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# A Comparative Study of Numerical Methods for Predicting Crack Propagation in Reinforced Concrete Hollow Core Slabs

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**ABSTRACT**

Hollow core slabs are commonly used in prefabricated building construction and are calculated and constructed using gravity loads. The dead loads of the structure are reduced by using this slab system. Different criteria, such as the initiation and propagation of cracks in the hollow core slab, are used to analyze these slabs. Fracture mechanics is the basis for studying crack propagation. The present study was conducted to analyze the propagation of cracks in hollow core slabs under common loading conditions using the finite element method and numerical modeling to analyze cracks in reinforced concrete members. This research is theoretically conducted using finite element software. This research takes into account the potential varieties of cracks in concrete slabs. Slabs should consider all three types of cracks, which are shear, flexural, and flexural-shear cracks obtained from the reference test. Two Contour integral and XFEM methods are used to analyze cracks in Abaqus software. To validate and control the modeling process, the laboratory results of the research of Ibrahim N. Najma, Raid A. Daudb, and Adel A. Al-Azzawi. December 2, 2019, has been used. The outcomes of this study showed that the probability of the formation of a flexural-shear crack in the slab is higher than in other crack forms.

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## 1. Introduction

Slabs are one of the important components of structures that carry the important task of carrying loads on the structure [1]. There are various methods for predicting the behavior of normal and solid slabs, the most important of which are the theories based on fracture lines. In the case of hollow core slabs, despite their increasing use, it can be said that due to the geometric diversity and characteristics of the holes or internal cavities of these slabs, there are many areas for research, especially in the field of predicting the occurrence and propagation of cracks. Its impact on the general behavior of the members is doubled, especially since the various theories and relationships presented by researchers in the field of crack analysis are also very diverse, and considering the relative youth of this branch of science, evaluating their effectiveness in hollow core slabs needs to be investigated.

N. Najma et al. (2019) conducted a study on the Behavior of reinforced concrete segmental hollow core

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slabs under monotonic and repeated loadings. The investigation includes testing of twelve specimens that are solid and hollow core slab models. The test program was carried out to study the effects of load type, core diameters, core shape, number of cores, and steel fiber existence. The test results showed that core shape and core number have remarkably influenced cracking pattern, ultimate load, and failure mode. Also, when considering repeated loading protocol, the ultimate load capacity, load at yielding, and ductility are reduced [2].

Salehi. et al, (2016), investigated the numerical study of the behavior of one-way prestressed hollow core slabs. Due to the earthquake-proneness of different regions of the world, Reducing the weight of buildings is one of the methods that have been considered to reduce earthquake forces. The use of prefabricated hollow slabs is one of the ways to reduce the dead load of the building. In this study, 4 types of hollow prefabricated slabs with different thicknesses were modeled under specific dead load in ABAQUS finite element software. With additional nonlinear static analysis, the capacity of slabs and their nonlinear behavior have been evaluated. The results show that with the increase in the thickness of the slab, the final shear strength of the slab increases. The results also show that the ultimate strength has decreased in the hollow slab with polygonal (non-circular) holes [3].

Shafizadeh. et al, (2014), investigated the introduction of a finite element modeling method for pre-stressed slabs with holes in the core by ABAQUS software and investigated the changes in friction coefficient. In recent studies, prefabricated prestressed hollow core slabs (HC) have generally covered the market of many countries for use in buildings with performance in the floor and ceiling area with an advanced method in the factory and with a low cost in installation. Today, hollow core slabs (HC) have strengthened their position. Prestressing increases the usability of hollow core slabs compared to reinforced concrete slabs, thus increasing the cracking moment and other functions of the slab. Therefore, in this research, a finite element modeling method has been introduced to simulate these slabs in ABAQUS software [4].

Aikaterini S. et al, (2015), In an article that studied Nonlinear finite element analysis of reinforced concrete slab-column joints under static and quasi-dynamic loads was performed to investigate their failure modes in terms of ultimate load and crack patterns. Three-dimensional finite element analysis (FEA) was performed with appropriate modeling of element size and mesh and constitutive modeling of concrete. The material parameters of the damaged plasticity model in ABAQUS were calibrated based on the results of the internal slab-column connection test. The predictive ability of the calibrated model was demonstrated by simulating different slab-column joints without shear reinforcement. Internal samples of slab-column under static loading, internal samples under static and reverse cyclic loading, and edge samples under static and horizontal loading were investigated. Comparison between experimental and numerical results shows that the calibrated model correctly predicts the shear response of punched slabs. [5]

R. J. C. Silva et al. (2021), investigated the punching shear strength of 21 hollow slabs. In the articles under this title, to compare the ultimate load of 10 hollow slabs with different sizes of holes, numerical modeling was done with the help of ANSYS software. Loads and failure modes were investigated and it was found that in the case of shearing in the area of the ribs of the hollow slab, samples with less solid parts have lower load-bearing properties than samples with more solid parts. Hollow slabs with areas that have a larger volume are punched like flat slabs and show similar behavior. The evidence showed that the samples with a solid area of 15% of the slab opening have a suitable capacity [6].

Al-Awazi and Al-Assadi (2017) in an article titled " Nonlinear behavior of one-way reinforced concrete hollow block slabs " investigated 11 slab samples, 8 of which were hollow and the other samples were flat slabs with simple supports. Two types of loading and geometric sections (23.3% and 29.1% volume reduction) were considered for the slabs. The proposed finite element model showed a good fit with the results. The difference in the bearing capacity obtained with the laboratory sample was only 10%, which is a small and appropriate difference. 29.1% reduction in cross-sectional area under two loading patterns showed an increase in capacity equal to 8.6% and 5.7% compared to flat slab. Despite the appearance of cracks in the hollow core slabs with a lower load than the reference slabs, the crack development in the hollow core slabs during loading is slower than that in the solid slab, which is a result of the presence of reinforcement in the upper web of the slab [7].

Al-Awazi and Al-Asadi (2016) in an article entitled Numerical analysis of reinforced concrete hollow-core slabs, in this study, three hollow slabs were investigated and compared with flat slabs. The purpose of this research was to investigate the effect of reducing the weight and size of the holes on the final capacity of the hollow slab. Parameters such as the ratio of the opening cut to the effective depth, the size and shape of the holes, the type of loading, and the effect of the upper rebars of the slab were taken into consideration. The results showed that reducing the weight of the slab with the help of holes has reduced the final bearing capacity of the slab. Increasing the cross-sectional area of the ribs in the section of the hollow block slab shows better results than increasing the number of ribs in the same percentage reduction of the cross-sectional area [8].

Somasekhar Anjaly et al. (2015) conducted a study on the effect of openings in hollow slabs and it was found that the openings that are located in the cavity area of the hollow slab with a width less than 10% of the width of the strips do not have much effect on the final load capacity of the hollow slab and the openings created by the two middle strips are surrounded and can be widened up to 40% of the width of the strips. Also, the openings that are surrounded by the column strip and the middle strip can have a width equal to 20% of the cases [9].

Sheikhnasiri Alireza conducted a Comparative study of numerical methods used in the prediction of post-crack behavior of waffle slabs. the waffle slab sample was modeled with two types of distributed and concentrated loading conditions and two types of simple and fixed support conditions. The models were modeled by two methods of concrete damage plasticity and smeared cracked concrete by Abaqus software. Various parameters of these samples, including the load-displacement diagram, the load coincident with the formation of cracks, the displacement in the middle of the slab opening, and the pattern of the formation and propagation of cracks, etc., were discussed and investigated. The outcomes of this study showed; a relatively good correspondence between the two methods of Concrete damage plasticity and the concrete smeared crack model, but due to the definition of failure in the Concrete damage plasticity method, more accurate results can be obtained. [10]

## 2. Methodology

This research is theoretically conducted using finite element software. This research takes into account the potential varieties of cracks in concrete slabs. Slabs should consider all three types of cracks, which are shear, flexural, and flexural-shear cracks obtained from the reference test. Two Contour integral and XFEM methods are used to analyze cracks in Abaqus software. To validate and control the modeling process, the laboratory results of the research of Ibrahim N. Najma, Raid A. Daudb, and Adel A. Al-Azzawi. December 2, 2019, has been used. According to the results, the most destructive type of crack in the slab and also the best method of crack analysis can be extracted from the software.

### *2.1. Validation*

To conduct the research, 7 samples of hollow slabs have been defined. The shape and location of cracks are defined based on the reference article. First, a sample without cracks is analyzed and compared with the laboratory sample. 6 other samples were analyzed in two groups with flexural, shearing, and flexural-shearing cracks using Contour integral and XFEM methods and then compared. Table (1) shows the mentioned models by type of crack analysis. Concrete with a compressive strength of 42.7 MPa and a modulus of elasticity of 29926 MPa has been used. Concrete was modeled by the concrete damage plasticity method. Rebars with a yield strength of 524 MPa ultimate strength of 650 MPa and modulus of elasticity of 200000 MPa were used.

### *2.2. Modeling*

Abaqus finite element analysis software was used to model and analyze samples. Fig. 1. To Fig. 4. show examples of hollow slab cracks modeled in Abaqus software. The location of the considered cracks in the model made by Abaqus was considered based on the location of the cracks in the laboratory sample.

Table 1: Type of crack analysis

| Type of crack analysis | No crack | Flexural crack | Shear crack | Flexural-shearing |
|---|---|---|---|---|
| None | Model 1 | - | - | - |
| Contour integral | - | Model 2 | Model 3 | Model 4 |
| XFEM | - | Model 5 | Model 6 | Model 7 |

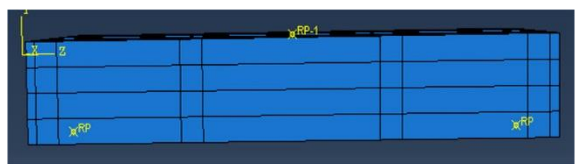


Fig. 1. Schematic view of the hollow core slab with no crack

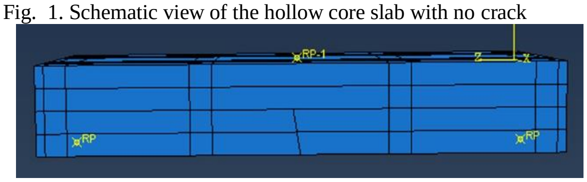


Fig. 2. Schematic view of the hollow core slab with flexural crack

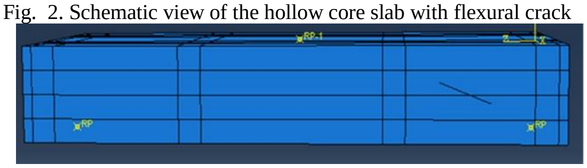

Fig. 3. Schematic view of the hollow core slab with shear crack

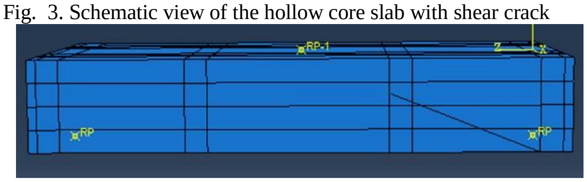


Fig. 4. Schematic view of the hollow core slab with shear crack

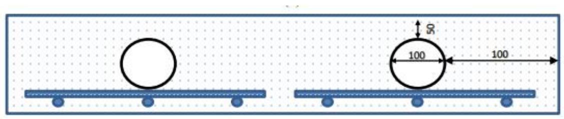


Fig. 5. Schematic view of rebars front section

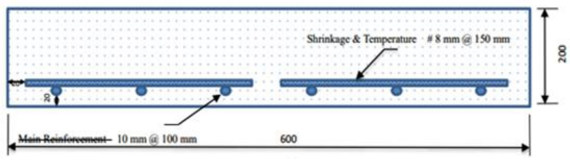


Fig. 6. Schematic view of rebars side section

The waffle slab was modeled with dimensions of 200 x 600 x 1200 mm. Two holes with a diameter of 100 mm and a distance of 100 mm from the short side and 50 mm from the upper and lower parts were considered. The reinforcement detailing on the bottom of slab #6mmØ and spacing of 100 mm for main rebars, and #8mmØ at 150mm for shrinkage. Fig. 5. And Fig.6. Shows rebar details.

The conditions of loading and support are such that the support on both sides of the beam is hinged and the beam is subjected to a monotonic load of 250 KN by a jack. Fig. 7. Shows load and boundary conditions for the slab model. Two analysis methods, Contour integral and XFEM, were considered for the samples.

First, model number 1 was analyzed under the mentioned specifications and its results were compared with the laboratory results for validation. Fig. 8. Shows the load- displacement of model 1, and Fig. 9. Is a comparison of numerical and experimental results.

By superimposing the two force-displacement diagrams obtained from Abaqus and the laboratory model, the difference between the experimental and numerical force was equal to 10 kilonewtons or 5%, and the displacement difference was equal to 0.4 mm or 2%.

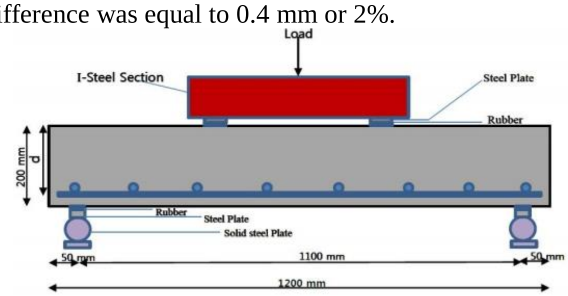


Fig. 7. Load and boundary conditions for the slab model

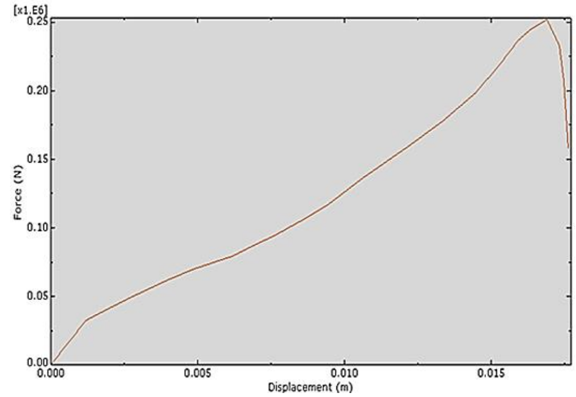


Fig. 8. Load- displacement of Abaqus model

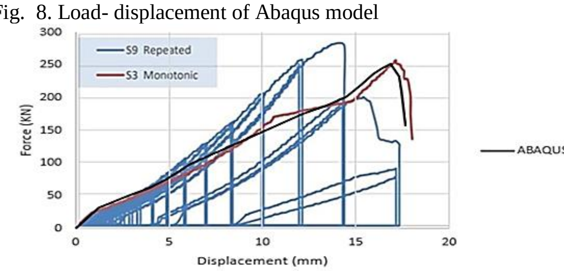


Fig. 9. Load- displacement of Abaqus model and experimental results

## 3. Results and discussion

The results of the load-displacement diagram of all 3 cracking models as mentioned are shown in Fig.10. and Fig.11. for the Contour integral and XFEM method.

For model 1, in both analytical methods, according to the diagram, at the maximum displacement of 17.8 mm, the applied force is equal to 250,000 newtons. For model 2 or sample with flexural crack and contour integral method, according to the diagram, in the maximum displacement of 6.7 mm, the applied force is equal to 100,000 newtons. In model number 3, at the maximum displacement of 9.5 mm, the applied force is equal to 140,000 newtons. For model 4, in the maximum displacement of 5.1 mm, the applied force is equal to 58,000 newtons. According to the diagram in Fig. 11. for model 5, at the maximum displacement of 8.1 mm, the applied force is equal to 130,000 newtons. For model 6, the maximum displacement is 11.5 mm, and the force is equal to 160,000 newtons. And for model 7, it is equal to 6.5 mm in force equal to 81000 newtons. It is also possible to see the amount of energy absorbed by the slab according to the first crack until the moment of failure of the slab are shown in Fig. 12. and Fig. 13.

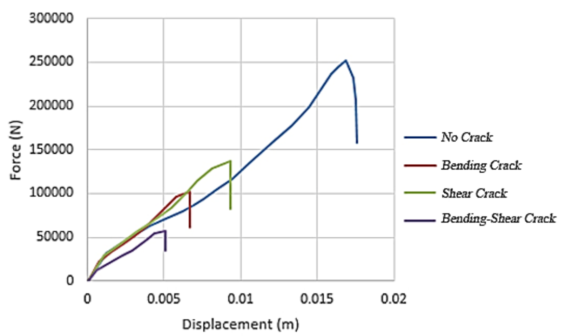


Fig. 10. Load- displacement of models 1, 2, 3, and 4 in the contour integral method

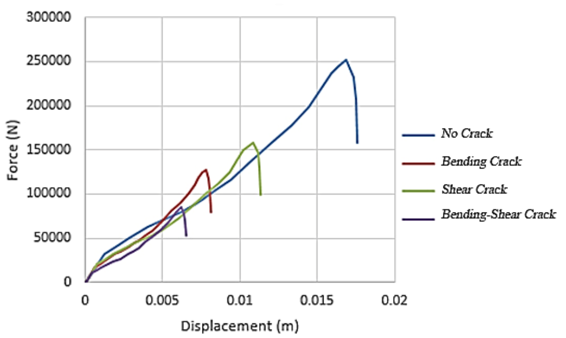


Fig. 11. Load- displacement of models 1, 5, 6, and 7 in the XFEM method

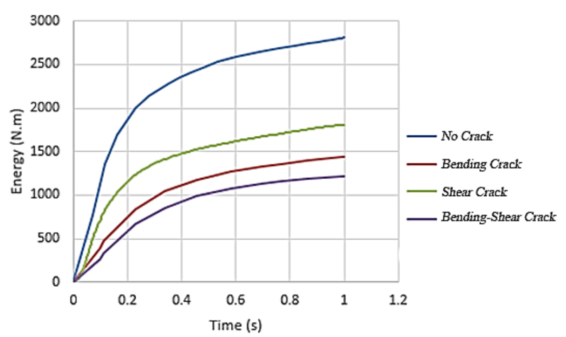


Fig. 12. Absorbed energy of models 1, 2, 3, and 4 in the contour integral method

Table 2: The maximum energy input to the structure, displacement, capacity, and strain of studied model.

| Model Number | Strain | Displacement mm | Load Capacity N | Maximum Energy N.m |
|---|---|---|---|---|
| 1 | 0.049 | 17.8 | 250000 | 2800 |
| 2 | 0.016 | 6.7 | 100000 | 1500 |
| 3 | 0.029 | 9.5 | 140000 | 1800 |
| 4 | 0.012 | 5.1 | 58000 | 1200 |
| 5 | 0.02 | 8.1 | 130000 | 1600 |
| 6 | 0.027 | 11.5 | 160000 | 2000 |
| 7 | 0.02 | 6.5 | 81000 | 1400 |

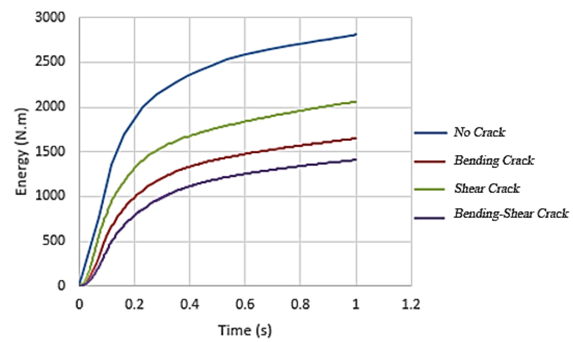


Fig. 13. Absorbed energy of models 1, 5, 6, and 7 in the XFEM method

Table 2 shows the maximum energy input to the structure, displacement, capacity, and strain of each model.

## 4. Conclusions

The following points were concluded based on the values obtained from the model.

- In the crack analysis by the Contour integral method, at the initiation of the first flexural, shear, and flexural-shear crack until the moment of slab failure, the bearing capacity is 60%, 44%, and 77% respectively, and for displacement 62%, 46%, and 71% and also for the absorbed energy is reduced by 46%, 36%, and 57%.
- In the crack analysis by the XFEM method, the creation of the first flexural, shear, and flexural-shear crack until the moment of failure of the slab, the bearing capacity is 48%, 32%, and 67% respectively, and for displacement 54%, 35% and 63%, and also for absorbed energy 42%, 28%, and 50% decrease.
- Modeling the crack initiation and propagation criteria in the Contour integral method requires the design of element meshes considering the possibility of crack growth. If modeling crack propagation and opening is also considered, the work will be much more complicated. In this way, the path of crack expansion should be predicted in advance and the surface of the elements should be placed on this path. In this method, a singularity is defined at the tip of the crack, which requires using a special type of element. In the new method known as XFEM or Extended Finite Element Method, many of the complications and limitations of the old methods have been solved by using enriched elements.
- In terms of the most destructive type of crack created in the slab, in order: flexural-shear crack,

flexural crack, shear crack (rarely happens in the structure)

- According to the load-displacement (capacity) diagram, the first flexural-shear crack at a force of 81000 newtons and a displacement of 6.5 mm, the first flexural crack at a force of 130000 newtons and a displacement of 8.1 mm, and the first shearing crack at a force of 160000 newtons and a displacement of 11.5 mm meters, so according to the results of the analysis, the probability of creating a flexural-shear crack in the slab is higher than other cracks.

## References

[1] Sgambi, Luca, Konstantinos Gkoumas, and Franco Bontempi. "Genetic algorithm optimization of precast hollow core slabs." Computers and concrete 13.3 (2014): 389-409.

[2] Najm, Ibrahim N., Raid A. Daud, and Adel A. Al-Azzawi. "Behavior of reinforced concrete segmental hollow core slabs under monotonic and repeated loadings." Structural Monitoring and Maintenance 6.4 (2019): 269-289.

[3] [3] Reza Salehi, Abbas Akbarpour Nik Qalb Rashti. Numerical study of the behavior of prestressed one-way hollow slabs. International conference on civil engineering, architecture, and urban planning of contemporary Iran, 2016. P. 1-11

[4] [4] Behzad Shafi Rad, Amir Saedi Darian. Introducing a finite element modeling method for precast hollow core slabs by ABAQUS software and checking the friction coefficient changes on it. The first conference on civil engineering, new developments, and economic development, 2014. P. 1-9

[5] Genikomsou, Aikaterini S., and Maria Anna Polak. "Finite element analysis of punching shear of concrete slabs using damaged plasticity model in ABAQUS." Engineering structures 98 (2015): 38-48.

[6] Silva, Ricardo José Carvalho, et al. "Punching shear strength of waffle flat slabs." Revista IBRACON de Estruturas e Materiais 14 (2021): e14106.

[7] Hasan, Haider H. Shear Behavior of One-Way Reinforced Concrete Hollow Slabs Voided with PET Void Formers. Diss. 2023.

[8] Al-Azzawi, Adel A., and Sadeq Aziz Abed. "Numerical analysis of reinforced concrete hollow-core slabs." ARPN Journal of Engineering and Applied Sciences 11.5 (2006): 9284.

[9] Somasekhar, Anjaly, and Preetha Prabhakaran. "Analysis of reinforced concrete Waffle Slabs with openings." International Journal of Emerging technology and Advanced engineering 5 (2015): 86-90.

[10] Sheikhnasiri, Alireza. "Comparative study of numerical methods used in prediction of post-crack behavior of waffle slabs." Journal of Civil Engineering Researchers 4.4 (2022): 12-19.