A Thesis Submitted to the Sylhet Engineering College for the Degree of

Bachelor of Science in Civil Engineering

Flexural Performance analysis of UHPC-NC Composite T-Beam

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The thesis titled **“Flexural Performance Analysis of Composite T-Beam”** submitted by **Trishna Datta and Rinky Deb**; Student ID: **2019333528 and 2019333563**; Session **2019-2020**, to the Department of Civil Engineering, Sylhet Engineering College, has been accepted as satisfactory in partial fulfillment of the requirement for the Degree of Bachelor of Science in Civil Engineering and approved as to its style and contents.

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Abstract

Abstract: Ultra-high-performance concrete (UHPC), a novel cement-based material known for its superior mechanical properties and durability, has gained significant attention in modern construction and structural rehabilitation. In composite beam design, optimal flexural performance can be achieved by placing the UHPC layer in the tensile zone (bottom) and the normal-strength concrete (NC) layer in the compression zone (top), forming what is known as a UHPC-NC composite beam. This study investigates the flexural behavior of reinforced UHPC-NC composite beams, focusing particularly on the influence of varying UHPC layer thicknesses. This paper presents a finite element (FE) analysis of Normal Concrete-Ultra High-Performance Concrete (NC-UHPC) composite T-beams under monotonic loading using ABAQUS. A numerical model is validated against existing experimental data with a 360 mm UHPC thickness. Parametric studies are conducted by varying the UHPC layer thickness (150 mm, 200 mm and only for normal concrete without UHPC). Results show that increasing UHPC thickness enhances flexural strength and stiffness. This study demonstrates the effectiveness of composite action in improving performance and can guide optimization of UHPC use in bridge decks and structural retrofits.

Keywords: Ultra-high-performance concrete (UHPC); composite beam; monotonic loading; T-beam; flexural behavior.

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Chapter 1: Introduction

1.1 Introduction:

Ultra-high-performance concrete (UHPC), a new cement-based material known for its high mechanical strength and excellent durability, has been widely applied in construction and rehabilitation projects in recent years.[7]

Ultra-High Performance Concrete (UHPC) has emerged as a promising material in modern structural engineering due to its superior mechanical properties, such as high compressive strength, enhanced durability. When combined with Normal Concrete (NC) in composite structural elements, UHPC can significantly improve the performance and service life of beams, bridge girders, and other flexural members while optimizing material usage and cost-effectiveness.

Ultra-high-performance concrete (UHPC) and other types of HPFRCC, such as engineered cementitious composites and ultra-high toughness cementitious composites (UHTCC), have been combined with NC elements to serve as composite beams [14-17]. Much research has been done on the composition, mechanical properties, and behavior of structures built using UHPC. Abbas et al. [8] reviewed studies related to the mix design and composition of UHPC, summarizing data on different binders, superplasticizers, aggregates, water-cement ratios, and steel fibers. The study also reviewed experimental research related to the fresh properties and mechanical properties of UHPC.

Flexural behavior refers to how a structural element—such as a beam—responds to bending loads. A flexural test (typically using a four-point or three-point bending setup) helps to determine the stiffness, cracking behavior, yield strength, ductility, and ultimate flexural capacity of a beam. In this test, the beam is simply supported at both ends, and load is applied at one or two points symmetrically to create a pure bending zone in the middle.

Flexural testing is particularly important for UHPC-NC composite beams because:

- It helps to understand the role of the UHPC layer in resisting bending and cracking.
- It reveals the crack initiation and propagation patterns.
- It allows comparison between different configurations (e.g., various UHPC layer thicknesses).
- It is essential for validating finite element models and predicting real-world behavior under service loads.

Therefore, flexural tests are a fundamental tool in both experimental and numerical studies for evaluating and optimizing structural performance.

RC beams strengthened with a thin UHPC strip (10 mm) under fatigue load were successfully rehabilitated despite the severity of the damage [9]. The use of a thin UHPC layer (5 mm) enhanced the flexural behaviour and the flexural bearing capacity of composite beams by about 135% [18].

An analytical model was proposed to predict the fatigue response of damaged beams strengthened with ground granulated blast-furnace slag (GGBS) based ultra-high performance concrete (UHPC) strips. The critical parameter controlling the fatigue behaviour of damaged beams strengthened with UHPC strips were a degree of damage in the reinforcing bars and thickness of GGBS based UHPC strips (5, 10 and 15 mm). The fatigue life of strengthened beams with GGBS based UHPC strip significantly improved with an increase of strip thickness [19].

Flexural behavior of reinforced concrete beams is a fundamental aspect of structural performance, particularly under service loads where bending dominates. T-beams, due to their flange-web configuration, are especially sensitive to flexural stresses, making their performance under bending a key design and evaluation criterion. Experimental flexural testing through four-point bending setups provides valuable insights into cracking behavior, stiffness degradation, ductility, and ultimate load capacity. However, full-scale flexural experiments are resource-intensive and often limited in terms of parameter variability. Numerical simulation using Finite Element Modeling (FEM) offers a viable alternative to assess flexural performance efficiently. By implementing nonlinear material models and proper boundary conditions, FEM allows for accurate prediction of stress distribution, crack initiation zones, and failure mechanisms in composite beams. Furthermore, it enables parametric studies—such as varying UHPC layer thickness—without the need for physical testing, making it a cost-effective and versatile tool for understanding and optimizing flexural behavior in UHPC-NC composite T-beams.

Wang et al. (2023) [5] investigated the fatigue life of UHPC-NC composite T-beams experimentally. Eleven beams were tested under monotonic and cyclic loading with varying UHPC layer thickness (0, 200, and 360 mm) and stated that the fatigue life improved with the increasing of UHPC layer.

Flexural performance of UHPC-NC composite beams is a key parameter in the design of structural elements, particularly in bridge decks and floor systems where bending is the dominant mode of loading. Understanding the flexural behavior is essential for evaluating load-carrying capacity, cracking resistance, stiffness degradation, and ductility. Although several experimental studies have provided valuable data on the static flexural response of such composite beams, full-scale testing remains labor-intensive, costly, and limited in scope. Additionally, physical experiments often restrict the ability to explore a wide range of design variables such as UHPC layer thickness, reinforcement configuration, and material properties. In this context, numerical simulation using Finite Element Modeling (FEM), particularly through software like ABAQUS, offers a highly effective alternative. It enables detailed analysis of stress distribution, crack development, and ultimate failure modes under flexural loading. Furthermore, numerical approaches facilitate parametric studies, model validation, and optimization of composite beam designs, making them indispensable tools in modern structural engineering research.

Therefore, this study aims to perform a detailed flexural performance analysis of UHPC-NC composite T-beams under four-point bending using Abaqus. Our study involves validating the proposed model by simulating one beams using data from **Jue Wang et al. [5]** to ensure accuracy and reliability.Additionally, we performed a parametric analysis by simulating new composite beams with varying UHPC layer thicknesses to evaluate their impact on flexural performance. The main objectives are to examine the effect of UHPC layer thickness on the flexural performance of composite T-beams by analyzing the load–deflection response under monotonic loading using finite element simulation. The study aims to compare flexural stiffness, cracking behavior, peak load capacity, ductility, energy absorption characteristics, and failure modes across different configurations. These parameters, extracted from the load–deflection curves, provide a comprehensive understanding of how UHPC thickness influences the bending response and structural efficiency of the composite beams. The outcomes of this research are expected to contribute to the better design and optimization of UHPC-NC composite beams, ensuring improved durability and long-term structural performance.

1.2 Scope of the study :

The primary scope of this study is to investigate the flexural behavior of Ultra-High Performance Concrete (UHPC) and Normal Concrete (NC) composite T-beams under monotonic loading. The study focuses on the effect of UHPC layer thickness, and loading level using finite element simulation in ABAQUS through four-point bending tests. This research contributes to the practical implementation of UHPC in structural strengthening and retrofitting.

1.3 Objective :

1. To simulate four-point bending tests of UHPC-NC composite beams using ABAQUS software.

2. To evaluate the influence of different UHPC layer thicknesses on the flexural performance of beams.

3. To compare numerical simulation results with experimental outcomes from literature.

Chapter 2: Literature Review

2.1 Introduction

Flexural performance is a critical aspect in the design and assessment of reinforced concrete structural elements such as bridge girders, floor slabs, and T-beams, where bending is the predominant loading mechanism. With the development of high-performance materials, Ultra-High Performance Concrete (UHPC) has gained considerable attention for improving flexural behavior due to its exceptional compressive strength, high tensile capacity, and crack resistance. Integrating UHPC with Normal Concrete (NC) in layered composite beams offers a practical and economical solution to enhance structural efficiency while optimizing material usage. In particular, using UHPC in the tension zone of T-beams improves flexural stiffness, delays cracking, and increases ultimate load capacity. This chapter reviews previous studies on the flexural behavior of UHPC-NC composite beams, focusing on both experimental and numerical investigations, and identifies research gaps related to parametric studies involving UHPC layer thickness.

2.2 Flexural Behavior in Reinforced Concrete Structures

Flexural behavior is a fundamental concern in reinforced concrete (RC) structures, particularly in elements such as beams, slabs, and bridge girders where bending dominates the load response. When subjected to service loads, RC beams experience tension in the bottom fibers, leading to crack formation, stiffness reduction, and eventual yielding of reinforcement. The distribution of stresses across the depth of the section and the development of flexural cracks significantly influence the load-carrying capacity and serviceability of the structure. Inadequate flexural performance can result in excessive deflection, early cracking, and brittle failure, which compromise both safety and durability. Therefore, understanding and enhancing flexural behavior is essential for ensuring long-term structural integrity, especially in demanding applications like highway bridges and high-rise buildings.To address this, many researchers have studied the use of fiber-reinforced concretes and high-performance cementitious materials to enhance the tensile performance in the tension zone [1].

2.3 Development and Benefits of UHPC

The development of UHPC can be traced back to the early 1980s. After decades of research, UHPC has emerged as a highly innovative product in the field of concrete technology, distinguished by its exceptional mechanical properties and superior durability. The service life of reinforced concrete structures is largely dependent on the durability of the concrete, and the excellent durability properties of UHPC can lead to a significant increase in service life, thus reducing maintenance costs [2].
As the Federal Highway Administration (FHWA) reports: UHPC is a cementitious material formulated by mixing Portland cement, fine silica sand, silica fume, quartz flour, high-range water reducer, discontinuous internal steel or organic fibers, and less than 0.25 water-to-cement (W/C) ratio [3].
UHPC is a dense, fiber-reinforced concrete known for its compressive strength (>120 MPa), tensile strength (>10 MPa), and low permeability. These properties make UHPC ideal for structural strengthening and repair. It can significantly delay crack formation and reduce the stress in embedded reinforcement, thus enhancing the fatigue life of structural elements [4].

The properties of UHPC such as strength, ductility, durability and aesthetic design flexibility, make it a smart material. Thanks to these unique properties of UHPC, various tasks can be achieved, such as load-bearing elements with thinner cross-sections (comparable to steel profiles), curved and more complex and sophisticated shapes .There is many successful applications of UHPC in buildings, bridges, and wind turbine towers in the world.

Nonetheless, there are some disadvantages associated with UHPC, particularly concerning shrinkage and cracking during the early stages of concreting due to autogenous and drying shrinkage. Consequently, there has been limited research conducted on the long-term behaviour of this concrete. Additionally, UHPC is more costly than normal concrete, raising concerns about its viability when unconventional concrete can economically meet design requirements. The primary limitation to the broader utilization of UHPC is the high cost of several expensive raw materials in the mix.

2.4 Previous study on UHPC-NC Composite Beams

In recent years, UHPC has been strategically applied to the tension zone of beams in the form of a bottom layer, forming a UHPC-NC composite beam.

Habel et al. (2006) [2] and Li et al. (2020) [3] demonstrated that the composite behavior of these beams depends highly on the interface bonding and the UHPC layer thickness. Properly designed composite beams can achieve flexural capacity similar to full-UHPC sections at reduced cost.

Wang et al. (2023) [5] conducted an extensive experimental study on T-beams combining UHPC and NC layers, focusing on fatigue performance. Eleven beams were tested under monotonic and cyclic loading with varying UHPC layer thickness (0, 200, and 360 mm), reinforcement ratio, and loading levels. Their results showed that:

- Increasing UHPC layer thickness significantly improved fatigue life
- A point of diminishing returns was observed beyond a certain thickness (e.g., from 200 to 360 mm)
- Higher reinforcement ratio (1.786%) led to about 3.2 times longer fatigue life compared to 1.184%
- UHPC helped reduce steel stress and delayed crack propagation

These findings suggest that both UHPC thickness and reinforcement configuration must be optimized for maximum fatigue resistance.

The interface between UHPC and NC is critical for composite action. Weak bonding may cause delamination or slip, reducing structural efficiency.

Graybeal and Baby (2013) [10] studied the shear bond behavior of UHPC when cast on existing concrete. They investigated surface roughness, moisture condition, and curing method. The results highlighted:

- Proper surface treatment (e.g., sandblasting or grooving) increases shear strength by up to 50%.
- Wet surface condition before casting UHPC improves bonding.
- Interface shear strength ranged from 4 MPa (smooth) to 12 MPa (rough).

These findings provide essential guidance for designing UHPC-NC composites, especially in rehabilitation or retrofitting scenarios.

Zhang & Yang et al. (2022) [11] stated that the flexural behavior of UHPC-NC layered beams is significantly influenced by the interfacial bonding strength, which is represented by cohesive stiffne**ss** in finite element models. When the cohesive stiffness is below 3, the beam is prone to delamination failure, resulting in reduced load capacity and larger mid-span deflection. However, when the cohesive stiffness exceeds 3, the beam behaves more like a monolithic UHPC section, indicating a strong bond and a flexural failure mode.Additionally, using NC as a core layer between two UHPC skins can maintain structural performance while significantly reducing material cost. This layered configuration offers a cost-effective alternative to full-UHPC beams without compromising flexural capacity.

Zhang & Zhu et al. (2020) [12] have highlighted that, when strengthening existing RC flexural members using UHPC overlays, two critical aspects must be considered in numerical modeling:

(1) The presence of pre-existing cracks in the RC substrate, and
(2) The bond interface behavior between the RC and the UHPC layers.

A finite element (FE) model was developed by researchers to simulate these phenomena by incorporating geometrical discontinuities representing cracks in the RC slab. Additionally, based on recent bond strength studies between UHPC and conventional concrete, a specialized interface model was introduced in the simulation.

The developed FE model was validated against experimental results published earlier by the same authors, and the numerical outcomes showed good agreement with test data. A parameter study was also conducted to examine the influence of various strengthening configurations and interface conditions.

Key findings from the study include:

- Pre-existing cracks significantly reduce the ultimate flexural capacity of the strengthened RC member and should not be ignored in simulation.
- The interface model used in the FE simulation accurately captured the interlayer behavior between UHPC and RC.
- The modeling approach enables efficient optimization of UHPC thickness, location, and bond characteristics without requiring large-scale physical testing.

This study emphasizes the importance of incorporating realistic cracking patterns and bond models when simulating UHPC-strengthened RC beams or slabs to ensure reliable structural predictions.

Tong & Yuan et al. (2021) [13] investigated the structural behaviors of UHPC-NC composite beams experimentally. The FE models are also constructed, which integrates the localizing nonlocal damage model for the UHPC and the NC, the Menegotto-Pinto steel model, and the proposed coupled cohesive-friction model. It is demonstrated that the FE models satisfactorily capture the composite beams' behaviors. Alongside, the evolution of normal and tangential tractions along the interface are presented, which offer a valuable insight to the interfacial behavior. It reveals that the UHPC-NC bond strength is critical and to some extent would govern the composite member's overall responses.

2.5 Research Gap and Significance of This Study

While several studies have investigated beams with UHPC layers, most focused on 200 mm and 360 mm thicknesses. Intermediate thicknesses such as 150 mm and 250 mm have not been thoroughly explored. Furthermore, existing experiments are limited in scale, and numerical simulation remains a cost-effective way to assess additional configurations.

This study addresses these gaps by numerically modeling T-beams with 150 mm, 200 mm, and 250 mm UHPC layers under flexural performance using ABAQUS. The outcomes will contribute to the understanding of optimum UHPC layer thickness for flexural performance and validate the application of nonlinear FEM tools in flexural performance.

Chapter 3: Methodology

3.1 Overview

This study focuses on the flexural performance of composite T-beams constructed with Ultra-High Performance Concrete (UHPC) and Normal Concrete (NC). Finite element simulations of four-point bending tests were carried out using ABAQUS software. The main objective was to investigate the influence of UHPC layer thickness on flexural behavior. Three different UHPC layer thicknesses — 150 mm, 200 mm, and— were modeled and analyzed.

3.2 Geometry and Material Properties of the Beam Model

The beam geometry was designed based on the experimental setup in the reference study, Wang et al. (2023), with some parameters customized for the simulation:

- **Total beam length:** 4400 mm
- **Span length:** 4000 mm
- **Total depth:** 500 mm
- **Flange width:** 400 mm
- **Constant moment region:** 1000 mm
- **UHPC layer thicknesses:** 150 mm, 200 mm,

Each model was defined as a T-shaped cross-section with the UHPC layer at the bottom and NC on top.

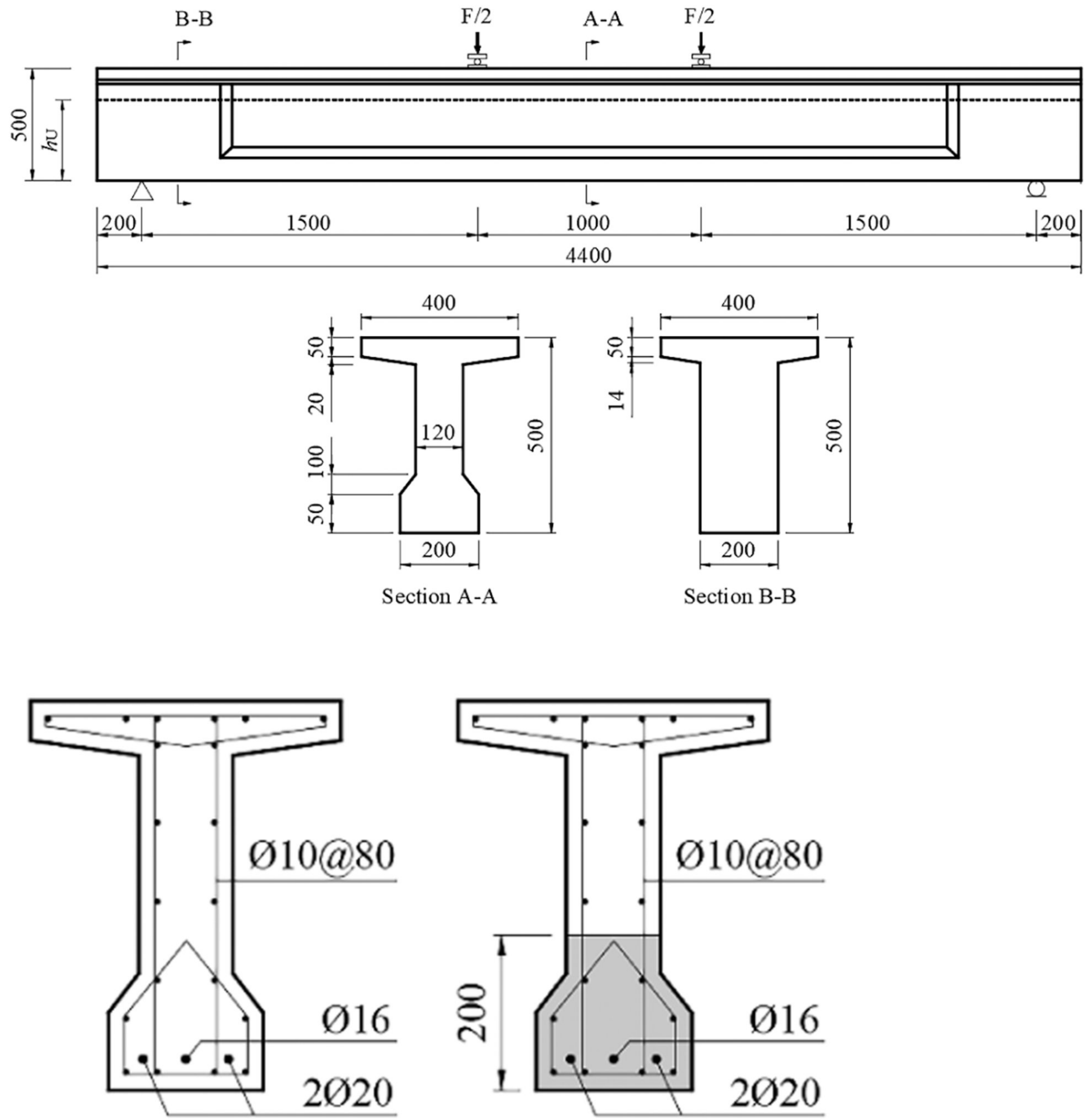


Fig. 1: Geometry and cross-sectional details of the UHPC-NC composite T-beam used in the simulation from Wang et al., 2023

Material Properties

Normal Concrete (NC)

- Compressive Strength: 60.42 MPa
- Flexural Tensile Strength: 6.67 MPa
- Elastic Modulus: 37.28 GPa

Ultra-High Performance Concrete (UHPC)

- Compressive Strength: 132.28 MPa
- Flexural Tensile Strength: 14.57 MPa
- Elastic Modulus: 44.95 GPa

Steel Reinforcement

- Elastic Modulus: 200 GPa
- Diameter: 16 mm (based on literature)
- Yield Strength: 456 MPa

3.3 Modeling in ABAQUS

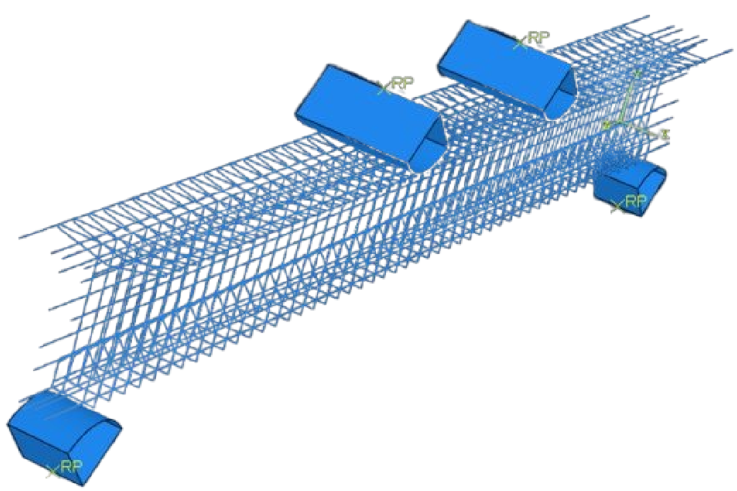
- **Concrete:**
  The Concrete Damaged Plasticity (CDP) model was used to simulate the nonlinear behavior of both NC and UHPC. Compressive and tensile stress–strain curves were

implemented based on test data from literature. Appropriate damage parameters, dilation angle, and viscosity coefficients were defined to ensure convergence.

- **Steel Reinforcement:**
  The steel was modeled as an elastic–perfectly plastic material. Reinforcement bars were embedded in the concrete beam using the *Embedded Region* technique.

- **Element Type:** C3D8R (8-node linear brick, reduced integration with hourglass control)
- **Mesh Size:** 50mm, with finer meshing in the constant moment region
- **Partitioning:** Separate regions were created for UHPC and NC layers

Reinforcement: Modeled as 1D wire elements and embedded within the 3D beam.



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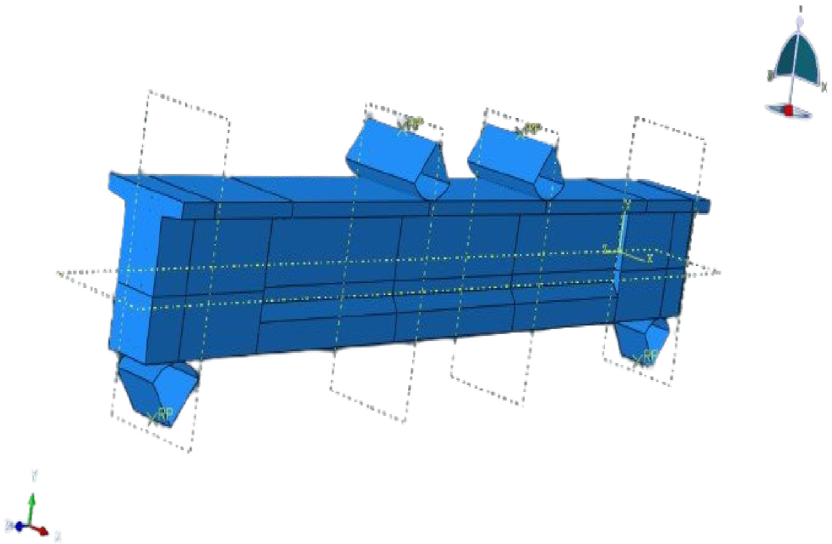

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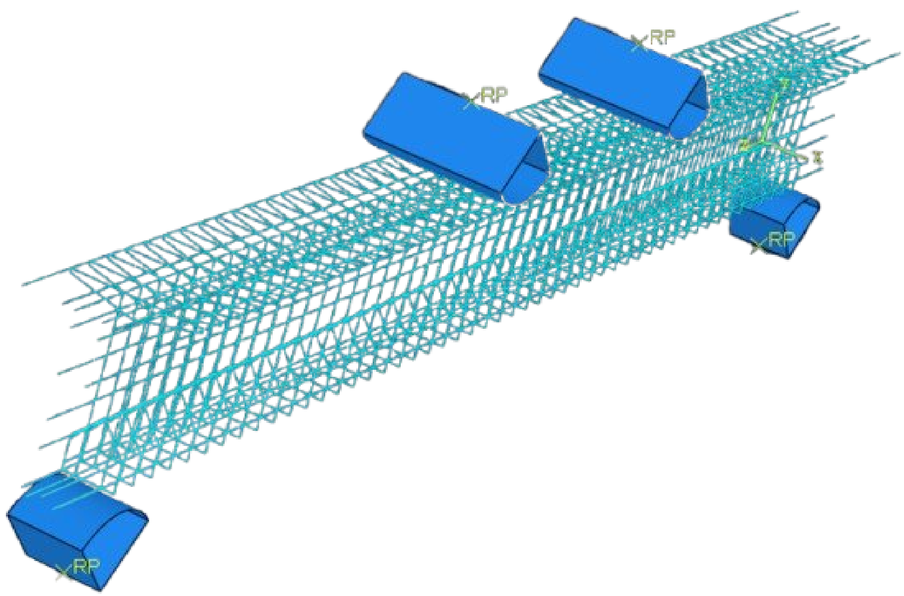
Fig. 2: Model after assembly



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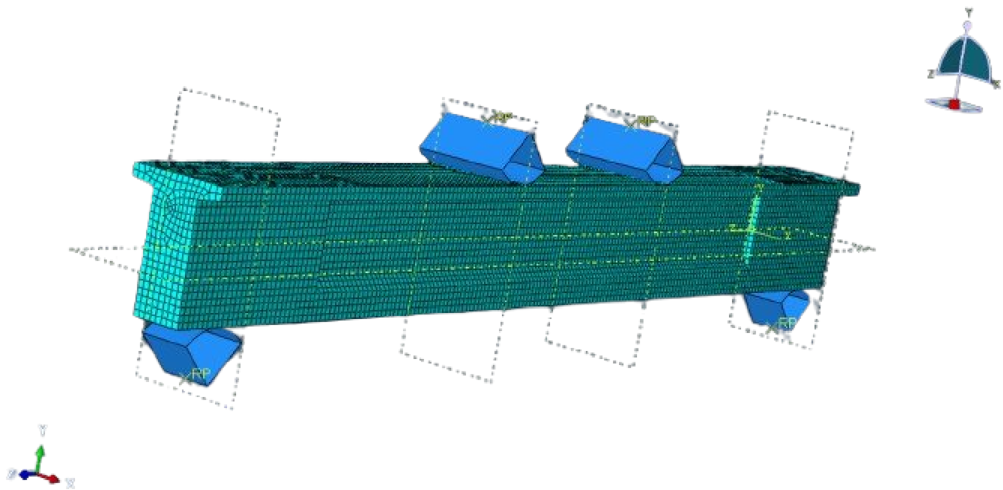


(b)

Fig. 3: Model after meshing

Boundary Conditions and Loading

- **Supports:**

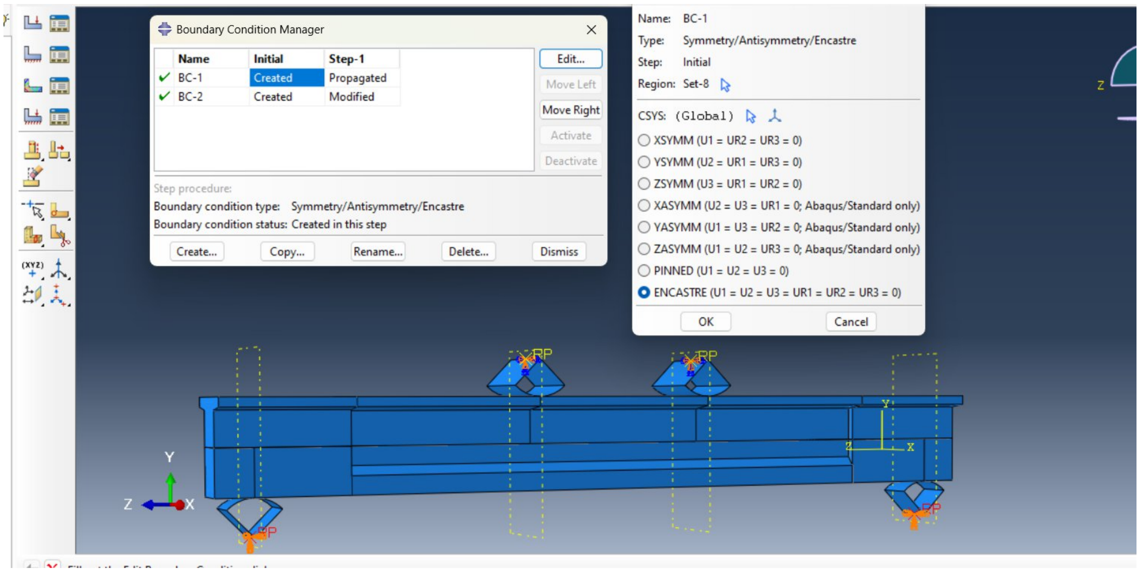
  Simply supported boundary conditions were applied:

  - One end: U1 = U2 = U3 = 0 (fully fixed)
  - Other end: U1 = U3 = 0, U2 free (to allow vertical translation)

- **Loading Configuration:**

  Two point loads were applied symmetrically to create a four-point bending scenario.

Loads were applied through *Reference Points* and *Coupling Constraints* to avoid local stress concentrations.



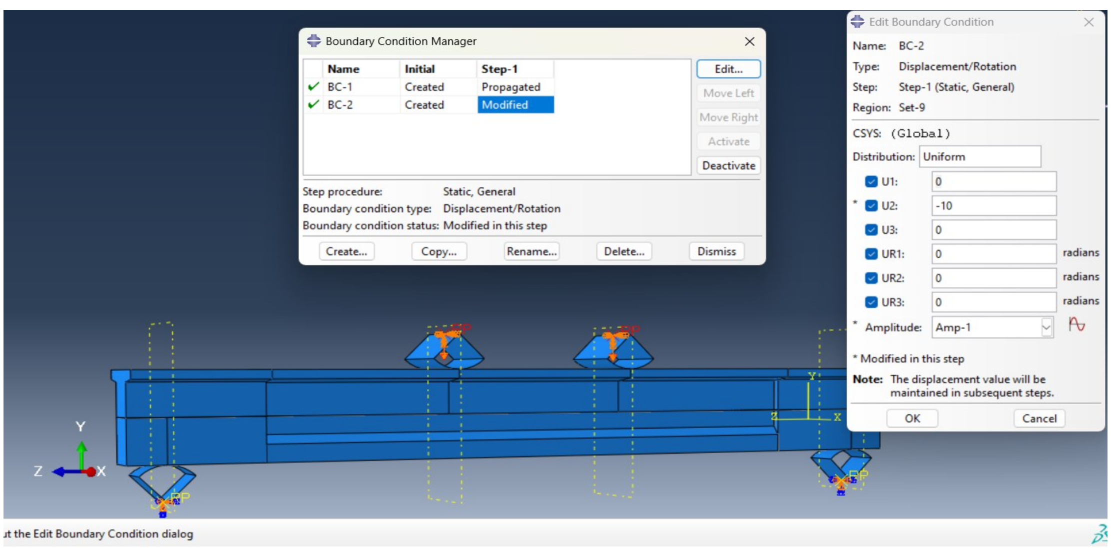


Fig. 4 : Boundary conditions and displacement-controlled loading configuration applied in ABAQUS.

- **Monotonic Load Test:**
  Initial simulations involved monotonic loading test for sample beam A-360-S for validation.
- **Static Load Test:**
  An Explicit solver was used to capture nonlinear behavior such as concrete cracking and damage evolution.
- **Failure Criteria:**
  Fatigue failure was indicated by sudden stiffness degradation, rapid increase in deflection, or rebar yielding/fracture within the constant moment region.

3.4 Output Parameters

The simulation was used to monitor and extract the following:

- Mid-span deflection (U2 displacement)
- Load–deflection behavior for flexural life estimation

Chapter 4: Result And Discussion

4.1 Load–Deflection Behavior

The displacement-controlled simulation applied a downward deflection of 10 mm at the loading points. The resulting reaction forces were extracted to construct the load–deflection curves for each UHPC layer thickness (150 mm, 200 mm).

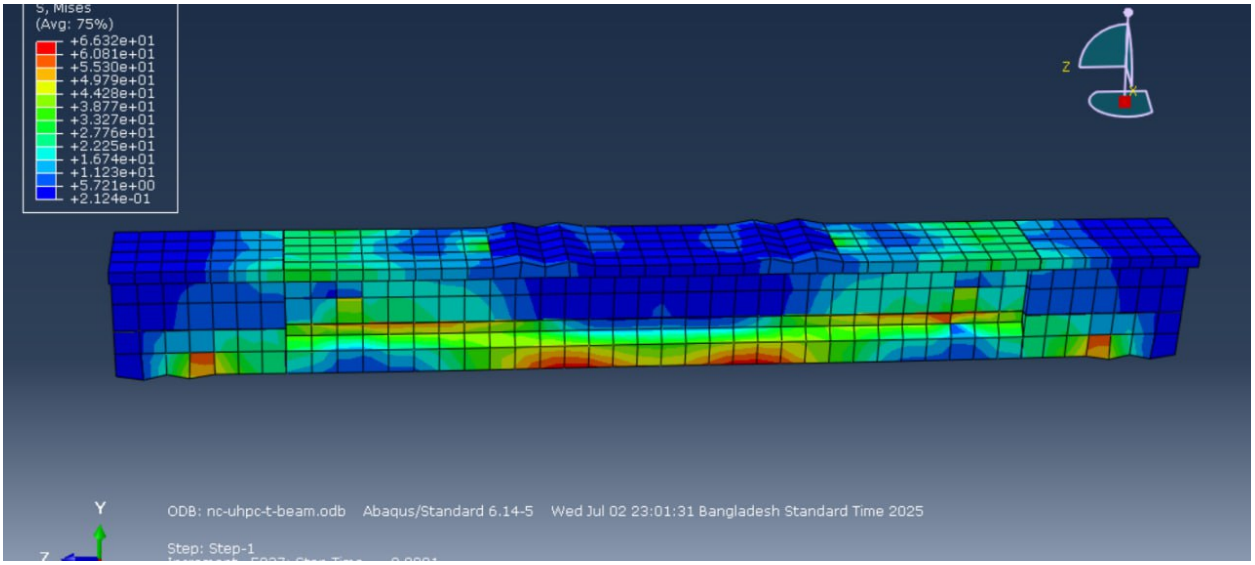
- **150 mm UHPC layer:** Exhibited moderate stiffness and load capacity, with earlier initiation of cracking in the tensile zone.
- **200 mm UHPC layer:** Showed higher stiffness and delayed cracking compared to the 150 mm model. The load-carrying capacity increased notably.

4.2Crack Pattern and Stress Distribution

Crack patterns were identified using the *tensile damage variable* (SDEG) and *plastic strain contour* in the UHPC region. In all three models, cracks initiated at the midspan bottom fibers and propagated upward into the NC region as loading increased.

- In the **150 mm UHPC beam**, cracks developed rapidly and reached the interface zone earlier due to reduced UHPC depth.
- In the **200 mm**, the cracks remained confined within the UHPC zone for longer, with delayed propagation due to higher tensile strength and fracture energy.
- The stress distribution indicated concentration of tensile stress at the bottom midspan, with compressive zones forming near the top flange as expected under four-point bending.

These observations affirm the crack-resisting advantage of thicker UHPC layers.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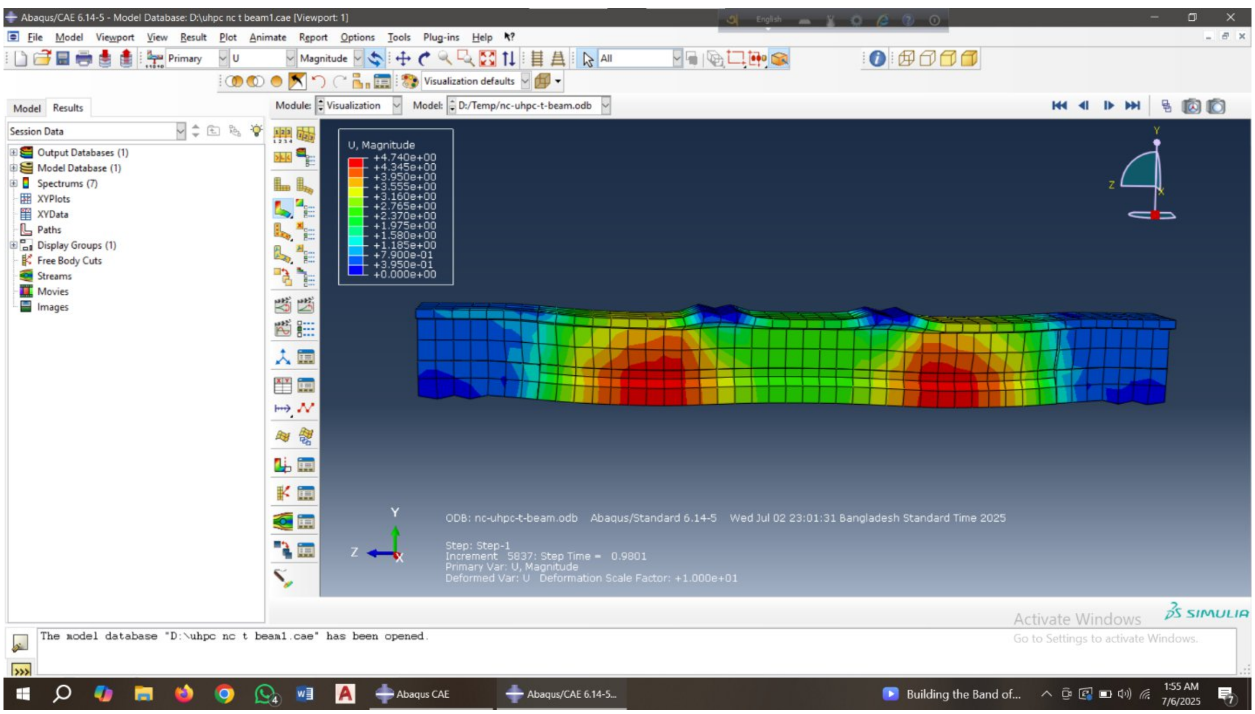
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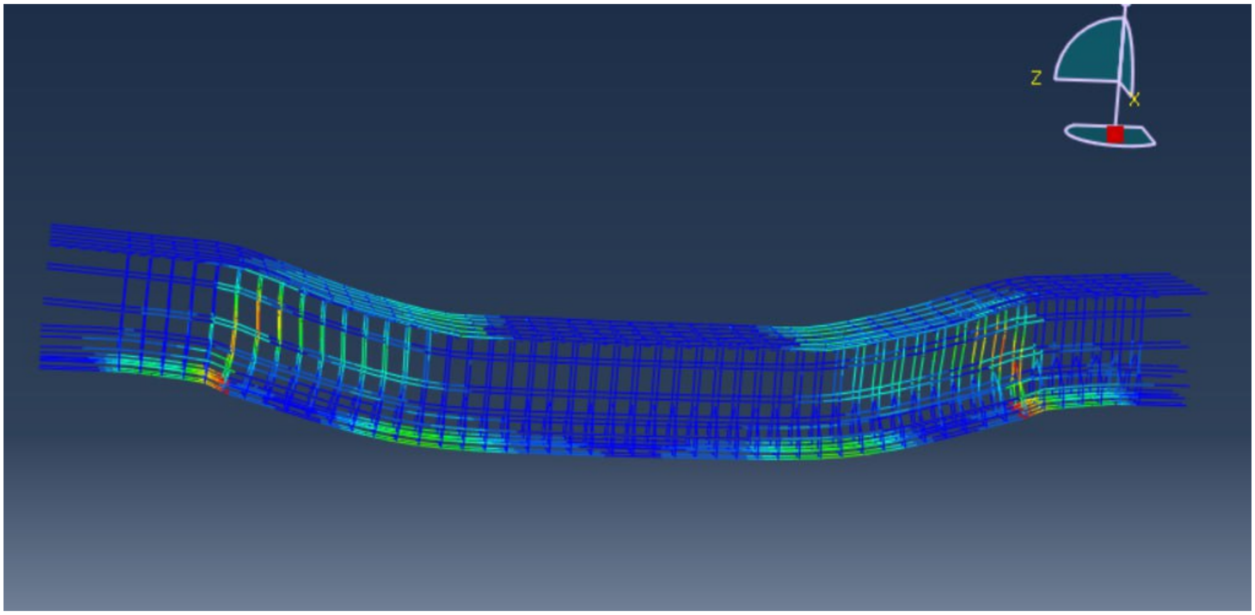

(c)

Fig. 5: Model after simulation

4.3 Comparison with Experimental Results

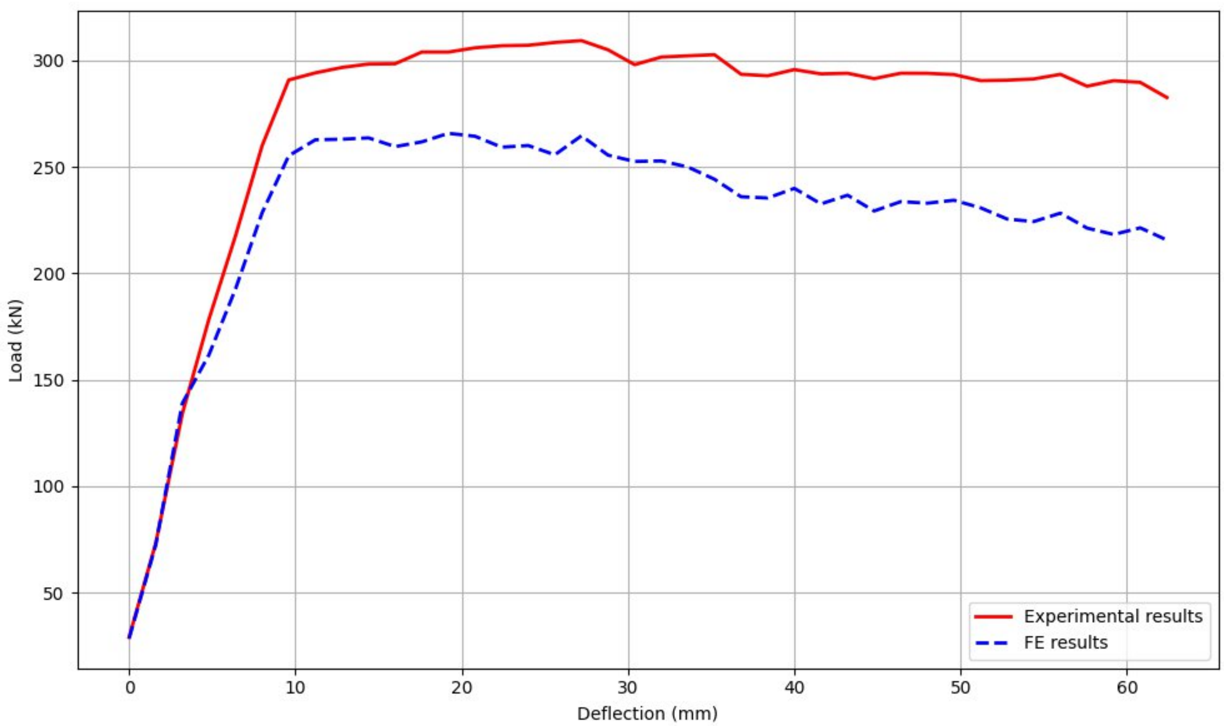

Fig. **6:** Comparison of load–deflection between FE and experimental results from Wang et. al (2023) for sample beam (A-360-S)

The simulation results were compared with the experimental findings reported by Wang et al. (2023). The load-deflection trend of the 360 mm UHPC model showed a strong correlation with the experimental results in terms of stiffness, peak load, and overall deformation pattern. While exact numerical values varied slightly due to modeling assumptions, the simulation successfully reproduced the characteristic three-stage response: elastic, crack propagation, and post-yield behavior.

The crack patterns observed in the simulation (via SDEG contours) closely matched the experimental failure modes, where initial cracking occurred in the midspan UHPC layer and propagated upwards toward the NC.

4.4 Interpretation of the Results

We performed numerical simulations for the three beams and obtained the following load vs deflection graph.

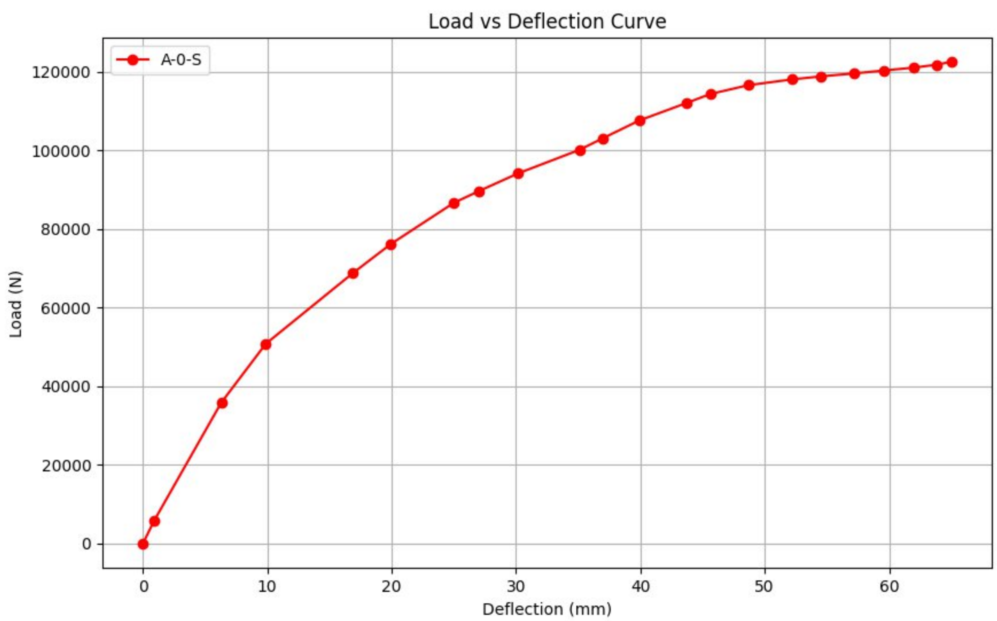

Fig. 7. Load–deflection FE results for sample beam (A-0-S)

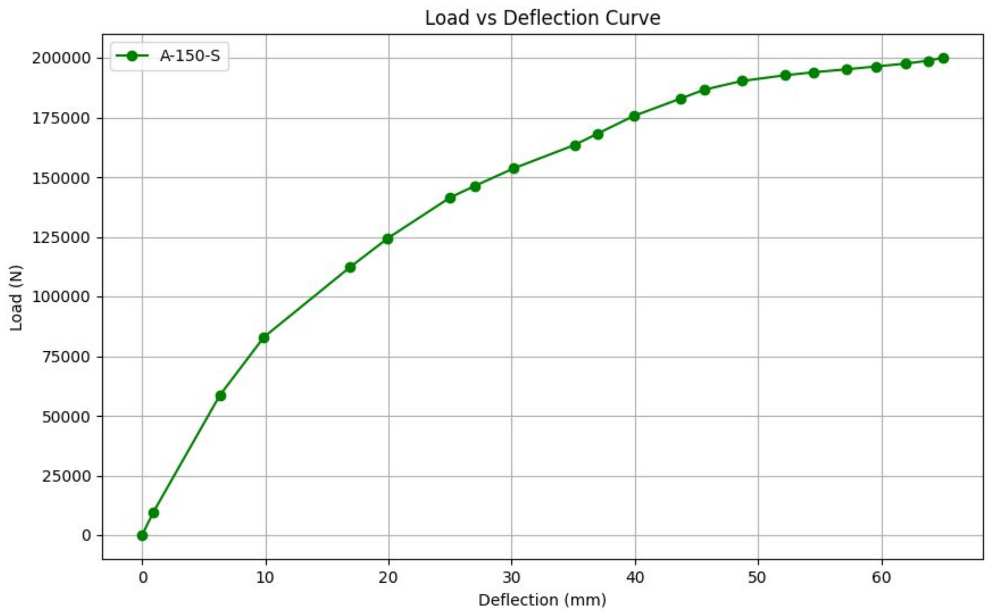

Fig. **8.** Load–deflection FE results for sample beam (A-150-S)

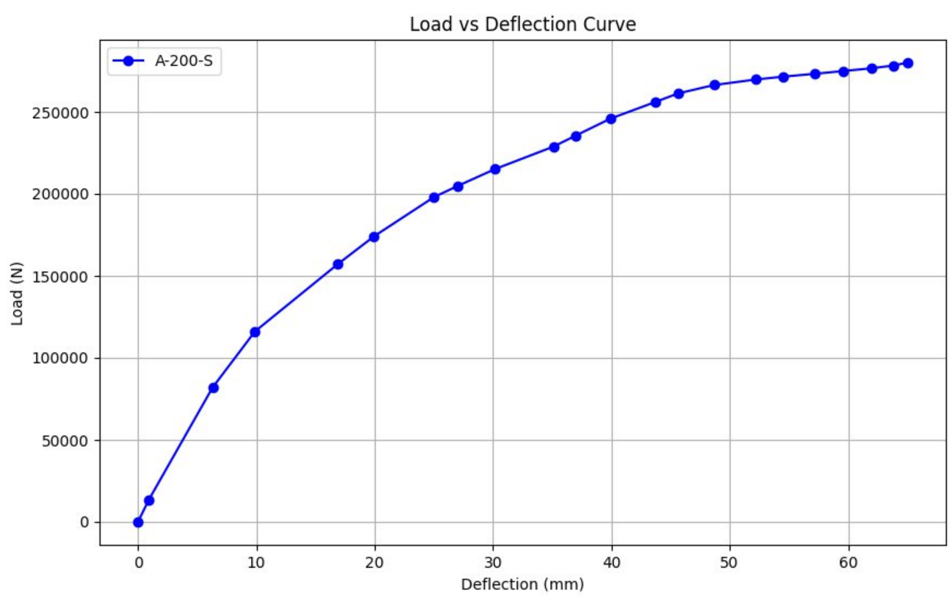

Fig. 9. Load–deflection FE results for sample beam (A-200-S)

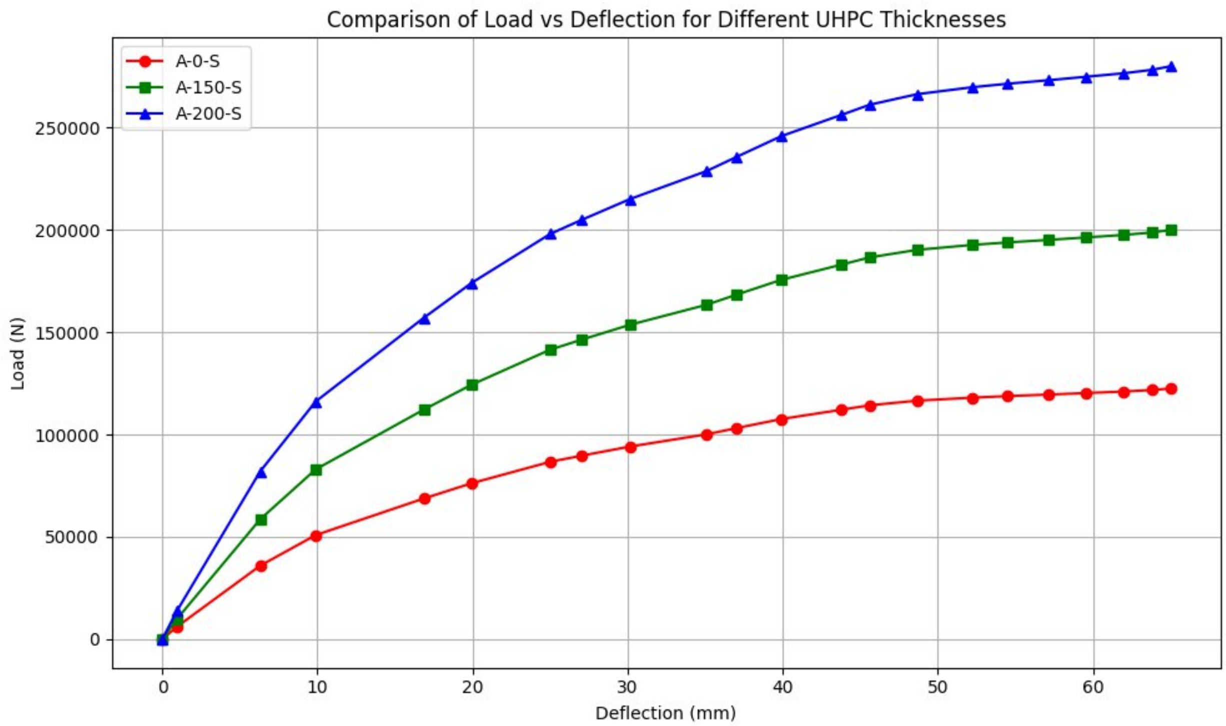

Fig. 10. Load–deflection FE results for sample beam

The flexural behavior of three UHPC-NC composite T-beams—A-0-S, A-150-S, and A-200-S—was compared based on their load versus deflection response under four-point bending. Each beam had the same maximum deflection of 65 mm but differed in their ultimate load capacities due to variation in the thickness of the UHPC layer placed in the tensile zone. The A-0-S beam, which had no UHPC layer, exhibited the lowest flexural capacity with an ultimate load of 122.5 kN, indicating a brittle response with early cracking and limited energy absorption. In contrast, the A-150-S beam with a 150 mm UHPC layer showed improved load-carrying ability, sustaining up to 200 kN, and exhibited a more ductile behavior. The A-200-S beam, with a 200 mm thick UHPC layer, demonstrated the best flexural performance, reaching a peak load of 280 kN. This significant enhancement is attributed to the extended UHPC region in the tensile zone, which provided superior cracking resistance, delayed failure, and greater energy dissipation. Therefore, among the three configurations, the A-200-S beam with 200 mm UHPC thickness exhibited the most favorable flexural performance.

4.5 Implications of Findings

The findings from this study indicate that UHPC layer thickness plays a crucial role in enhancing the flexural performance of composite beams. A thickness of 200 mm or more provides improved flexural resistance and delay in crack propagation, making it a promising choice for structural strengthening applications.

Moreover, the results imply that UHPC can be effectively used in critical tension zones of RC members, reducing the need for full-depth UHPC elements. The validated numerical model can serve as a predictive tool for optimizing composite beam designs without the need for exhaustive experimental testing.

4.6 Limitations

Despite the overall success of the finite element model, several limitations must be acknowledged:

1. The model is validated only for 360 mm UHPC thickness; other thicknesses are analyzed numerically without experimental confirmation.

2. The study considers only monotonic loading and does not account for long-term effects like creep, shrinkage, or environmental degradation.

3. Mesh sensitivity and convergence issues limited the refinement level in some regions, especially near stress concentration zones.

4. UHPC and NC are modeled using Concrete Damage Plasticity (CDP), which may not fully capture UHPC's fiber bridging behavior

Chapter 5: Conclusion

5.1 Conclusion

This research numerically investigated the flexural behavior of UHPC-NC composite beams with varying UHPC layer thicknesses (150 mm, 200 mm, 250 mm) under four-point bending using ABAQUS. The simulation results confirmed that increasing the UHPC layer thickness enhances stiffness and extends flexural life up to an optimum point. The comparison with experimental data validated the model within acceptable limits.

Despite some limitations, such as idealized bond assumptions and lack of full-scale testing, the findings contribute valuable guidelines for designing cost-effective composite beams. Future studies may focus on interface behavior, varying reinforcement ratios, and real-life flexural testing to strengthen these numerical insights.

This thesis aims to help bridge the gap between advanced UHPC design and practical structural applications, ultimately contributing to more durable and sustainable infrastructure.

5.2 Future Work

Future work can address the current limitations and improve model accuracy in the following ways:

1. Extend the analysis to include cyclic loading, interface slip behavior, and long-term effects like creep, shrinkage, and environmental exposure.

2. Investigate the influence of different reinforcement configurations, such as varying stirrup spacing or bar diameters, on flexural performance.

3. Perform multi-objective optimization to balance UHPC thickness, cost, and structural efficiency for practical design applications.

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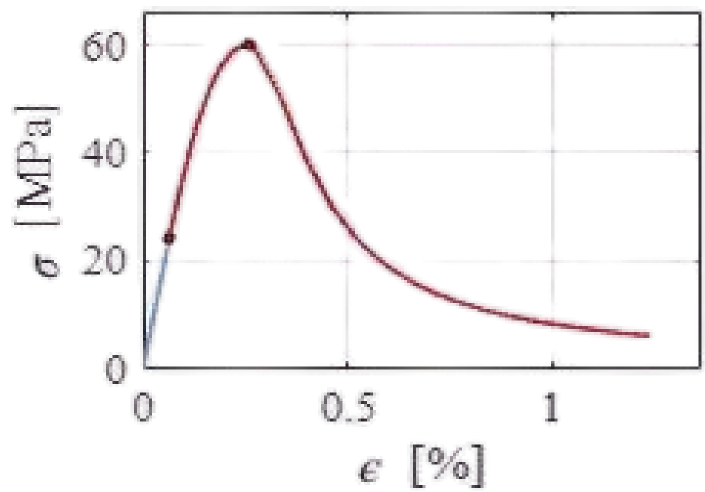
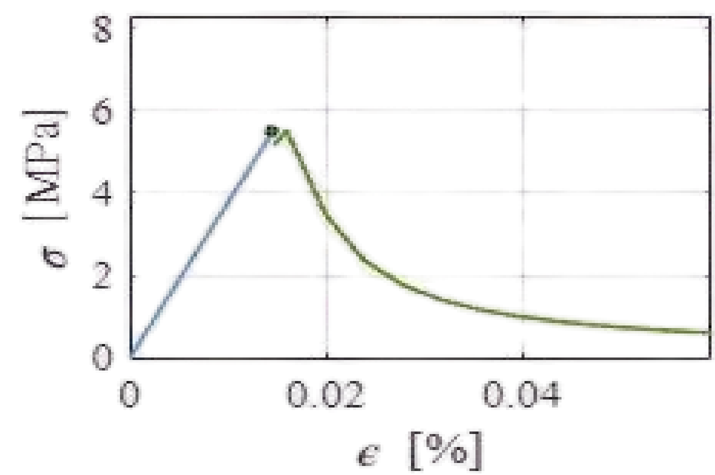
Appendix

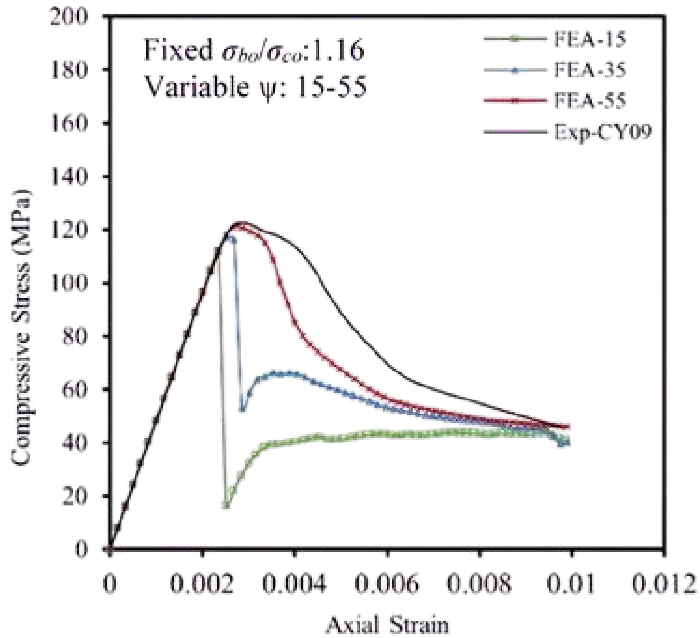


(a)

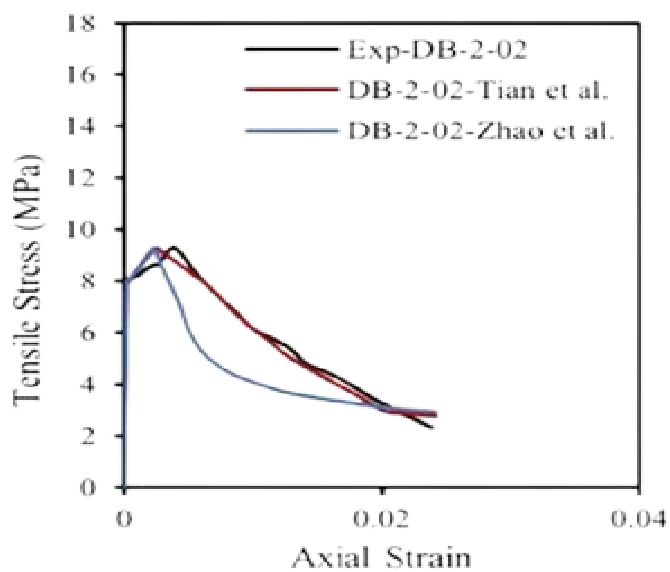


(b)

Fig 1: (a) Compressive stress strain curve of NC & (b) Tensile stress strain curve of NC



(a)



(b)

Fig 2: (a) Compressive stress strain curve of UHPC & (b) Tensile stress strain curve of UHPC

	B	C	D	E
2	dc	inelastic s	e	plastic
3	0	0	37565	0
4	0.00422	0.00112	37565	0.00112
5	0.1602	0.00201	37565	0.00191
6	0.35772	0.00298	37565	0.00277
7	0.50688	0.00386	37565	0.00361
8	0.61017	0.00467	37565	0.00441
9	0.68227	0.00543	37565	0.00518
10	0.73411	0.00616	37565	0.00591
11	0.77261	0.00687	37565	0.00663
12	0.80205	0.00756	37565	0.00734
13	0.82516	0.00825	37565	0.00804
14	0.84369	0.00892	37565	0.00872
15	0.85884	0.00959	37565	0.00941
16	0.87143	0.01026	37565	0.01009
17	0.88204	0.01092	37565	0.01076
18	0.89109	0.01158	37565	0.01143
19	0.89889	0.01224	37565	0.0121
20	0.90567	0.0129	37565	0.01276
21	0.91163	0.01356	37565	0.01345
22	0.9169	0.01421	37565	0.01413
23	0.92158	0.01487	37565	0.01481
24	0.92578	0.01552	37565	0.01548
25	0.92956	0.01617	37565	0.01614
26	0.93298	0.01682	37565	0.0168
27	0.93609	0.01747	37565	0.01745
28	0.93893	0.01812	37565	0.01811
29	0.94153	0.01877	37565	0.01876
30	0.94392	0.01943	37565	0.01941
31	0.94613	0.02007	37565	0.02006
32	0.94817	0.02072	37565	0.02071
33	0.95006	0.02137	37565	0.02136

Fig. 3: CDP compression data for NC

dc	inelastic	E	plastic
0.70438	0.00013	37565	0.00012
0.76421	0.00017	37565	0.00016
0.80339	0.00021	37565	0.00021
0.83087	0.00025	37565	0.00025
0.85114	0.00029	37565	0.00029
0.86671	0.00033	37565	0.00033
0.87904	0.00037	37565	0.00037
0.88906	0.00041	37565	0.00041
0.89735	0.00045	37565	0.00044

Fig. 4: CDP tension data for NC

	A	B	C	D	E
1	Young Modulus (MPa)	Poisson's ratio			
2	51000	0.19			
3	Dilation angle	Eccentricity	fb0/fc0	K	Viscosity paramet
4	56	0.1	1.1	0.66	0.
5	Compressive behavior		Compression damage		
6	Yeild stress	inelastic strain	Damage parameter	Crushing strain	
7	49.5	0	0	0	
8	55.4539425	0	0	0	
9	61.4019362	0	0	0	
10	67.3339546	0.000001	0	0.000001	
11	73.2267778	0.000003	0	0.000003	
12	79.0305318	0.000008	0	0.000008	
13	84.6451067	0.000018	0	0.000018	
14	89.8822573	0.000039	0	0.000039	
15	94.4120639	0.000082	0	0.000082	
16	97.7038876	0.000162	0	0.000162	
17	99	0.000302	0	0.000302	
18	97.4026108	0.000529	0.016135	0.000529	
19	92.1670816	0.000865	0.069019	0.000865	
20	83.1720769	0.001314	0.159878	0.001314	
21	71.2649421	0.001851	0.280152	0.001851	
22	58.0817314	0.002426	0.413316	0.002426	
23	45.3662506	0.002987	0.541755	0.002987	
24	34.3246816	0.003497	0.653286	0.003497	
25	29.7	0.003729	0.7	0.003729	

Fig. 5: CDP compression data for UHPC

Tensile behaviour		Tension damage	
Damage paramter		Damage parameter	Cracking strain
11.34	0	0	0
6.29125875	0.000516	0.4897365	0.000516
4.4571786	0.00093	0.6676461	0.00093
3.4902945	0.001317	0.7614354	0.001317
2.8872774	0.001693	0.819929	0.001693
2.47277415	0.002063	0.8601362	0.002063
2.1691005	0.002429	0.8895931	0.002429
1.9363617	0.002794	0.9121695	0.002794
1.75189035	0.003156	0.9300632	0.003156
1.60181805	0.003518	0.9446206	0.003518

Fig. 6: CDP tension data for UHPC