سێ رەهەندی مۆدێلەکانیان لە پرۆگرامی ABAQUS دروست کراون. گشت نمونەکان دابەشکراونە سەر دوو گروپی A وM . یەکەمیان سێ سلاب لە خۆ دەگرێت کە بە شێوەی بازنەیی و تیرەیی شیش رێژ کراون و دووەم گروپ بە شێوەی چوارگۆشەیی.

بەراوردێکی ووردی ئەنجامەکانی تاقیگەیی سترێس بە هەردوو ئاراستەی تێرەیی و بازنەیی، هەروەها دابەزینی سلابەکان کراوە، لەگەڵ ئەنجامەکانی تیۆری و ژمارەیی بە رێگای FEM. لە ئەنجام دا دەرکەوت کە ئەنجامەکانی پشکنینی تاقیگەیی و FEM زۆر لە یەک نزیکن. لە کاتێکدا هاوکێشەکانی کلاسیک پێویستیان بە پێداچوونەوە و هەندێک گۆرانکاریی هەیە لە کاتی بەکارهێنان بۆ پلێتی کۆنکریتی. لە ئەنجام دا پێشنیاری زیاد کردنی هۆکارێکی نوێ بۆ هاوکێشەکانی ئاماژەپێکراو کراوە تاکو بکرێت راستەوخۆ بۆ ئەمجۆرە سلابانە بەکار بێن.

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في هذا البحث تم فحص ستة بلاطات دائرية ومسلط عليها حمل حلقي عمودي وذات تسليح مختلف في الاتجاهين المتعامدين والاتجاه الشعاعي. تم قياسه تجريبيًا الهطول والاجهاد في مواقع محددة للبلاطات الخرسانية المسلحة في المختبرة مع ثلاث نسب مختلفة من نصف القطر الداخلي إلى الخارجي ومسنودة فقط في المحيط الخارجي. تم تنفيذ نموذج ثلاثي الأبعاد للبلاطات الخرسانية المسلحة الحلقية تحت حمل حلقي موحد بالقرب من الحافة الداخلية، ودراسة حالة الإجهاد ونسبة الاستطالة في المرحلة المرنة. تحتوي هذه الدراسة على مناهج مختلفة تعتمد على نظرية الألواح الرقيقة الكلاسيكية (CTP) وأجرت نموذجًا ثلاثية الأبعاد بواسطة العناصر المحدودة (finite-element, FE) للتنبؤ بمجالات الاجهاد الشعاعي والمحيطي وهطول البلاطة. وكذألك التحقق تجريبياً عُرض الشقوق ونمط الشقوق لمجموعتين من الألواح (المجموعة A - المسلحة شعاعياً) و(المجموعة M – المسلحة بشكل متعامدة).

بالإضافة الى ذلك في هذا البحث تم إضافة عامل تصحيح إلى معادلات CTP، والتي تستخدم لتحديد كل من الاجهادات الشعاعية والمحيطية. واخيراً، التحقق في ظهور الشقوق الأولى والانحراف ووضع الفشل والقيمة القصوى لحمل الفشل في كلتا حالتي التسليح.