Finite Element Analysis of UHPC Beams with Transverse Openings

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Abstract

Ultra-high-performance concrete (UHPC), a cementitious material with extraordinary mechanical properties, is becoming increasingly used in civil engineering projects. Recent research has investigated the flexural and shear performance of members constructed fully or partially with UHPC. To facilitate the passage of pipes and ducts needed for essential services (e.g. electricity, HVAC, internet), beams and girders are oftentimes constructed with transverse openings. Such openings disrupt the internal force flow, cause stress concentrations, and might affect the load carrying and deformation capacities. This study develops a robust three-dimensional (3D) finite element (FE) model to study the behavior of UHPC beams with transverse openings. The model was able to replicate the load deflection curves, capture various behavioral aspects, and predict the peak load with a maximum difference of 7%. Furthermore, it successfully simulated all failure modes, particularly the shear diagonal cracking around the opening corners which is typically encountered in beams with openings and oftentimes difficult to predict numerically. The validated model will be used in a parametric analysis studying the effects of various key parameters and establishing a large database to assist in developing simple design tools for predicting the capacity of UHPC beams with openings and presenting recommendations for opening location, shape, and size, and reinforcement techniques in the opening vicinity.

Keywords: UHPC, beams, openings, RPC, shear, UHPFRC, finite element, ANSYS.

1. Introduction

One of the advanced materials making strides in the construction market is ultra-high performance concrete (UHPC) which is a new class of concrete with exceptional mechanical properties, including a compressive strength over 21 ksi, and a tensile strength exceeding 0.7 ksi with a strain hardening response resembling metallic ductility, high energy absorption capacity, and good durability (Jawdhari and Fam; Kadhim et al.). Several studies were conducted on the behavior of UHPC beams. As an example, Yoo et al. (Yoo, Lee and Yoon) and Kang et al. (Kang et al.) performed tests on UHPC prisms with various fiber volumetric ratios to study the impact of fiber content. It was observed that the flexural characteristics rose pseudo-linearly as the fiber content continued to increase up to 3%; however, further increasing the fiber content had a negative effect on the static flexural efficiency, likely because further increase in fiber content results in increasing the air content of the material and decreasing its density (Yu, Spiesz and Brouwers).

From an architectural perspective, transverse holes can be used to create compact designs of structural members by reducing the dead region of fake ceiling and hence reducing the height of the entire building (Tehranizadeh and Barkhordari). These holes also facilitate the transfer and placement of ducts, pipes, kitchen smoke exhausts, and other mechanical, sanitary, and electrical facilities in a building. From a structural perspective, however, they are viewed as weak locations in beams or other building elements resulting in stiffness and strength reductions and lose of integrity. For this reason, some researchers investigated the effect of openings in reinforced concrete (RC) beams. For instance, Abdel-Kareem (Abdel-Kareem) tested RC beams with rectangular web openings that were mechanically strengthened with FRP composites, bonded around the openings. The geometry and reinforcing details were the same for all tested beams. The size and placement of opening in the shear zone, strengthening pattern, and quantity and type of FRP composite are some of the design factors considered in the study. The effects of those parameters on the ultimate load, failure modes, and beam stiffness, were carefully analyzed. Herrera (Herrera, Anacleto-Lupianez and Lemnitzer) investigated the cyclic performance of T-shaped beams with openings using a large-scale experimental campaign. The study reported on the beam's behavior in terms of failure progress and plastic hinge formation, strength and stiffness deterioration, and energy dissipation capability.

Remarkably, majority of these studies used specimens made of normal- or high-strength concrete (NSC, HSC); while research into UHPC beams with openings is still lacking (Barkhordari et al.). Because of its much higher strength and elastic modulus and ductile tensile response due to fiber bridging phenomenon, the effects of transverse openings in UHPC members might be significantly different than those in NSC or HSC counterparts. The goal of this study is to build a high fidelity three-dimensional (3D) FE to examine the behavior of UHPC beams with transverse openings. The model outputs, including ultimate load, failure mechanism, and load-deflection curves were validated using data from 4 beam tests from literature, showing excellent match with experimental data. The model will serve as a cost-effective platform to conduct a parametric study on multiple variables, such as opening shape, location, and size; strengthening the opening (e.g., with internal steel rebars, externally bonded fiber reinforced polymer (FRP) plates); UHPC compressive strength and fiber content. The numerical results will aid in developing a design tool to predict the capacity of UHPC members with openings, and recommendations to the location, size, shape of inevitable openings, and reinforcement around them.

2. Experimental Reference

Two experimental campaigns from literature were selected to calibrate and validate the FEM results. Given the scarcity of physical tests on UHPC beams with transverse openings, the validation program was conducted against two different sets of experiments: (a) UHPC beams without openings from Kodur et al. (Kodur et al.), and (b) beams with openings from Sardar et al. (Ali and Saeed) that were constructed with NC and high strength concrete (HSC). Four test specimens, two from each study, were chosen for the validation and had variety of geometries, opening dimensions, concrete strengths, and loading conditions. In the following sections, a brief discussion about the material properties and beam geometry is provided.

2.1. Kodur et al. specimens (Kodur et al.)

Two specimens from Kodur et al. (Kodur et al.), UB-3, and UB-4, differing mainly in loading scheme with the first tested under flexure and the latter under shear, were selected for validation purposes. Figure 1 shows the geometric, loading, and reinforcement details of the two specimens. They had dimensions of 400 mm x 180 mm x 270 mm, for length x width x height. Given UHPC's high compressive strength and significant shear strength, no shear stirrups were used. All specimens had a concrete cover of 35 mm. The compressive strength (f_c'), elastic modulus (E_c), and tensile strength (f_t) were reported by (Kodur et al.) to be 167 MPa, 46 GPa, and 6 MPa, respectively. The yield and ultimate strengths, and ultimate strain of the steel rebars used as longitudinal reinforcement are 436 MPa, 696 MPa, and 0.122, respectively.

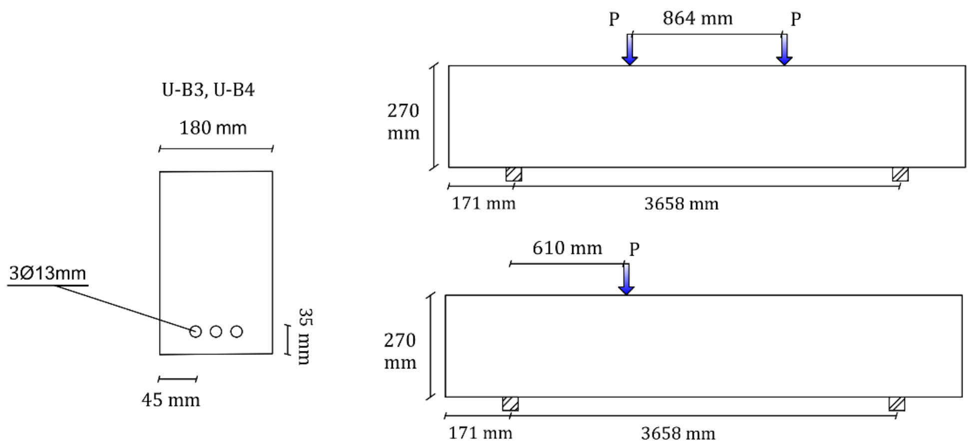


Figure 1 Geometric details of Kodur et al. (Kodur et al.) specimens.

2.2. Sardar et al. (Ali and Saeed)

In the second campaign from Sardar et al. (Ali and Saeed) study, two specimens were selected, (a) beam B2 made with NC having f_c' and E_c of 48 MPa and 29.7 GPa, respectively, and (b) beam B8 with the same respective properties of 89 MPa and 43.91 GPa. The RC beam specimens have a length of 2200 mm and a cross-section of 200× 400 mm. The beams were simply supported and subjected to three-point bending load to failure. Longitudinal steel reinforcement consisted of 4 ϕ20 mm for tension and 2 ϕ10 mm for compression. Closed stirrups of ϕ8 mm were used as shear reinforcement and spaced at 167 mm. The region surrounding the opening was strengthened with 2 ϕ10 on either (top or bottom) side of the opening and ϕ8 mm stirrups that encapsulate the additional longitudinal reinforcement and main ones, as shown in Figure 2. Vertical and side covers for the bottom longitudinal reinforcement were 40 and 25 mm, respectively. Figure 2 shows the geometric and reinforcement details of the beams.

3. Finite element modeling

The beams discussed above were modeled with the commercial software ANSYS mechanical APDL (ANSYS), using a three-dimensional (3D) modeling approach. Due to symmetry in loading, geometry, and material properties, and to reduce computations, a quarter-size model with appropriate constraints at each plane of symmetry was employed. The load was applied via an increasing displacement, to simulate displacement-controlled loading which is usually more stable than force-controlled loading and can simulate load drops. The concrete parts and steel plates, added at loading support locations to minimize local failure, are meshed with 8-node brick elements (SOLID185). Two-node truss element (LINK180), with axial-only stiffness, was used to model the steel reinforcement. An element side length of 20 mm was used for all beams, resulting an approximately 8262 elements for Kodur et al. specimens, and 6316 elements for Sardar et al. [] specimens. The concrete parts, i.e. NSC, HSC, and UHPC, were modeled using the Menetrey-Willam (MW) material model. The MW model (Willam), which integrates dependence on three separate stress tensor invariants, is built on the Willam-Warnke yield surface (Willam). The Willam-Warnke surface is analogous to the Mohr-Coulomb surface, however, the surface of the latter does not have the sharp corners present in the former that sometimes impede its stress response. MW has characteristics common with the Drucker-Prager model but is more accurate and stable in simulating the behavior of bonded aggregates like concrete. The loading surface of MW model is defined by the following equation:

$$F(\xi,\rho,\theta)=\frac{C_2}{C_3}[\sqrt{2}\xi+r\rho]+\rho^2-\frac{1}{C_3}$$

$$r=\frac{4C\cos^2(\theta)+D^2}{2C\cos(\theta)+D\sqrt{4C\cos^4\theta+5e^2-4e}},C=1-e^2,D=2e-1,e=\frac{1+m}{2-m} \quad (1)$$

Where C_2, C_3, and m are calculated using the uniaxial compressive strength, uniaxial tension strength, and biaxial compressive strength. ξ, ρ, and θ are Haigh-Westergaard coordinates. The steel reinforcement was modeled with an isotropic hardening plasticity model which requires defining the elastic modulus (E_s), Poisson's ratio (v), and yield strength (f_y). Values of 200 GPa and 0.3, were used for E_s, and v respectively (Kadhim, Jawdhari and Peiris), while numbers reported in section 2 are used for f_y.

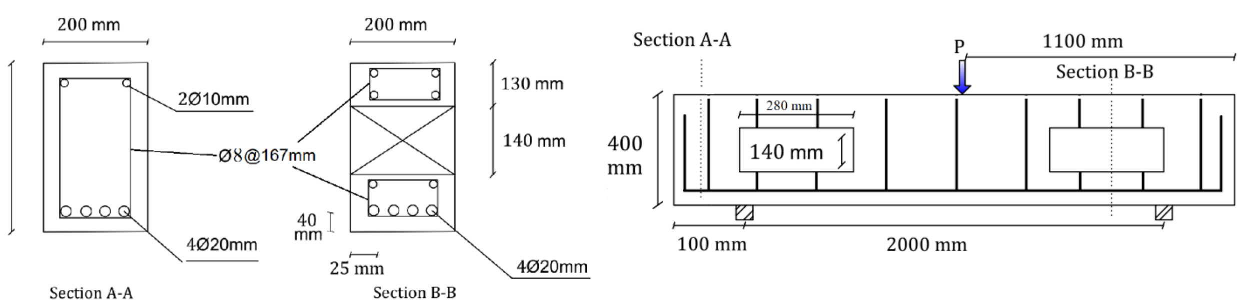
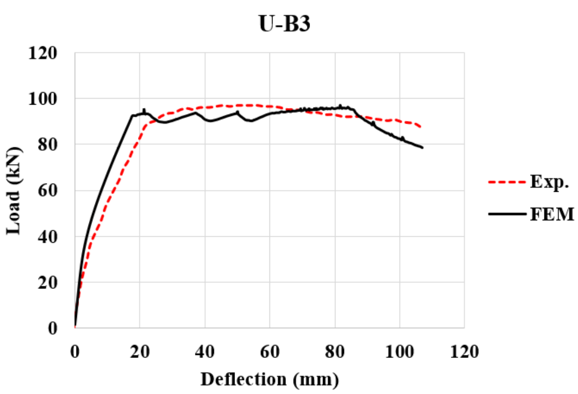


Figure 2 Configuration and cross section of Sardar et al. specimens.

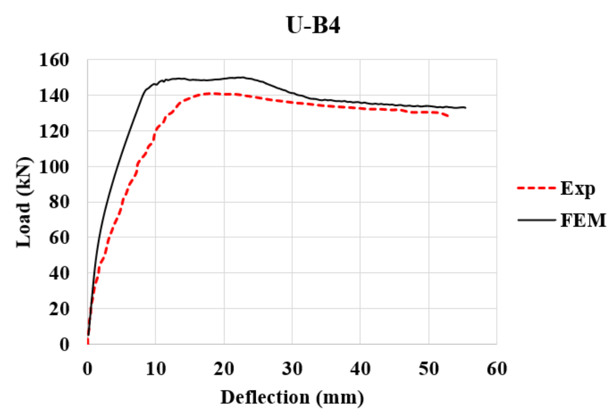
4. Results and Discussions

This section compares the FEM predictions with experimental results, to showcase the model validity. Figure 3 shows the load versus mid-span deflection (P-Δ) curves, from tests and FEM analysis, for Kodur et al. (Kodur et al.) specimens. The model response matched the experimental with an acceptable level of accuracy. The model was able to simulate various milestones such as yielding of steel and ultimate failure. Table 2 lists, for the FE and physical tests, several critical load points. The ratio between FEM and test values for cracking load, yielding load, and peak load was in average 0.9, 1.125, and 1.02, respectively, for the two specimens U-B3, and U-B4. Figure 3 displays the crack patterns from the experiments and corresponding ones (principal strains) from the model, and shows a good match between the two, attesting to the model's ability in capturing the flexural and shear failure from the beam tests.

Figure 6 shows the measured and computed load vs. deflection curve for Sardar et al. [8] specimens. Apart from a stiffer response within the cracking to yielding stage for beam B2, the model seems to corelate very well with the load deflection behavior for beams with openings. Table 3 lists, for Sardar et al. [8] specimens, the values of computed and measured peak loads and shows a ratio between the two ranging from 0.92 to 1.07. Figure 7 depicts the crack patterns observed in the experiments and corresponding ones from the FE model. In the two specimens with openings, the governing failure mode was due to diagonal cracks that emanate from the corner of the openings. The failure, while is normally a challenge to simulate numerically (Dutta, Jawdhari and Fam), is seen to be predicted very well in the developed FE model. The above results attest to the high fidelity of the model, allowing it to be used for parametric analysis on UHPC beams with transverse openings.



a) U-B3 specimen

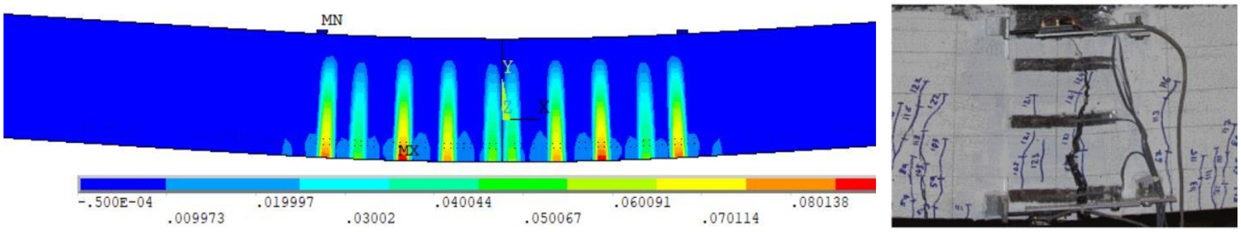


b) U-B4 specimen

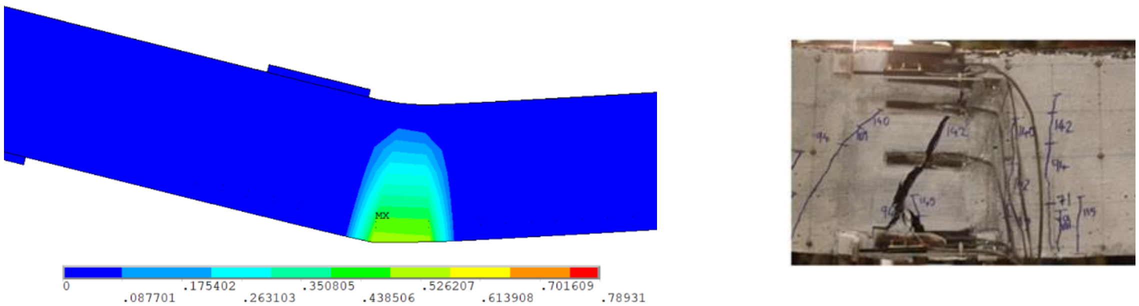
Figure 3 FEM and test comparisons, load vs. deflection curves for Kodur et al. (Kodur et al.) specimens.

Table 1 Key load comparisons between FEM and tests, Kodur et al. (Kodur et al.) experiments.

Beam		Cracking load (kN)	Rebar yielding load (kN)	Peak load (kN)
Flexural loading				
U-B3	Exp.	26.2	81.1	97.1
	FEM	20.53	92.3	96.8
	FEM/Exp.	0.78	1.13	0.99
Shear loading				
U-B4	Exp.	39.1	126.7	142.1
	FEM	40	142	150
	FEM/Exp.	1.02	1.12	1.05

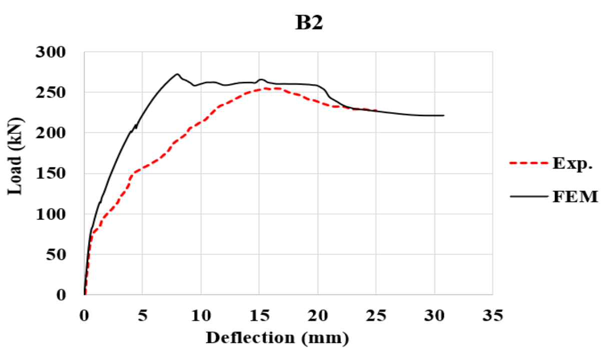


a) U-B3 specimen

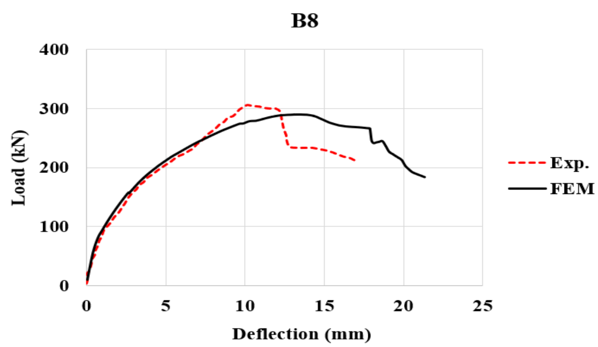


b) U-B4 specimen

Figure 4 Crack pattern comparison, Kodur et al. (Kodur et al.) specimens.



a) B2 specimen

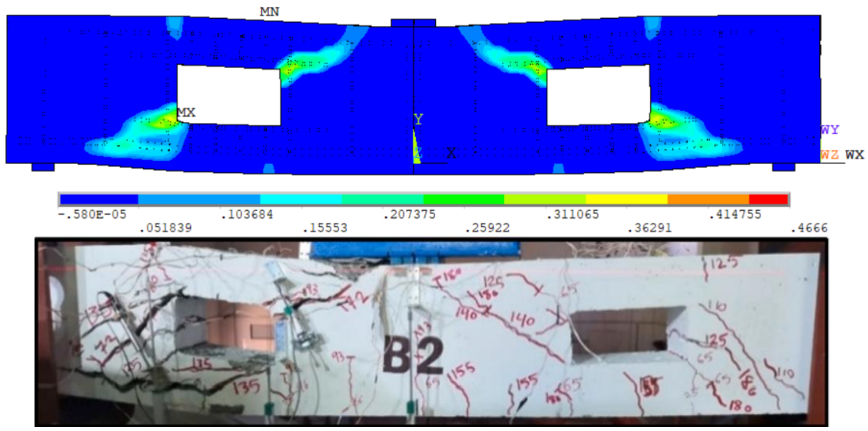


b) B8 specimen

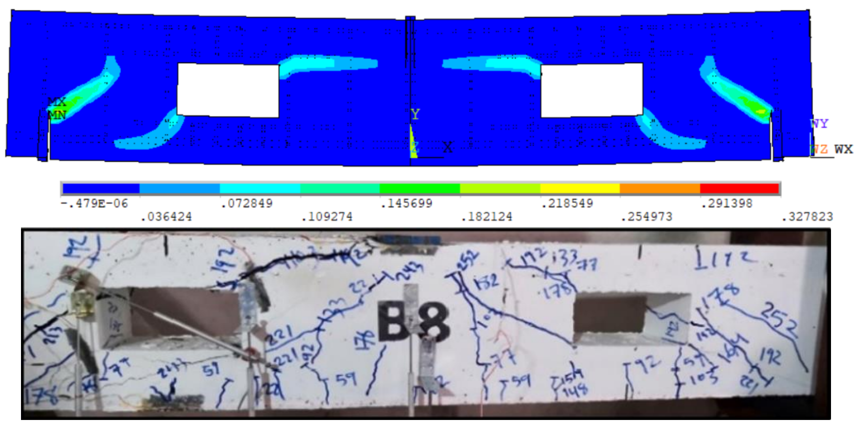
Figure 5 Load vs. deflection curve of Sardar et al. (Ali and Saeed) specimens.

Table 2 Load values ratio at peak load of Sardar et al. (Ali and Saeed) specimens.

Beam		B2	B8
Peak load (kN)	Exp.	254	305
	FEM	272	290
	FEM/Exp.	1.07	0.95



a) B2 specimen



b) B8 specimen

Figure 6 Crack pattern comparison, Sardar et al. (Kodur et al.) specimens.

5. Conclusions

In this study, three-dimensional finite element (FE) analysis was conducted using ANSYS software to simulate the response of UHPC beams with transverse openings and develop a cost-effective virtual platform to conduct further parametric studies into this newly introduced topic. The model included robust features such as large strain analysis and nonlinear material law capable of simulating cracking and crushing of concrete. Four test specimens from literature, containing various geometric, material, reinforcement, and loading conditions, were simulated, and used to validate the FE model. Results confirmed the model's ability in reproducing the experimental results, including the load deflection curves, ultimate loads, and failure modes. The maximum difference in ultimate load between predicted and test values was 7%. The model will be used evaluate the effects of various geometric and material properties and aid in the development of design tools and recommendations for placing and sizing openings within structural members made of UHPC and reinforcing techniques to mitigate the openings effects.

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