Analytical Study on Shear Response of Hollow Core Slab Subjected to Elevated Temperature using Extended Finite Element Method

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Abstract – Pre-stressed hollow core slabs are members without transverse reinforcement and are often exposed to shear failure, especially in elevated temperatures.The study of shear response in the precast pre-stressed hollow core slab is essential to study the tension-compression damage of the flexural member. The hollow core slab is subjected to typical shear failure loading conditions and the loading condition is simulated throughthe finite element model in ABAQUS. The 3D model depicting the actual shear behaviour of the hollow core slab is developed with the simple concrete damage plasticity model. Extended Finite Element Method (XFEM) analysis is used to study the propagation of cracks, from which displacement and cracking patterns are obtained for the slab with the varying depth of 200 mm, 250 mm, and 300 mm. Effect of varying depth on the shear behaviour of hollow core slab under elevated temperature are determined and the results obtained from the finite element analysis are validated for the accuracy with the ACI equation for shear behaviour and it is observed that there is good agreement in the ultimate load values obtained. The real-time behaviour of the hollow core slab under the combined effect of shear and elevated temperature is depicted with the help of crack propagation analysis. Further, the developed finite element model can be used for crack propagation study of hollow core slabs under shear failure.

Keywords – Elevated Temperature, Shear Response, Shear Failure, Simple Concrete Damage Plasticity, Crack Propagation, XFEM Analysis.

I. INTRODUCTION

The evolution of the prestressed concrete structures is impeccable. Among the various prestressed concrete structural members, a hollow core slab plays a significant role in pushing infrastructure development beyond the limits because of its economically and structurally effective characteristics. A hollow core slab is a precast prestressed component that has core holes along its width throughout the span. The hollow cores contribute to the lesser self-weight of the slab; for buildings and bridge structures, these slabs are used as roofs and decks. Atypical HC floor slab is 1.2 m wide and varies in depth between 150 mm to 400 mm based on the requirement. HC slabs are cost-effective as they use only 70% of concrete and 50% of steel used by a conventional concrete slab. In the case of a prestressed hollow core slab, anchors are not used commonly because of the splitting stress; the pre-stressing force is transferred through the bond stresses between strands and concrete [1].

Based on various studies, the hollow core prestressed slab is one of the most effective precast concrete elements. The failure of the hollow core slab under normal loading conditions occurs due to four failure modes: Flexure, Anchorage, Shear compression, and Shear tension. The current studies only consider the flexural failure of the HC slab; there is an equal chance of shear failure. The straightforward idea of shear failure and anchorage failure falls in the grey area between safety and economy. The perfect design to overcome this has not yet arrived. So, a deeper study of the behaviour of hollow core slabs in different loading conditions leading to shear crack and shear failure is necessary. This article elaborates on the various aspects of the hollow core slab subjected to shear failure under elevated temperatures. The present study attempts to develop the finite element model simulating the crack initiations and crack development in hollow core slabs subjected to elevated temperatures. The concrete is modelled with a concrete damage plasticity model to simulate the actual behaviour of concrete.

II. RESEARCH BAC0KGROUND

Many studies in the past focused on studying the behaviour of prestressed hollow core slabs subjected to fire [2–5]. Some studies specifically studied the shear performance of prestressed hollow core slabs subjected to elevated temperatures by conducting experimental investigations [6–9] and analytical investigations [10–13].Based on the literature review, it is inferred that there is limited research carried out on studying the shear response of hollow core slab subjected to elevated temperature through XFEM (Extended Finite Element Method) analysis. Hence, a new computational model incorporating the concrete damage plasticity model to simulate the actual behaviour of concrete is developed and the analysis is carried out to study the mechanism of crack propagation and failure**.**

III. MATERIAL PROPERTIES

The 3D finite element model is developed by incorporating material properties of M50 concrete grade and prestressing tendon with a tensile strength of 1375 N/mm^2. The concrete properties are taken from IS 456:2000 [19] and the prestressing tendon properties are obtained from IS: 1785 Part 1:1985 [20]. Concrete is incorporated with concrete-damaged plasticity property with maximum yield stress to simulatecrack propagation. The concrete-damaged plasticity model is based on the assumption of scalar (isotropic) damage [15] and is designed for applications in which the concrete is subjected to arbitrary loading conditions, including cyclic loading. Table 1 shows the material properties considered for the present study.

Table 1. Material properties for Finite Element analysis

Property	Values
Compressive strength of concrete – 28 days (N/mm^2)	50
Tensile strength of steel (N/mm^2)	1375
Poisson's ratio for steel	0.3
Poisson's ratio for concrete	0.2
Dilation angle	30
Eccentricity	0.1
f_{b0}/f_{c0}	1.16
k (Concrete damage plasticity parameter)	0.667
Viscocity Parameter	0.0005

IV. FINITE ELEMENT MODELLING USING ABAQUS

ABAQUS 6.14 is the version used to model the hollow core slab and proceeded further with the finite elementanalysis of the developed model [17].The slab is modeled with solid elements (C3D8R) in ABAQUS. The model is an eight-node element with three translation degrees of freedom at each node. To simulate prestressing tendons, the truss element (T3D2) is adopted. It is 2-noded elements having 3 degrees of freedom in each node (translations in X, Y, and Z directions). Frictional contact between the steel and concrete in ABAQUS is achieved by using embedded technology. The finite element model used for the present study is incorporated with concrete damage plasticity models and the XFEM crack method is used to trace the crack pattern due to shear compression and shear tension failure under normal loading. Thermal analysis is carried out to find out the heat transfer capacity and temperature distribution. The fracture energy of the material is used to determine the post–cracking behaviour and the crack is initiated when the tensile strength of the material becomes less than the maximum principal tensile stress [16].

The finite element model is created based on the standard dimension of the specimen slab as given in Table 2. The model is created using the part modelling method, and the properties are defined for concrete and prestressing tendons. The prestress tendons of 13 mm diameter are used and prestressing of the tendon is done by a cooling method where the temperature load is assigned as 0 in the initial step and as -476 in Step 1 to simulate the prestressing effect. The concrete damage plasticity method is used, and the compression and tension parameters of the M50 concrete grade for 20 mm aggregate are incorporated into the model. Hollow core slabs with the dimensions as given in Table 2 is considered for analysis, and the cross-section of the slab varies with the increase in the depth of the slab.

Table 2. Specifications of Hollow Core Slab

S. No.	Model	Width of the slab (m)	Thickness of the slab (mm)	Diameter of Tendon (mm)	Number of Tendons	Diameter of core (mm)
1	S1	1.2	200	13	Bottom 7/ Top 3	150
2	S2	1.2	250	13	Bottom 10/Top 4	190
3	S3	1.2	300	13	Bottom 11/ Top 3	240

V. HEAT TRANSFER ANALYSIS

The hollow core slab specimens are subjected to a heat flux of 27901 W/m^2 calculated based on the ISO 834 standard fire curve [21] for the temperature of 1000°C. The finite element analysis is performed using coupled thermal stress analysis and the slabs are investigated for thermal response and structural response. Temperature contour and mid–span deflection is determined from the analysis.

Thermal response

Slabs S1 (Depth = 200 mm), S2 (Depth = 250 mm), and S3 (Depth = 300 mm) are subjected to the net heat flux with a maximum temperature of 1000°C and the model is analyzed with a transient step for the maximum duration of 2 hours. The net heat flux is applied at the bottom of the slab to simulate the temperature-exposed surface, and the unexposed surface is subjected to room temperature. Figure 1 shows the temperature distribution obtained from the analysis at mid-depth for the slabs S1, S2, and S3 and it is observed that temperature progression is similar for all the slabs. The temperature decreases with the increase in the depth of the slab.

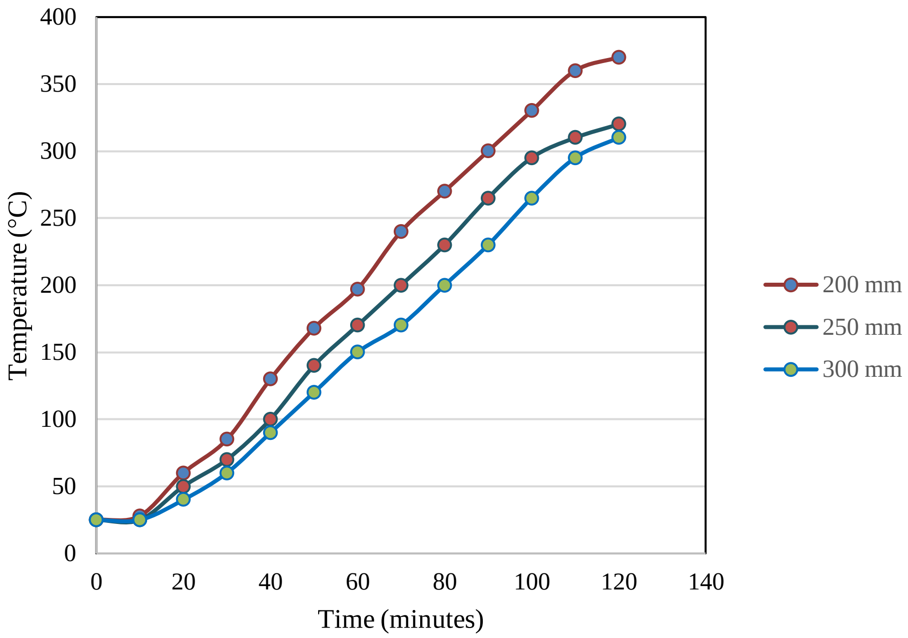

Fig 1. Temperature distribution for Slab S1, S2 and S3 at mid-depth

Structural response

The mid-span deflection of slabs S1, S2, and S3 are determined from the analytical investigation, and the stress-strain behaviour is determined. Figure 2 shows the maximum deflection obtained for the hollow core slab with varying depths. As expected, the deflection of the slab decreases with the increase in the depth of the slab. Also, load-carrying capacity increases with the increase in the depth of the slab.

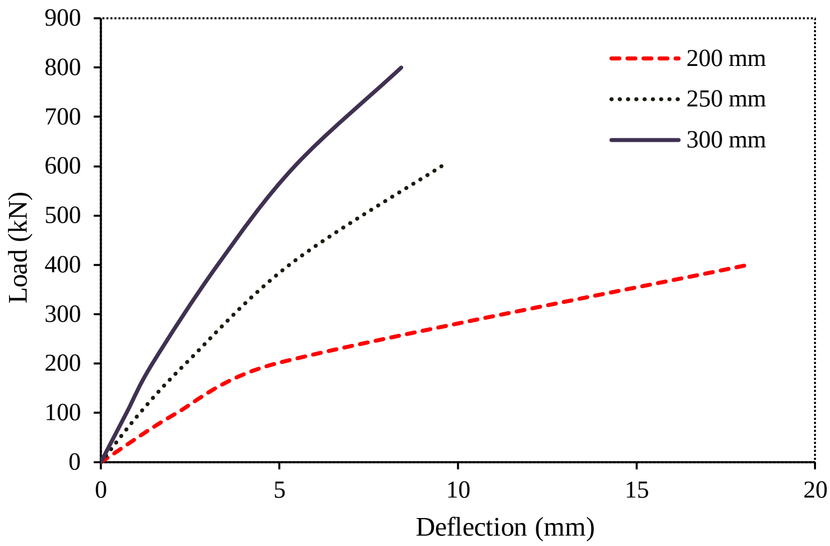

Fig 2. Load (Vs) Deflection for hollow core slab with varying depth

Table 3 shows the stress-strain values for slabs with varying depths and it is observed that a slab with 200 mm has a greater stress value at the ultimate load point compared with slabs of 250 mm and 300 mm.

Table 3. Comparison on stress-strain values for Slabs S1, S2 and S3

S1		**S2**		**S3**	
Stress (N/mm^2)	**Strain**	**Stress (N/mm^2)**	**Strain**	**Stress (N/mm^2)**	**Strain**
0	0	0	0	0	0
9.36844	5.24E-05	3.22666	1.79E-05	0.245805	1.35E-06
12.8219	7.18E-05	6.60466	3.66E-05	0.49161	2.70E-06
15.9542	8.92E-05	7.47023	4.14E-05	0.860318	4.73E-06
17.3165	9.69E-05	8.36619	4.64E-05	1.41338	7.78E-06
20.4638	1.16E-04	9.83981	5.46E-05	2.24355	1.23E-05
22.1988	1.31E-04	10.4113	5.78E-05	3.50622	1.93E-05
23.4408	1.42E-04	11.2684	6.25E-05	4.98855	2.75E-05
24.7181	1.54E-04	12.5604	6.97E-05	-	-
25.7537	1.64E-04	13.0254	7.23E-05	-	-
26.1861	0.000169	13.7236	7.62E-05	-	-
-	-	14.4225	8.01E-05	-	-

VI. SHEAR RESPONSE AND CRACK PROPAGATION

The shear response of the hollow core slab is studied by considering Rankine's and Coulomb's failure criteria as given in **Fig 3.** Based on the critical section for shear as given in the figure, the section for cracks is defined in the developed finite element model using a shell element with the depth of the crack as 100 mm. The crack propagation is simulated using XFEM (Extended Finite Element Method) analysis. The cracks are initiated at the critical section of the member and the cracks get propagated with the increase in the load using XFEM analysis.

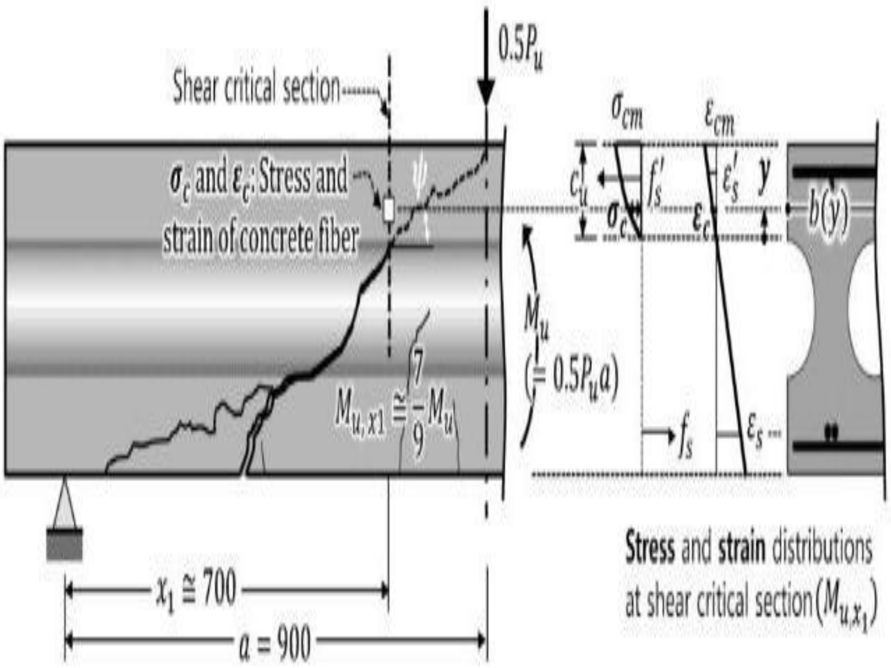

Fig 3. Shear-tension failure mechanism [14]

ACI equation for shear strength validation

The shear values and the ultimate load obtained from the XFEM analysis are validated with the values obtained from the ACI 381-05 Equation [18] for the verification of the shear strength of the member. The geometric properties required for determining the web shear strength of the hollow core slab are given in Table 4.

Table 4. Geometric properties for calculation of shear strength [9]

Slab Depth (mm)	A mm^2	I_x mm^4	Y_b mm	b_w mm	f_{pu} MPa	f'_c MPa	f'_{ci} MPa	S_w kPa
200	152000	7.17×10^8	96.6	352.5	1860	41.4	20.7	3.02
250	165230	13.2×10^9	121	244	1860	41.4	20.7	3.54
300	187000	2.19×10^9	146.0	232	1860	41.4	20.7	4.12

Fig 4 and Fig 5 showthe input given and output obtained fromthe crack propagation study, and Figure 4 shows the shear crack pattern given for the developed propagation model and the crack propagation is visible. Figure 5 shows the propagation obtained from XFEM analysis and the first crack first appears just below the loading point and travels at an angle of 30° - 35° beyond further loading. The ultimate load values are obtained from ACI 348 Equation and the results are compared with the ultimate load obtained from analytical investigation. Table 5 shows the comparison of the ultimate load and it is observed that the developed finite element model can be used as a crack propagation model for further investigation to depict the actual shear behaviour of hollow core slab subjected to elevated temperature. The percentage deviation in predicting the response is lesser for greater depth and this can be attributed to the fact that the greater depth governs the shear response for the developed model.

Table 5. Validation of XFEM results

Slab depth (mm)	Ultimate load (kN)	Crack width (mm)	ACI Equation ultimate load (kN)	% Deviation from ACI equation
200	37.7	5.2	42.8	11.9
250	49.7	3.6	55	9.6
300	74.3	1.2	81	8.3

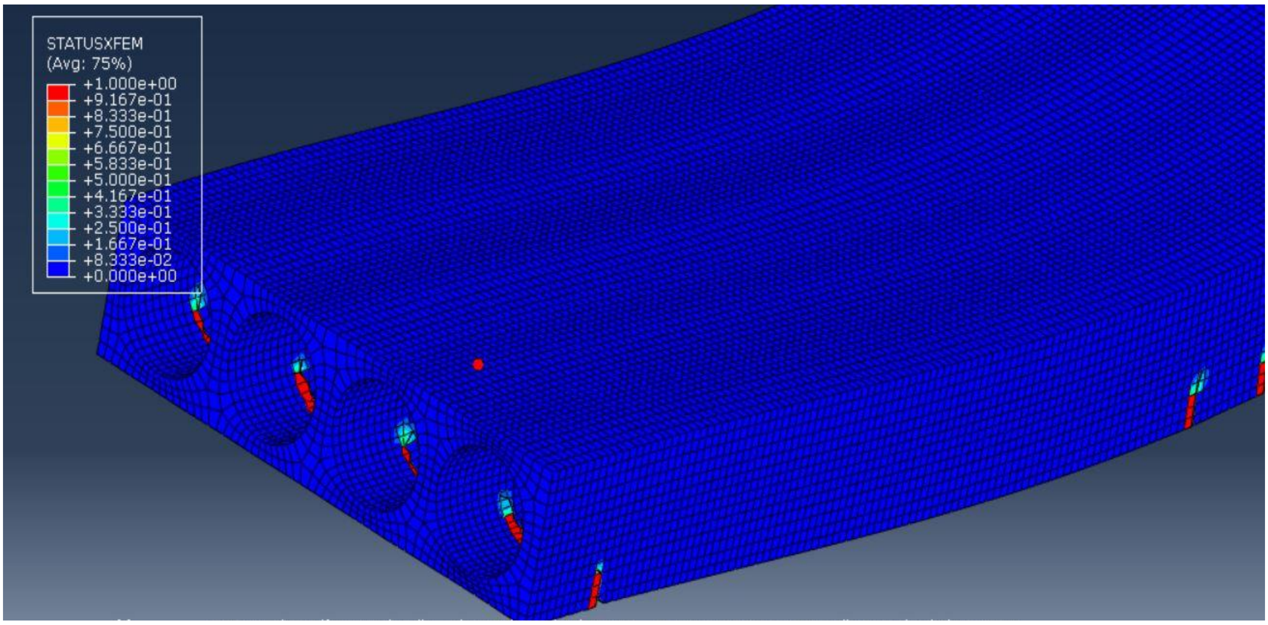

Fig 4. XFEM crack pattern defined in ABAQUS

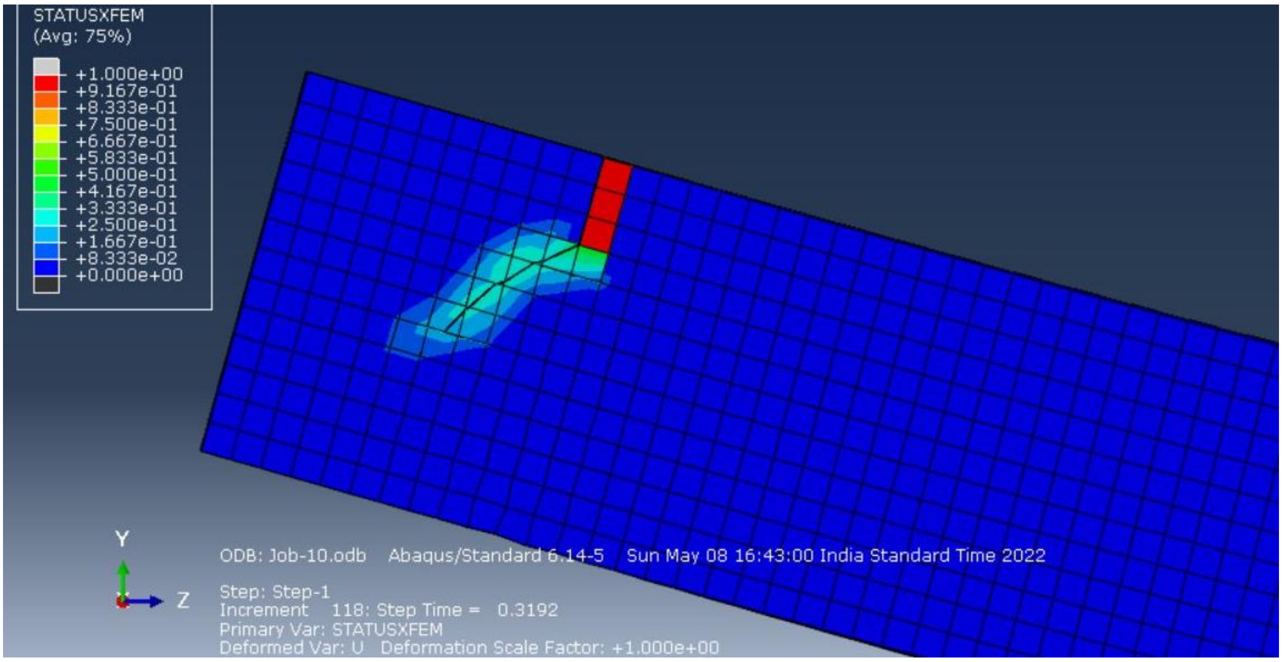

Fig 5. Shear crack propagation after XFEM analysis

VII. CONCLUSION

The concluding remarks based on the obtained results are as follows:

- The crack mechanics performedin the present work using the XFEM approach showing crack propagation and initial cracking load helps in studying the shear behaviour of prestressed hollow core slab.
- There is good agreement in the values of ultimate load obtained from the developed model and ACI Equation with the variation of 8.3% to 12%.
- The developed 3D finite element model can be used for further investigation on hollow core slabs with varying parameters and loading conditions.
- Since the proposed analytical model has a slight deviation in results compared with the numerical investigation with the increase in depth, the experimental study would be even more supportive to emphasize the results.
- A further study is required for the combination of thermal and external loading which will lead to further understanding and development of hollow core slab with maximum fire resistance and shear stability.

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