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Finite Element Analysis and Parametric Study of Fiber Reinforced Lightweight Hollow Core Slabs Under Flexure using ABAQUS

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Abstract

This research investigates the flexural behaviour of fibre-reinforced lightweight hollow core slabs (FR-LWHCS) using numerical simulations. A three-dimensional finite element (FE) model is developed to replicate the response of the HCS in a four-point bending test. The HCS consists of lightweight aggregate and contains 0.6% of synthetic fibres. The nonlinear FE analysis is conducted using ABAQUS software and validated against previously published experimental results. The numerical model accurately predicts load-deflection behaviour demonstrating good agreement with experimental findings. Additionally, the FE analysis provides insights into crack patterns and failure modes of HCS. Detailed parametric studies considering the effects of changing the reinforcement, the HCS's depth, and the shear span to depth ratio, size of core, and shape of core have also been performed.

Keywords: non-linear finite element analysis, lightweight aggregates, ABAQUS, fibre reinforced concrete, slabs, hollow core floors.

1 Introduction

Lightweight concrete finds diverse applications in producing precast elements like hollow core slabs (HCS), girders, and offshore structural components [1]. HCS are precast floor elements with longitudinal cores running along the span primarily provided to reduce self-weight. These HCS are used in a variety of applications, including flooring, wall panels, staircases, and facade components [2]. This reduces dead weight and makes the cross-section more efficient by forming I-sections. The key advantages of hollow core slabs are: decreased self-weight, quick and easy installation, increased durability, less thermal expansion, better sound insulation, and increased fire resistance [3]. The density of the concrete can be reduced further by using lightweight aggregates in place of natural coarse aggregates[4]. Under the application of loads, the hollow core slabs can crack. Crack propagation is faster in the lightweight hollow core slab as the crack passes through the softer aggregate in lightweight concrete. Adding fibres improves post-peak behaviour in compression and post-cracking behaviour in tension [5,6]. The addition of fibres limits the growth of macro and micro cracks. Most importantly, incorporating fibres improves the strength and serviceability performance of lightweight hollow core slabs [7].

Several researchers have examined the behaviour of HCS by performing numerical analysis using the finite element method [8,9]. A numerical finite element simulation of a HCS having 8900 mm length, 300 mm width, and 250 mm thickness is performed using a finite element program called LUSAS. The model is checked for suitability for different hollow shapes such as spherical, elliptical and mushroom [2]. Azzawi et al [10] performed a numerical analysis of HCS using a finite element software called ANSYS. The analysis showed that experimental results were consistent with analytical results with a 4-8% difference in ultimate loads. Furthermore, a parametric study determined the effects of concrete strength, core size, reinforcement, and load type. In this study, numerical analysis has been performed using a finite element simulation software called ABAQUS [11]. Aboul-Nour et al. conducted a numerical analysis of Layered Hollow Core Slabs (LHCS) using ANSYS, which validated experimental data for all tested slabs with less than 10% deviation [12]. Previously, researchers [13–16] have explored the flexural behaviour of normal concrete and validated it through numerical analysis using ABAQUS [17]. The application of the finite element method using ABAQUS towards lightweight concrete has been explored by previous researchers [18–20]. However, a numerical study on fibre-reinforced lightweight hollow core slabs (FR-LWHCS) has not yet been conducted.

The current study seeks to investigate the flexural behaviour of FR-LWHCS through finite element (FE) analysis. The objectives of this research include: (i) Understanding the load-deflection and failure mode response of FR-LWHCS consisting 0.6%% synthetic fibre dosage tested under a shear span to depth (a/d) 10 (under flexure). (ii) Comparing these results with experimental findings from the author's companion paper [7] and (iii) Conducting comprehensive parametric studies to investigate the effects of varying reinforcement, slab depth, a/d ratio, core size, and core shape at different a/d ratios.

2 Methods

Finite element model for simulating the non-linear behaviour of FR-LWHCS tested under 4- point bending configuration (Fig 1) is developed in the finite element software ABAQUS [17]. The model is created using different parts: hollow core slab, reinforcement, loading, and support to replicate the test setup. The dimensions of the hollow core slabs are 3400 mm in length, 600 mm in width, and 150 mm in depth.

The cross-section of the HCS used in the experiment is also provided in Fig 1. The HCS was tested at an a/d 10. The experimental work of the current study considered the HCS to be reinforced with five steel bars of 10 mm diameter corresponding to ρ=0.7%. The core diameter of the HCS used for validation core is 106 mm.

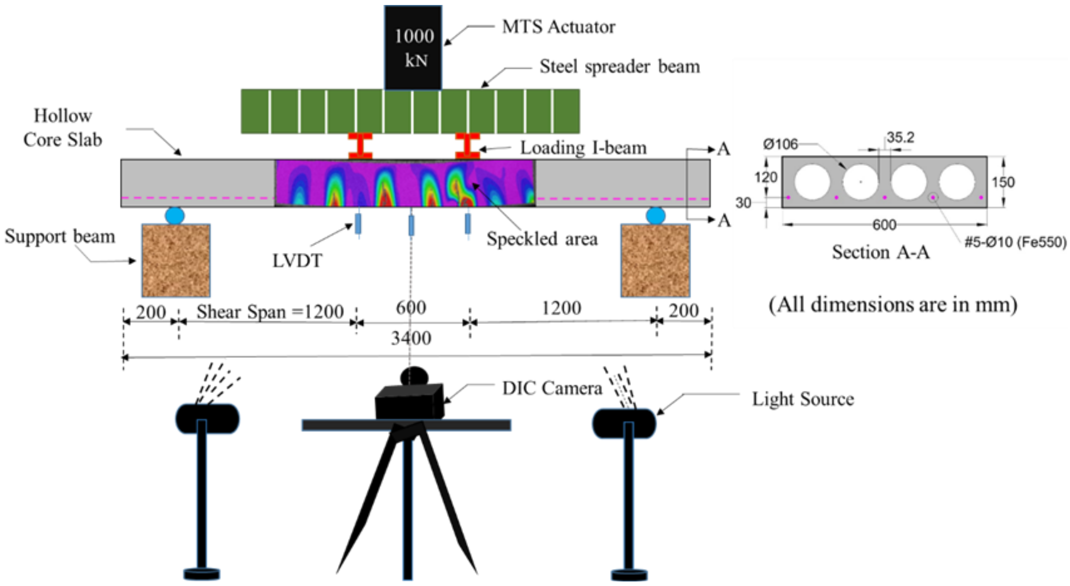

Fig 1. Geometrical configuration and test setup of the tested HCS and its cross-section

The developed FE model is depicted in Fig 2. The first one is a hinged support that stops rotation around the Z-axis and displacement in all directions. The second support is a roller that limits displacements along the X and Y axes as well as rotation around the Z-axis. The entire line of nodes was deflected downward by 150 mm. Following a mesh sensitivity analysis, the HCS analysis used an ideal mesh size of 20 mm.

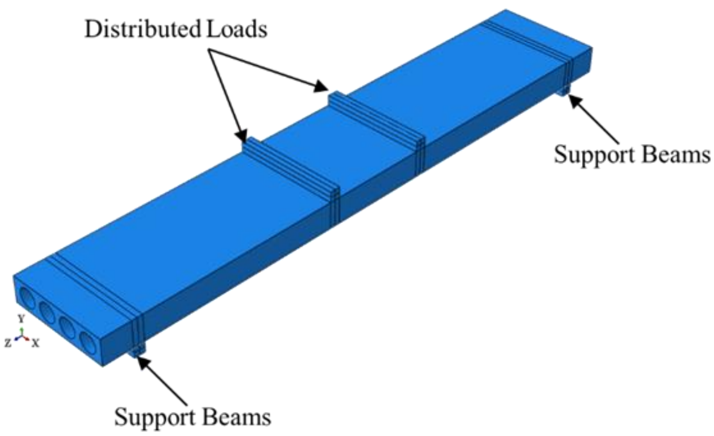

Fig 2. Developed FE model

The concrete damage plasticity (CDP) model, that precisely reflects the behaviour of concrete material, is employed for simulating the damage behaviour of concrete. The CDP model was established on the principles introduced by Lubliner et al. [21] and Lee and Fenves [22]. In this study, the CDP model defines 2 fundamental failure mechanisms such as concrete crushing in compression and cracking in tension. The compressive stress-strain response of Fibre-reinforced lightweight concrete (FRLWC) consisting of lightweight aggregate and 0.6% synthetic fibre dosage is shown in (Fig 3 (a)) is considered for material modeling based on the experimental results of the author's companion paper (Sahoo et al.) [1]. The tensile stress-strain curves shown in (Fig 3 (b)) generated by performing inverse analysis are used to model the tensile response of the concrete [23].

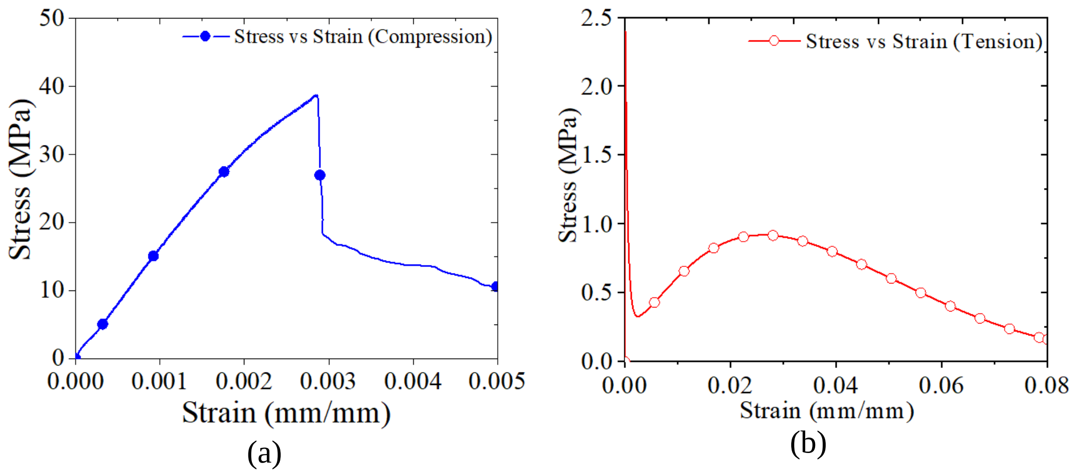

Fig 3. Material constitutive model for FRLWC (a) in compression [1] (b) in tension [7]

The CDP model can be used to represent progressive material damage because damage is an important element influencing concrete nonlinearity. The damage variable ranges from 0 to 1. Damage in compression (d_c) and in tension (d_t) is calculated according to Equation (1) and Equation (2) from Huang and Liew [24]. Stress, strain, and modulus of elasticity all have an impact on concrete damage variables, and the damage parameters under consideration reflect this.

$$d_c = 1 - \frac{\sigma_c + n_c f'_c}{[E_c\,(n_c\,\sigma_c\;/\;E_c + \varepsilon_c)]} \tag{1}$$

$$d_t = 1 - \frac{\sigma_t + n_t f_t}{[E_c\,(n_t\,\sigma_t\;/\;E_c + \varepsilon_t)]} \tag{2}$$

where,

σ_c = Compressive stress, σ_t = Tensile stress, f'_c = Cylinder compressive strength of concrete, E_c = Modulus of elasticity of concrete, ε_c = Concrete strain in compression. ε_t = Concrete strain in tension, n_c = compressive stress- strain response constant and n_t = 2 tensile stress- strains responses constant.

The CDP model takes into account various parameters such as dilation angle (ψ)=40, eccentricity (ε)=0.1, the ratio of biaxial yield stress to uniaxial yield stress

(f_{bo}/f_{co}) =1.16, viscosity parameter (μ)=0.0005 and the coefficient to obtain the shape of the deviatory cross-section (K)=0.667 are considered for fibre-reinforced lightweight concrete from Al-Thairy et al. [19].

3 Results

The accuracy of the proposed FR-LWHCS models is confirmed by comparing their anticipated load-mid span displacement curves, failure modes, and crack patterns to those obtained from experimental test results in the author's published paper [7] on HCS.

3.1 Validation of Load-Deflection Behaviour and Failure Mode

The model created predicts the load- mid span deflection behaviour with high accuracy. The results of the FE simulation show that the performance of lightweight HCS with 0.6% synthetic fibres can be anticipated using ABAQUS.

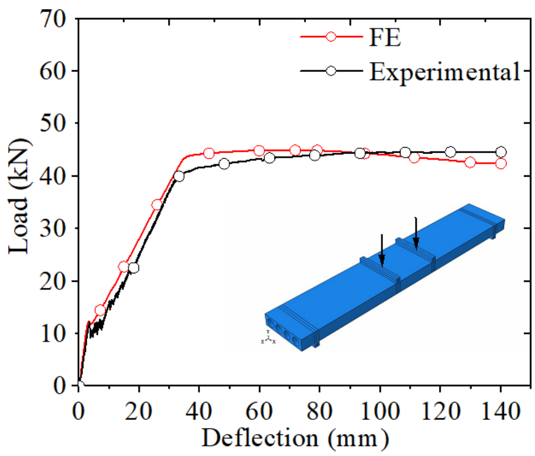

Fig 4. Load vs Deflection (FE vs Experimental)

The load-deflection behaviour of HCS determined from experiment and FE are compared in Fig 4. The summary of the FE results and experimental results is shown in Table 1. The discrepancy between peak load determined by the test findings and the findings of FE is within 5%, demonstrating that the modelling approach is efficient. The cracking load determined by FE remained similar. Similarly, the energy absorption capacity (area under load-deflection curve) calculated from experimental findings and FE simulation are within 5%.

Table 1. Summary of experimental and FEM results

CL_{EXP} (kN)	CL_{FE} (kN)	PL_{EXP} (kN)	PL_{FE} (kN)	SE_{EX} (Joule)	SE_{FE} (Joule)	$\frac{CL_{EXP}}{CL_{FE}}$	$\frac{PL_{EXP}}{PL_{FE}}$	$\frac{EA_{EXP}}{EA_{FE}}$
12.2	12.1	44.6	44.9	5404.0	5515.0	1.01	0.99	0.98

Note: CL_{EXP} = Experimental cracking load, CL_{FEM} = FE cracking load, PL_{EXP} = Experimental peak load, PL_{EXP} = FE peak load, EA_{EXP} = experimental energy absorption capacity, EA_{FEM} = FE energy absorption capacity.

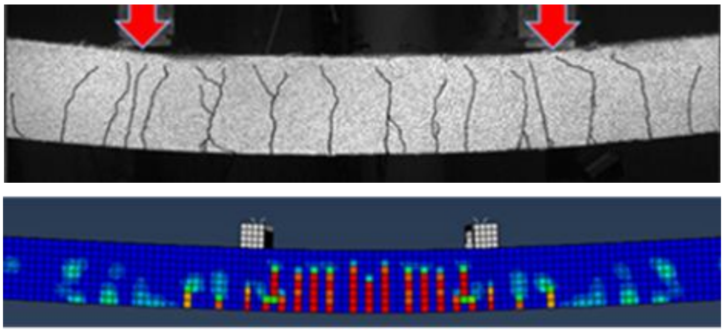

Fig 5. Comparison of failure mode

Flexural cracks were observed in the FE analysis which agrees with the tested results (Fig 5). The major cracks originated at a constant moment zone of the HCS. Hence, the FE model correctly predicted the crack patterns and failure mode.

3.1 Parametric studies

The developed numerical models have been employed to investigate the effect of change in reinforcement ratio (ρ), influence of depth of HCS, change in core diameter (ϕ), change in shape of the core and variation in shear span to depth ratio on the load vs mid-span deflection of the FR-LWHCS.

3.1.1 Effect of change in reinforcement ratio

The experimental work of the current study considered the HCS to be reinforced with five steel rebars of 10 mm diameter resulting in a reinforcement ratio ρ=0.7%. The examination for the effect of the change in reinforcement on the load capacity were evaluated by varying the reinforcement ratios of the HCS. Three reinforcement ratio considered for the present research are 0.45%, 0.7% and 1% The other conditions for the HCS such was kept similar to the validated models. Fig 6 depicts the influence of varying reinforcement ratios on load-deflection behaviour. The cracking load and peak load at ρ=1% increased by 8% and 38%, respectively, compared to ρ=0.7%. The cracking and peak load decreased by 9% and 45%, respectively, in ρ=0.45% compared to ρ=0.7%. The HCS failed in flexural mode in all the cases which agrees with experimental failure modes.

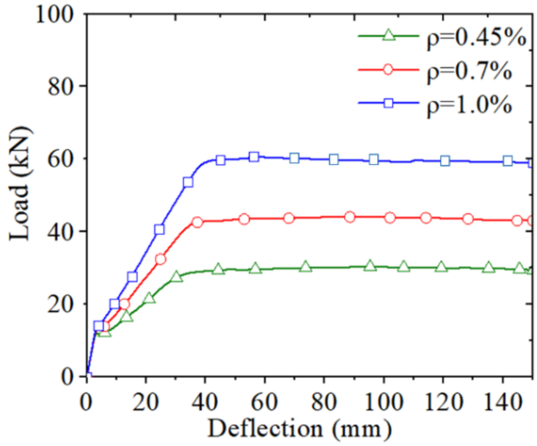

Fig 6. Effect of change in reinforcement ratio on load-deflection behaviour

3.1.2 Influence of depth of HCS

The experimental work of the current study considered the HCS of 150 mm depth. To evaluate the effect of changing the slab depth on load capacity, the HCS depth was varied to 175 mm and 200 mm. The other conditions for the HCS were kept consistent with the validated models. The influence of change in depth on load-deflection behaviour is illustrated in Fig 7.

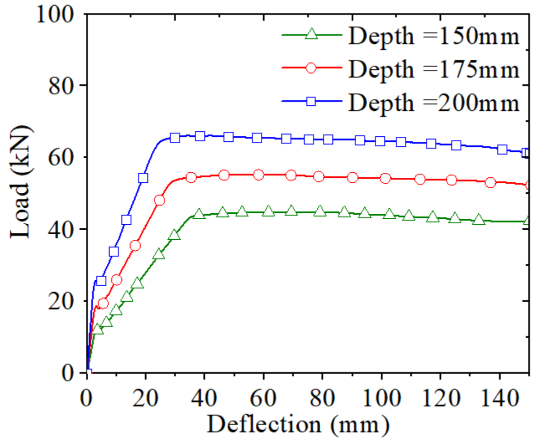

Fig 7. Effect of depth of HCS on load-deflection behaviour

It was seen that a depth increase to 175 mm led to a 42% improvement in the cracking load and a 26% improvement in the peak load, compared to the 150 mm depth. With the depth increasing to 200 mm, the cracking and peak loads improved by 100% and 52%, respectively. The analyzed specimens failed in flexure mode which agrees with experimental results.

3.1.3 Effect of core diameter

The experimental work in this study focused on HCS with a core diameter (ϕ) of 106 mm. To evaluate the impact of core diameter on load capacity, the diameter of the core was varied to 116 mm and 96 mm, while keeping all other conditions consistent with the validated models. It is observed that the load-deflection behaviour remains unchanged with the change in diameter of the core which is shown in Fig 8.

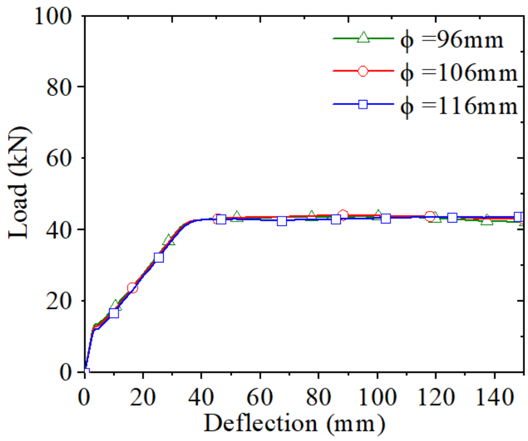

Fig 8. Effect of core diameter on load-deflection behaviour

3.1.4 Effect of shape of the core

The current study's experimental work took into account the circular shape of the core, which had a diameter of 106mm. To assess the effect of shape modification, a square core form of 94 mm x 94 mm was modelled with an equivalent area of circular core while keeping all other HCS parameters constant, according to validated models. Fig 9 displays a load-deflection comparison between circular and square-shaped cores. It was discovered that changing the shape of the core had a minimal effect on the load-deflection behaviour. The cracking load is unchanged, while the peak load is marginally reduced. Both types of HCS failed at flexure.

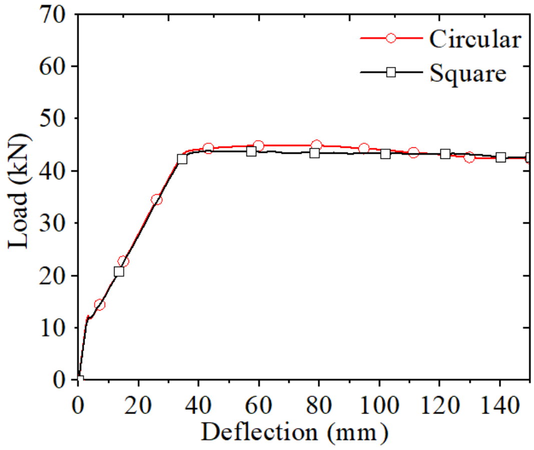

Fig 9. Effect of core size on load-deflection behaviour

3.1.5 Effect of a/d ratio

To examine the influence of varying a/d ratio on the load-deflection behaviour of HCS, six a/d ratios were taken into account: 2, 3.5, 5, 7, 8.5 and 10 and presented in Fig 10. It is observed that both cracking and peak loads increased as the a/d ratios decreased. The HCS had a cracking load of 12 kN at a/ d ratio 10. Compared to it, the cracking load increased by 13 %, 40 %, 100 %, 230 %, and 430 %, respectively, at a/d ratios of 8.5, 7, 5, 3.5, and 2. The peak load for the HCS analyzed at a/d ratio of 10 was found out to be 44.9 kN. However, it increased by 24%, 44%, 100%, 160%, and 250% respectively when analysed at a/d ratio 8.5, 7, 5, 3.5 and 2 respectively. The HCS exhibited shear failure at a/d ratios below 3.5, flexural shear failure at a/d between 3.5 and 7, and flexural failure at a/d ratios above 8.5.

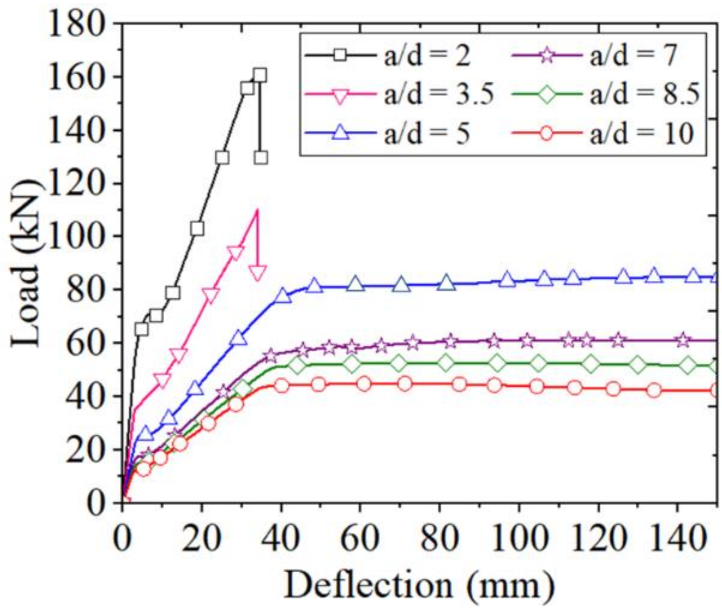

Fig 10. Effect of a/d ratio on load-deflection behaviour

4 Conclusions

Numerical analysis of FE models was conducted to investigate the flexural behaviour of fibre-reinforced lightweight hollow core slab. The numerical model was validated using ABAQUS software by comparing its load-mid span deflection behaviour, failure modes with the previously published experimental findings. The validated model was then employed to study the effect of change in reinforcement ratio, the diameter of hollow core slab, size of the core, shape of the core and a/d ratio. The finite element results were well aligned with experimental findings. It was observed that the load capacity increased significantly with increased reinforcement ratio and depth of the slab. However, the behaviour of load-deflection curve remains unchanged with a change in the shape and size of the core. It was also observed that with decrease in a/d ratio the load capacity increased. The HCS exhibited shear failure at a/d ratios below 3.5, flexural shear failure at a/d ratios between 3.5 and 7, and flexural failure at a/d ratios above 8.5.

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