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INFLUENCE OF OPENINGS ON THE STRUCTURAL PERFORMANCE OF ONE-WAY UHPFRC SLABS: A NUMERICAL STUDY

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Research paper

Abstract: *This study performed a nonlinear finite element analysis on an ultra-high performance fiber reinforced concrete (UHPFRC) one-way reinforced concrete slab with openings. This study contributes to a comprehensive understanding of the previously unstudied behavior of one-way UHPFRC slabs with slits of varying sizes and placements; additionally, a comprehensive comparison is made between the structural behavior of conventional concrete RC slabs and UHPFRC slabs. This study constructed and validated a finite element model (FEM) using the authors' experimental data. Ten models are included in this analysis: In this experimental investigation, the aperture widths and positions of the slabs are altered to determine their effect on the results. In the initial phase of this numerical investigation, a FEM was constructed, and its accuracy was validated against five experimental data, one of which is a closed-loop reference. ABAQUS was utilized for the analyses. Behavior under a total load, maximal load, and failure modes of the validated FEM using experimental data closely match those of the experiment. Due to the use of UHPFRC to reduce the impact of openings on load capacity, the finite element analysis results were very near to the test results, with an average error of 2.232%. Five specimens of UHPFRC were analyzed with finite elements using a validated analytical model and the results of load-displacement behaviors. The finite element method is ideal for investigating the nonlinear behavior of multi-perforated slabs due to its reliability and efficiency.*

Keywords: *Finite element, Reinforced Concrete Slab, Openings, Abaqus, UHPFRC*

Research Significance

Numerous Theoretical and Practical Studies on the Effect of Openings on RC One-Way Slabs are Conducted Using Various Forms of Concrete. However, there are few

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investigations on using UHPFRC in RC one-way slabs. Consequently, the research described in this paper represents the first investigation into the effect of various opening sizes and locations on the structural behavior of UHPFRC one-way slabs. In this study, we demonstrate how to use nonlinear finite element analysis in Abaqus to model the complete load-deflection behavior of the tested specimens, including their ultimate load capacities and collapse mechanisms. Due to the difficulties associated with testing such large specimens, these numerical modeling techniques can be used to expand the applicability to UHPFRC one-way slabs. This method can validate the yield line analysis results for various configurations and combinations of slab sizes and reinforcements.

1. Introduction

Due to the rapid development of technology and the ever-increasing demand for consumer products, manufacturers require larger machines and more expansive production facilities to meet consumer demand (Huang, Kumar, & Dai, 2023). Because each factory has a unique structure, each must have its unique architecture. Engineers and architects must generate concepts that meet several requirements when designing these specialized structures. These designs present numerous challenges when it comes to the placement of cable channels, gas and water lines, air ducts, and sprinklers. It is conceivable for structures to necessitate a large number of apertures of varying sizes. The designers must determine how to mitigate the damage that these apertures could cause. The slab's voids will be reduced. Its load-bearing capacity, energy dissipation capacity, and flexibility. It is essential to investigate various techniques for reinforcing slabs to counteract the negative effects of openings in slab reinforcement. These methods should consider the size and location of the openings (Li et al., 2023).

Ultra-high-performance fiber reinforced concrete (UHPFRC) is a newly developed cementitious composite with high compressive and tensile strength, strain-hardening behavior, and exceptional durability. UHPFRC's potential value derives primarily from its superior mechanical properties enhancing the structure's resistance to fracture and load-bearing capacity. In addition, the dense microstructure of UHPC prevents water and contaminants from penetrating the material. Incorporating UHPC into the concrete deck foundation is gaining popularity. With this material, the self-weight is decreased, the span range is increased, rapid construction is achieved, and the structure's durability is improved (Huang et al., 2023).

Developing structures made from cementitious materials necessitates acquiring mechanical qualities as a prerequisite for the design and construction processes. In addition, the maturation of rigidity and tensile properties plays a crucial role in the onset of early-age cracking (Huang et al., 2023). The progression of strength influences the construction process, such as when to remove the formwork and commence prestressing (Li et al., 2023). The development of mechanical characteristics significantly affects the carrying capacity and stiffness of ancient structures (Dawood & Taher, 2021b). This effect is amplified as the structure's age increases. Their compressive and tensile strengths are well above average at over 150 and 8 MPa, respectively, and under uniaxial tension, they exhibit strain-hardening behavior. Ultra-High Performance Fiber-Reinforced Concretes, abbreviated UHPFRC, are cementitious composites with superior material properties. UHPFRC can be used in various applications, including as a waterproofing layer in bridge decks (Dawood & Taher, 2021a) due to the thick matrix's exceedingly high impermeability. Only UHPFRC, which has not been subjected to heat or pressure for curing, can be used in field applications.

Researchers and engineers have evaluated UHPFRC extensively for its potential use in constructing new buildings, reinforcing existing structures, and restoring civil infrastructure. UHPFRC is widely used in bridge infrastructure (De la Varga, Haber, & Graybeal, 2018), which consists of decks (Liu et al., 2018), pillars (Tazarv & Saiidi, 2015), and robust but lightweight bridge girders (Graybeal, 2008). UHPFRC's low permeability also makes it a viable option for mitigating environmental exposure risks (Alkaysi et al., 2016), requiring fewer restorations over time and lasting longer before replacement is required. Engineers can use UHPFRC to produce novel structural members with improved mechanical performance despite having fewer steel reinforcements, less reinforcement congestion, and smaller cross sections. Tai and El-Tawil (2020) UHPC members are frequently reinforced with steel reinforcing bars (UHPFRC) to enhance their composite behavior for structural applications. Despite their generally superior structural performance, the structural mechanics and failure mechanisms of UHPFRC members can be somewhat distinct from those of conventional RC members. In particular, the material's ultrahigh mechanical performance can negatively impact the behavior of UHPFRC structural members (Aghdasi & Ostertag, 2018). Because UHPFRC members cannot be used interchangeably with conventional RC members, special care must be taken during the design and analysis phases to account for their unique properties. Nonetheless, due to a shortage of research, there is a lack of unified design and analytical methods for UHPFRC structural members. Quantifying the safety margin of the design provisions for UHPFRC members is essential for the safe deployment of UHPFRC. Consequently, identifying the primary factors influencing the structural behavior of UHPFRC members is of the utmost importance. This study aims to demonstrate the structural behavior of one-way UHPFRC Slabs with diverse aperture sizes and placements. In addition to constructing a dependable FEM model, this study assists researchers in weighing the advantages and disadvantages of conducting additional research. Remember that there is a shortage of theoretical and applied research on this form of concrete slab with openings.

2. Experimental Database

The five one-way RC slabs in the experimental program were evaluated under a constant load. The same mixture of concrete, steel reinforcing, and cross-sectional characteristics was used throughout the manufacturing process to produce the slabs. As a control specimen, one slab was fabricated without an opening, while the other four slabs were fabricated with varying sizes and locations of perforations. All specimens were constructed with dimensions of 1000 mm by 3000 mm by 150 mm, and 10 mm-diameter ribbed bars were used as longitudinal reinforcement. The longitudinal reinforcement ratio was determined to be 0.0058. As transverse reinforcements, 10-mm-diameter ribbed bars were placed with a 250-mm distance between each bar in the short orientation. Three distinct 400 mm and 500 mm square sides were drilled with holes during the experimental study. Figure 1 provides information on the dimensions and locations of the apertures. Steel reinforcement has a diameter of 10 mm, a yield strength of 480 Mpa, and a tensile strength of 627 Mpa (Kaya & Anil, 2021).

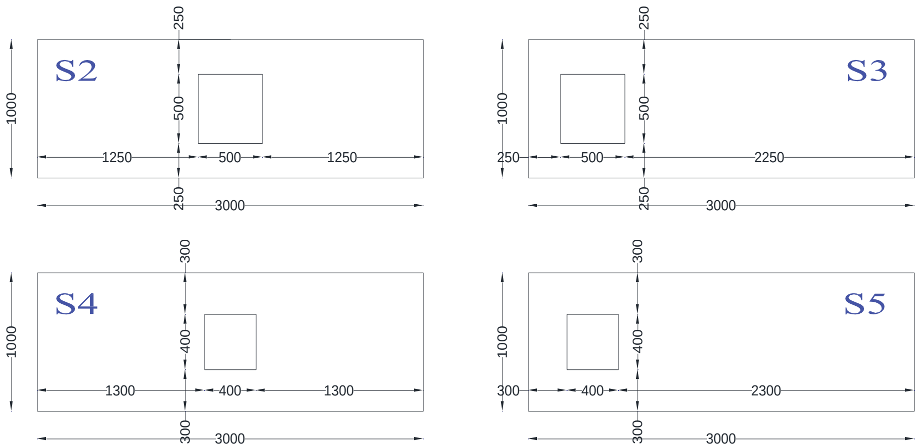

Figure 1. Location and dimensions (in mm) of each opening

Regarding compressive strength, the average value of the test specimens was 18.24 MPa. The authors intended to produce concrete with a compressive strength of 20 MPa, the lower limit of the normal strength concrete category. However, the authors could only produce concrete with an average compressive strength of 18.24 MPa. Each specimen was subjected to the rigorous four-point loading test. Each specimen was evaluated as a basic slab under a four-point stress, and the effective depth-to-shear span ratio was set to 7. The force on the slab's central point was symmetrically divided into two focused loads, which were then applied to the specimens. In the test configuration, high-strength steel loading and support plates measuring 100 mm by 1000 mm by 25 mm are utilized at both the reaction slab and test specimen support positions. A 600 kN capacity hydraulic jack was used to impart the load, and a 400 kN capacity load cell was used to measure it (Kaya & Anil, 2021).

3. Finite element modeling

The analysis of a perforated, one-way RC slab using finite elements. Using the ABAQUS/Standard 2018 program from the ABAQUS/Standard 2018 package, monotonic loads were simulated using ABAQUS/Standard 2018. The concrete damage plasticity (CDP) technique is employed to characterize the inelastic behavior of concrete. Concrete's compressive behavior is defined by equations that characterize it in terms of compressive stress and inelastic strain. Stress-strain equations represent the behavior of concrete in compression.

$$\sigma_c = E_c \frac{\varepsilon_c}{1+(\frac{\varepsilon_c}{\varepsilon_o})^2} \qquad (1)$$

$$\varepsilon_{oc}^{el} = \frac{\sigma_c}{E_c} \qquad (2)$$

$$\varepsilon_c^{\sim in} = \varepsilon_c - \varepsilon_{oc}^{el} \qquad (3)$$

Where σc compressive stress at any compressive strain εc of the concrete, εo maximal compressive stress equals the strain under compression (2□′□□□), ε_{oc}^{el} the elastic strain of the concrete, $\varepsilon_c^{\sim in}$ the elastic strain and the inelastic strain of the concrete.

Due to the significance of the mechanical response of the concrete in the CDP method, the stiffness of degradations of compression behavior and the stiffness recovery under cycle loading was established. To put it another way, the damage parameter of the compression behavior of concrete (dc) is the ratio between stresses in the declining segment of the stress-inelastic strain curve in compressive behavior and the compressive strength of the concrete (fc′). It can range from zero to one to represent the material undamaged to total losses of load-bearing capacity. The ABAQUS user manual recommends adopting the default value(wc=1) for the compression stiffness recovery), which is regained at crack closure as the load shifts from tension to compression (Taher & Dawood, 2022).

$$d_c = 1 - \frac{\sigma_c}{f_c'} \quad (4)$$

$$\sigma_t = f_{cr}\left(\frac{\varepsilon_{cr}}{\varepsilon_t}\right)^{0.4} \quad (5)$$

$$\varepsilon_{ot}^{el} = \frac{\sigma_t}{E_c} \quad (6)$$

$$\varepsilon_t^{ck} = \varepsilon_t - \varepsilon_{ot}^{el} \quad (7)$$

Where σ_t is the tensile stress, f_{cr} the modulus of rupture, ε_{cr} the cracking strain at the maximum tensile stress of the concrete, ε_{ot}^{el} the elastic tensile strain, andε_t^{ck} the cracking strain at the maximum tensile stress of the concrete, all in millimeters per millimeter. Finally, characterize the degrading stiffness and recovering stiffness of the concrete's tension behavior. The tensile damage parameter (d_t) is defined as the ratio of the stress at cracking (strength of rapture f_{cr}) to the stress at cracking (decreasing segment of the stress-cracking strain curve). The ABAQUS user manual suggests leaving the tension stiffness (w_t) at its default value of 0 due to experimental evidence showing that quasi-brittle materials, such as concrete, do not regain their wt after being subjected to a crashing micro-crack (Taher & Dawood, 2022).

Before performing finite element analyses, the system in question must be segmented into finite elements, which are more manageable portions. After generating the finite element mesh, the appropriate material model is chosen in the modeling study. This is a necessary phase in the procedure. Within the confines of the investigation's scope, ten distinct numerical analyses were performed. Five of these studies are test specimens for perforated, one-way RC slabs. These test samples contain experimental results that can be used to validate the FEM that was developed. In the five remaining investigations, the validated FEM was used to represent the UHPFRC slabs that were not tested in the experimental study. This model was developed to generalize the experimental results and provide the equations for calculating the utmost load that a structure can support (Wang et al., 2023).

Eight-nodded hexahedral (brick) elements (C3D8R) were utilized to produce concrete with diminished integration, as determined by an ABAQUS simulation of the slab's behavior to prevent the shear locking effect. As shown in Figure 2, modeling reinforcements are required using T3D2-designated 2-node linear truss elements. Since it was presumed that the connection between the concrete and the reinforcement was perfect, reinforcement was placed within the concrete to replicate this connection. The concrete damage plasticity (CDP) technique is employed to simulate the behavior of inelastic concrete. This modeling technique applies to both conventional concrete and UHPFRC (Li et al., 2023). The wire planer type was used for the steel reinforcement, while all of the concrete slabs were formed using a 3D model space and deformable type with a solid extrusion type as the fundamental feature. Depending on the requirements, the slabs were sketched in various aperture configurations and sizes. Each concrete slab and steel reinforcement was assembled as a separate instance of a dependent item within the global system (Taher & Dawood, 2022). To generate the subsequent interaction surface, embedded region limitations were applied to the steel reinforcement and whole concrete to develop the new surface. A static general step procedure was adopted to accurately represent the displacement at the upper face of the slab (Huber et al., 2023), with the influence of inertia and time-dependent material omitted. The slab's burden and supports were specified following the analysis's methodology. All models were created using a technique known as finite element mesh, which has a global dimension of approximately 10 mm (Lagier, Massicotte, & Charron, 2016).

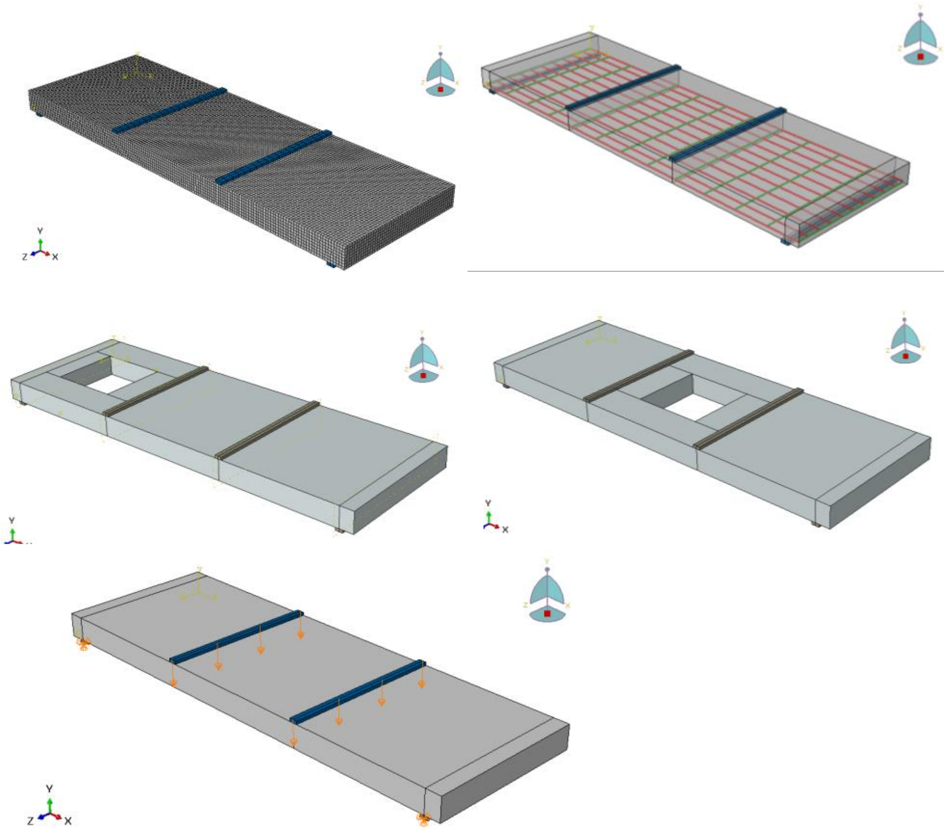

Figure 2. Simulation slabs using ABAQUS.

4. Results and Discussion

4.1 Validation of study results

Compared to experimental investigations that obtained load-displacement graphs from an actual slab, finite element analyses were found to be adequate for modeling the behavior of slabs (Kaya & Anil, 2021). Figure 3. The results of the experimental investigation and the finite element analyses are compared to the yield stress, motion, and ultimate load level. The findings are concisely summarized in Table 1. Here, we examine the initial crack growth patterns calculated from the finite element analysis of the five specimens used in the experimental investigation. As depicted in Figure 4, the limited element analysis results demonstrated that the fracture propagation in each slab was comparable to the experimental investigation results. The bending zone was where the first fractures in the slabs appeared, resulting in the formation of an aperture there. The shear zone was where the first cracks in the slabs appeared, and these breaches resulted in the construction of an aperture. During the experimental investigation, it was discovered that angled cracks moved closer and closer to the loading plate. The numerical results demonstrated a substantial overlap between the experimentally tested beams and the finite element analysis for the failure load.

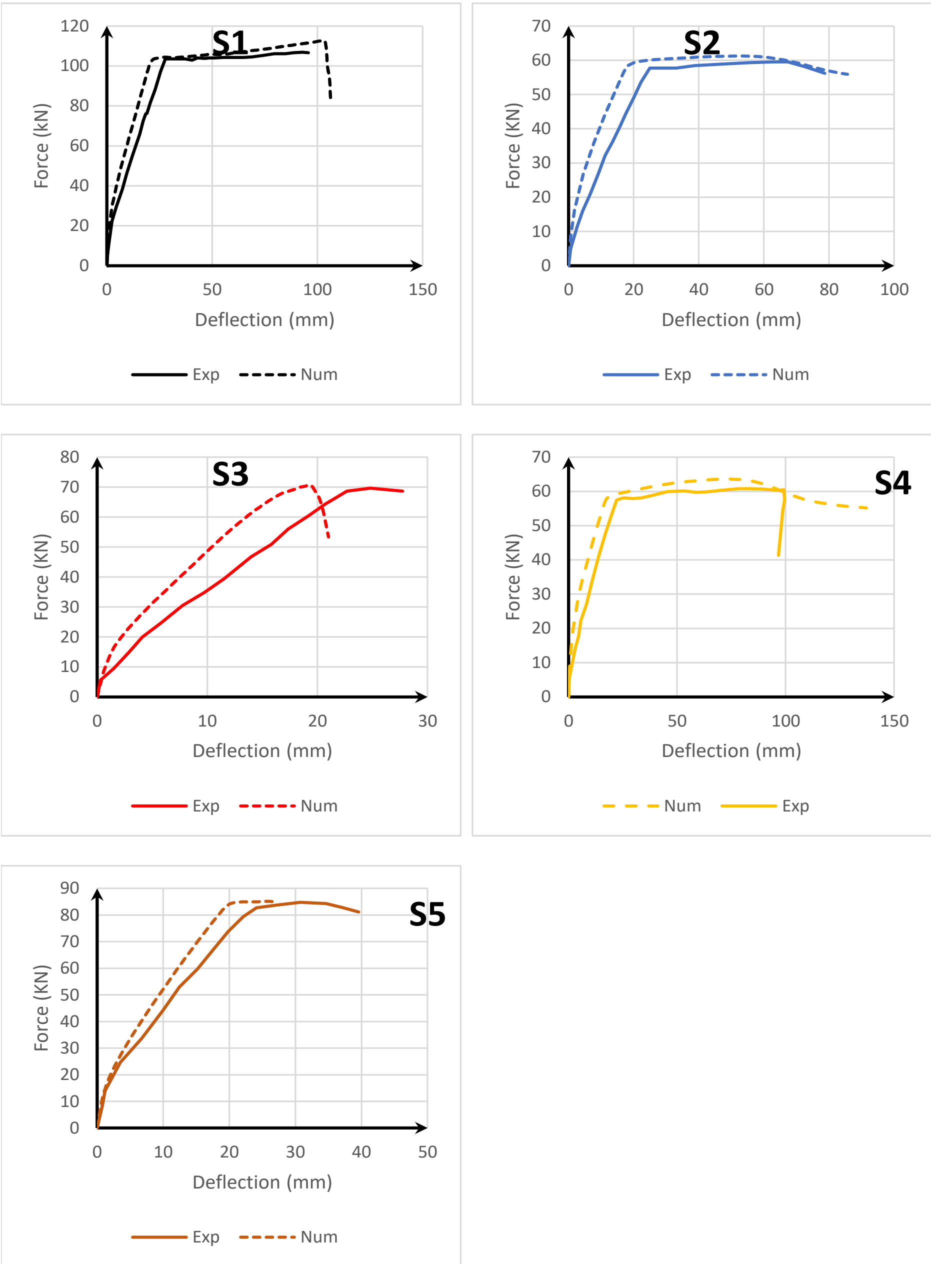

Figure 3. Comparison of Experimental vs. numerical load-deflection curves.

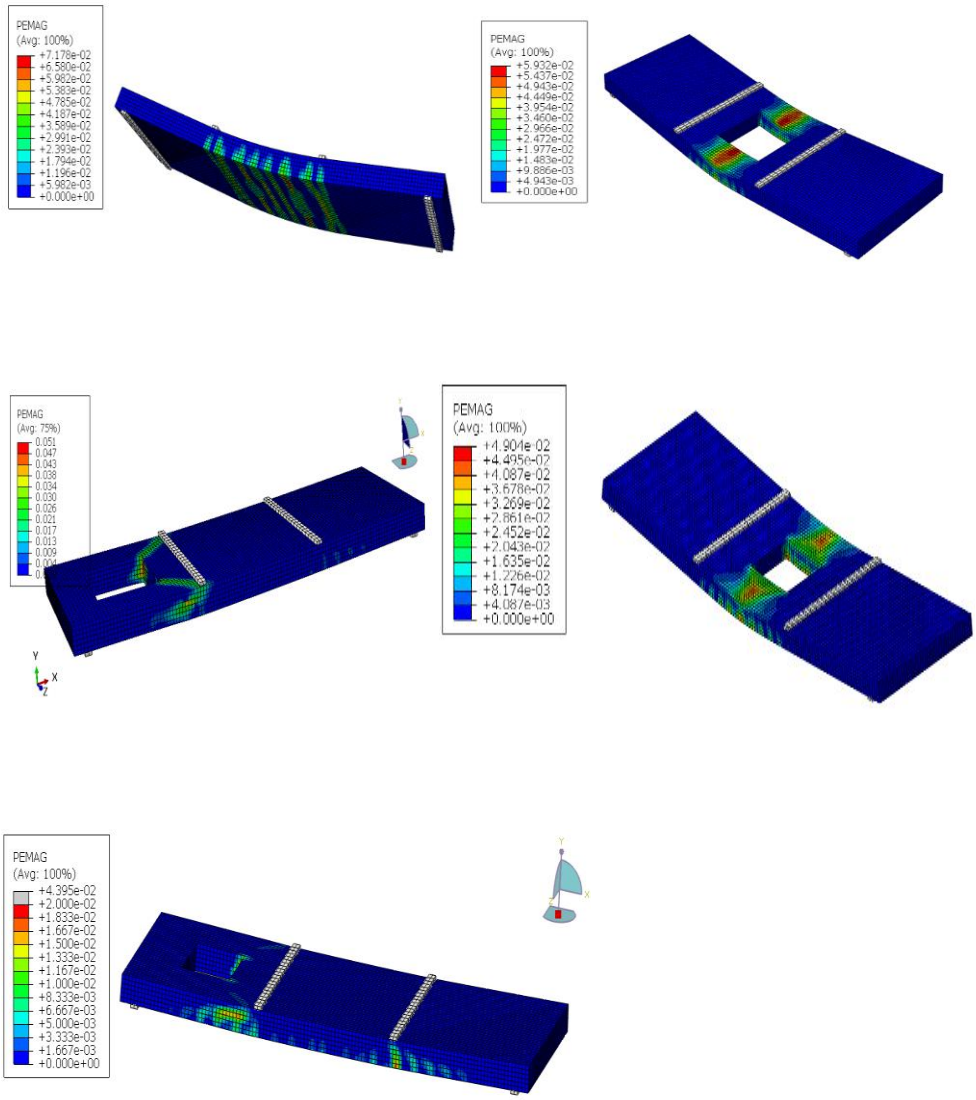

Figure 4. Finite element model crack propagation.

Table 1. Results from finite element analysis and experiments are compared.

Model ID	Ultimate load (KN)		FE/EXP.
	P_u Exp	P_uNum	Ultimate load ratio
S1	106.93	112.754	1.054
S2	60.05	61.243	1.019
S3	70.60	70.755	1.002
S4	61.82	63.612	1.028
S5	84.59	85.106	1.006

After the load-carrying capacity of a one-way RC slab without apertures has been calculated using any of the methods recommended by the rules, the proposed equations can be used to calculate the utmost load capacity of a one-way RC slab with an aperture. When there are openings in the maximal moment area of a one-way slab, its ultimate load capacity is diminished. However, openings in the shear span zone have a minimal effect on the maximum load capacity. While ductility ratios decrease, energy dissipation capacities increase. The aperture in the shear span zone exacerbated shear cracking, which was already a prevalent failure mode.

It has been demonstrated that openings in one-way RC slabs reduce the slab's eventual load capacity. They significantly reduced the permitted maximum weight. This prompted the Authors to question why one-way RC slabs cannot have any openings unless it is essential. Instead of the zone of greatest acceleration, the optimal location for the aperture is in the shear span zone. In the zone of maximum moment, the ultimate load-carrying capacity decreases more than in the zone of maximum shear span. Therefore, it is best to abandon the aperture once the shear span zone is reached. When apertures are added to the shear span zone, the one-way RC slab's failure mechanism becomes more fragile. If the aperture dimension is less than 5% of the total expanse of the one-way RC slab, the ultimate load-carrying capacity may be reduced by no more than 20%. Perforations in the one-way RC slab cannot exceed 5% of the total area. In the event of a mandatory emergency, it is recommended that the regulations be revised to indicate that the inferior strength value should be used to determine capabilities.

4.2 Parametric Study Results

A FEM was constructed so that an investigation could be conducted on a reinforced concrete surface with various aperture sizes and positions. The validity of the finite element model has been validated by the experimental research and work conducted by the authors themselves. The validated model was subsequently used to conduct finite element simulations of artificial slabs, designated as models S1, S2, S3, S4, and S5 of a one-way UHPFRC slab. These simulations were conducted on a computer and did not contain any experimental data. When UHPFRC 4% is used, the compressive strength, tensile strength, and Young's modulus are 115, 13.9, and 36,800 MPa, respectively (Lagier et al., 2016). Figure 5 depicts the graphs of the projected values of the load-deflection curve for every UHPFRC slab. Figure 5 demonstrates that, compared to the one-sided example, the advantageous influence of the higher compressive strength of UHPFRC is more pronounced for all aperture sizes and positions. It is important to observe that when using new concrete, the holes' effect on the ceiling diminishes. With the use of this new concrete, the structural enhancement of the hole will be enhanced. Compared to NC slabs, it is evident that the enhancement has substantially increased the ultimate load of UHPFRC slabs with openings.

Table 2. Comparison of NC and UHPFRC finite element analysis results.

Model ID	P_u(KN)		% increase in ultimate load
	NC	UHPFRC	
S1	112.754	141.764	25.728
S2	61.243	90.415	47.633
S3	70.755	108.555	53.423
S4	63.612	99.525	56.456
S5	85.106	133.001	56.276

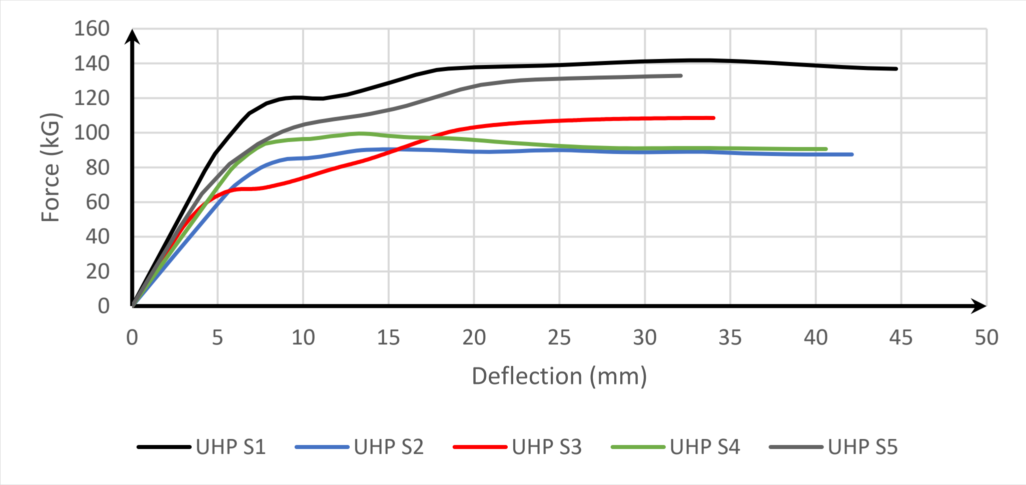

Figure 5. Load-deflection curves of UHPFRC slabs

The effect of UHPFRC was extremely obvious with different aperture sizes and positions employed in this investigation, where a decrease in the ratio of reduction in ultimate load comparison with slab without opening when using UHPFRC, as explained in Table 3, was observed.

Table 3. Comparison of the opening effect

Model ID	P_u(KN)		%Reduction P_u	
	NC	UHPFRC	NC	UHPFRC
S2	61.243	90.415	45.68441	36.22147
S3	70.755	108.555	37.24835	23.42555
S4	63.612	99.525	43.58338	29.79529
S5	85.106	133.001	24.52064	6.1814

As evidenced by the first FE study of fracture growth distributions of the five UHPFRC slabs, crack propagation in all slabs takes longer to initiate in UHPFRC slabs than in RC slabs. The first fractures appeared at the deformation zone, exposing the slabs. At the shear zone, the first fractures in the slabs occurred and opened. As observed in the experiment, cracks propagated at an angle toward the load plate. Figure 5 illustrates the outcomes of finite element analyses of UHPFRC slabs, demonstrating that these analyses can simulate the slabs' behavior. Using a finite element model, one-way ultra-high-performance fiber-reinforced concrete (UHPFRC) and reinforced concrete (RC) slabs with various opening diameters and positions were analyzed. The results of the experimental investigation validate the finite element model. Based on the validated model, one-way UHPFRC slab models were generated, and FE simulations of synthetic slabs were conducted in a computer environment. The second table provides a summary of the results. The ratio of the ultimate load-carrying capacity of UHPFRC slabs to that of RC slabs can be altered from 25.7% to 56.4%, as shown in Table 2. The maximal load-carrying capacity of one-way UHPFRC slabs and reinforced concrete slabs with the aperture can be accurately predicted using finite element models. UHPFRC slab FE calculations revealed much larger displacement values at maximal load levels. As the slabs' load increased, the reinforcing failed, and fractures appeared.

The manuscript's findings corroborate the conclusions of the investigations mentioned above. Under the assumption of a linear relationship, the ultimate load-carrying capacity of apertures in one-way UHPFRC slabs with a flexural dominant failure mode mechanism can be computed. On the other hand, when shear failure mode is determined to be predominant, the quadratic relation can be applied. According to the authors, the publication's research is significant, and its findings contribute substantially to what is already known. The maximal load-carrying capacity emphasizes the failure processes where shear is most effective, as it is considerably more difficult to predict and depends on more variables. This literature was used to support the claim that the current study's findings were consistent with previous research. For RC slabs with openings, the proposed load-bearing lowering coefficient for the adjustment of maximum loading capacity in the event of failure techniques when shear is effective in one direction can be estimated using a significantly more complex correlation.

5. Discussion

In this study, it was discovered that nonlinear Finite Element Analysis using the ABAQUS software enhanced the efficacy of the numerical models. In this study, the prescribed values for material properties are revised to reflect empirically determined values while the previously approved forms of the material models are maintained. Models written in the safety format accurately approximate the experimentally observed behavior. The findings of this study indicate that the recommendations are valuable for predicting the performance of ultra-high performance fiber reinforced concrete one-way reinforced concrete slabs with varying aperture sizes and positions.

The UHPFRC slabs with varying openings, whether in the middle or on the side, are more transparent at the larger openings, allowing us to increase the size of the openings in future research. The work also validates the previously predicted critical position of these slabs using a shear fracture angle, which brings us to our second observation. Due to the slab's quantity and shape requirements, the capacity of the provided steel bars cannot be accounted for in standard evaluation calculations.

The evaluation outcomes disclose the most probable cause of failure for RC slabs. Despite its high flexibility, UHPFRC is variable. The flexural and shear cracking loads are more sensitive to load level. This variable has less of an effect on the overall burden. Slabs are distinctive because their design is based on the need for zero or minimal tensile stresses in the cross-section, making serviceability requirements a crucial stage of the process. When fractures appear in a slab, it no longer performs as expected and fails to meet standards for serviceability. This emphasizes the critical need for additional research into nondestructive methods for determining the stress level in extant slabs, which is essential for evaluation.

Guidelines for applying nonlinear finite element models are useful for putting these models into practice. Users using nonlinear finite element models to predict failure loads and behavior have occasionally been criticized for generating widely divergent forecasts. Consistency in the Guidelines for using nonlinear finite element models can enhance the quality of the findings by reducing the number of decisions the user must make. The results of this study pave the way for the widespread application of nonlinear finite element models in the evaluation of preexisting concrete slabs of various varieties.

6. Conclusions

Based on previously published experimental results (Kaya & Anil, 2021), the author employs proven FEMs to accurately simulate the behavior of one-way normal RC slabs under load and displacement with apertures. In addition, the influence of the maximum allowable load for a one-way reinforced concrete slab, the effect of opening size, and the impact of UHPFRC use was analyzed. The following is a summary of the study's findings: The final burdens derived from the finite element analyses deviated from the theoretical values by an average of 2.232%. The result demonstrates that the approved FEM representation can provide realistic and consistent experimental data predictions of the maximum load rating of one-way RC slabs. The discrepancy between the two sets of yield displacement values is hypothesized to result from the FEM's rigid behavior, in contrast to the experimental specimens' pliability. The validated FEM predicts the maximal load that the one-way RC slab with openings with promising accuracy can support. Openings drastically reduce the one-way load slabs supporting the maximum moment zone. Utilizing UHPFRC reduces the absolute maximum bearing capacity, albeit marginally, whenever apertures are positioned within the shear span zone. Before the opening in the shear span zone, shear cracking was already a prominent failure mode. The opening made it even worse. It was discovered that the utmost load that one-way RC slabs can support decreases when designed with apertures. They drastically reduced the maximum allowable weights. As a result, UHPFRC was utilized significantly less.

7. Recommendation

Not included in this investigation are the following areas that require additional research:

1. The finite element method provides a firm foundation for future research testing the design approach with varying loads. In addition to multiple loading points, cyclic loading, and numerous opening forms, the vertical positioning of transverse apertures in UHPFRC one-way slabs is investigated.
2. The strength of UHPFRC one-way slabs can be increased by reinforcing the area around the entrance with UHPFRC with a higher strength or steel reinforcement.
3. The study suggests examining the UHPFRC one-way slabs with different-sized, shaped, and positioned openings.

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