"Experimental Study and Finite Element Validation of Hybrid Layered Beams with Conventional Concrete"

Manjunath N K[1], Vanaja Kumari R[2], Dr. N Jayaramappa[3]

[1]Research Scholar, Dept. of Civil Engineering, UVCE, Bengaluru
[2]Student of Master in Technology, Department of Civil Engineering, Major: Prestressed concrete, University of Visveswaraya college of Engineering, Bangalore, Karnataka, India,
[3]Professor, Dept. of Civil Engineering, UVCE, Bangalore, Karnataka, India,

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Abstract - *The concept of layered concrete members has gained attention as an efficient approach for enhancing structural performance while making effective use of different concrete grades. This study focuses on the flexural behaviour of a 2-layered reinforced concrete beam, where two concrete layers with varying strength properties are combined within a single beam section. The objective of the study is to evaluate the structural response of the 2-layered beam under bending and to validate its performance using numerical analysis. Experimental investigations were carried out on simply supported beam specimens subjected to monotonic loading. Key performance parameters such as load–deflection behaviour, first crack load, yield load, ultimate load, and failure mode were recorded and analysed. To support the experimental findings, a finite element model of the 2-layered beam was developed using Abaqus, incorporating realistic material models, proper layer interaction, and boundary conditions. The numerical results showed good agreement with experimental observations, with deviations within an acceptable range. The results demonstrate that the 2-layered beam exhibits improved flexural performance, enhanced stiffness, and a more uniform stress distribution compared to conventional beams. The validated numerical model confirms the effectiveness of layered concrete systems and highlights their potential application in structural engineering practice.*

Keywords- **2-Layered Beam, Layered Concrete, Flexural Behaviour, Finite Element Analysis, Abaqus, Load–Deflection Response, Reinforced Concrete Beam**

1. INTRODUCTION

Reinforced concrete beams are one of the most commonly used structural elements in buildings and infrastructure. Traditionally, these beams are cast using a single grade of concrete throughout the cross-section. However, in flexural members, the stress distribution is not uniform, with higher compressive stresses occurring at the top region and tensile stresses dominating the bottom region. This non-uniform stress demand has led to the development of **layered concrete beams**, where different concrete grades are strategically placed to improve structural performance and material efficiency.

A 2-layered beam is formed by combining two different concrete layers within a single beam section, typically with a higher strength concrete placed in the compression zone and a relatively lower or conventional concrete in the tension zone. This configuration aims to enhance load-carrying capacity, stiffness, and crack resistance while reducing material cost. The layered approach also promotes sustainable construction by enabling the effective utilization of high-strength concrete only where it is structurally required.

Several experimental and numerical studies have reported that layered concrete beams exhibit improved flexural behaviour compared to conventional homogeneous beams. Parameters such as first crack load, ultimate load, deflection characteristics, and failure mode are significantly influenced by the arrangement and properties of the concrete layers. However, accurate prediction of the behaviour of 2-layered beams requires reliable numerical models that can capture material nonlinearity, cracking, and interlayer interaction. With the advancement of finite element software, numerical tools such as Abaqus have become effective for simulating the nonlinear behaviour of reinforced concrete structures. By incorporating appropriate material models and boundary conditions, finite element analysis can closely replicate experimental responses and reduce the need for extensive physical testing. Validation of numerical models against experimental results is therefore essential to ensure their accuracy and applicability.

In this study, the flexural performance of a 2-layered reinforced concrete beam is investigated through experimental testing and validated using finite element analysis. The study focuses on load–deflection behaviour, cracking characteristics, stress distribution, and failure patterns. The outcomes of this research aim to provide a clearer understanding of the structural efficiency of 2-layered beams and to support their practical application in modern structural engineering.

2. LITERATURE REVIEW

[1] Desai and Krishnan developed a well-defined stress–strain relationship for concrete, which has been extensively used in the nonlinear analysis of reinforced concrete members. Their model provides a realistic analytical description of concrete behaviour under compressive loading by accounting for the nonlinear increase in stress with strain up to peak strength, followed by a gradual softening response. This stress–strain relationship has been widely incorporated into numerical and finite element models to simulate the flexural behaviour of concrete beams with greater accuracy. The study emphasized that linear elastic assumptions are insufficient to represent actual concrete behaviour, especially near ultimate load conditions. By highlighting the role of material nonlinearity, the authors demonstrated that accurate prediction of load–deflection response, cracking behaviour, and failure modes of reinforced concrete beams strongly depends on the proper representation of concrete constitutive behaviour. Their work continues to serve as a fundamental reference for analytical and numerical studies involving reinforced and layered concrete beam systems.

[2] Hognestad et al. carried out detailed experimental investigations on the flexural behaviour of reinforced concrete beams to understand stress distribution across the beam depth under increasing load. Their study revealed that concrete in different regions of the beam section is subjected to varying stress and strain demands during loading. The compression zone was found to play a dominant role in governing the ultimate load-carrying capacity of the beam, while the tension zone primarily influenced crack initiation and crack propagation. The authors also observed that cracking occurs well before ultimate failure, leading to redistribution of stresses within the section. These findings clearly demonstrated that a uniform concrete grade across the entire depth may not be the most efficient use of material. This fundamental understanding provided the theoretical basis for the concept of layered concrete beams, in which concrete with different strength and stiffness properties can be strategically placed in regions according to structural demand, thereby improving overall flexural performance and material efficiency.

[3] Barros and Figueiras carried out detailed numerical investigations on reinforced concrete beams and validated their finite element models using corresponding experimental results. Their study demonstrated that numerical models incorporating layered material properties were able to represent the actual behaviour of reinforced concrete beams more realistically than homogeneous concrete models. In particular, the layered modelling approach captured stiffness degradation after cracking and the nonlinear post-cracking response with greater accuracy. The authors observed improved prediction of load–deflection behaviour, crack development, and stress redistribution when different material properties were assigned across the beam depth. These findings clearly highlight the effectiveness of layered material modelling in simulating the flexural behaviour of reinforced concrete beams and support its application in analysing conventional layered concrete beam systems

3. FINITE ELEMENT MODELLING USING ABAQUS

In the present study, finite element modelling is carried out using ABAQUS to simulate the flexural behaviour of conventional layered concrete beams. The numerical model is developed to closely replicate the experimental configuration in te.rms of geometry, material properties, boundary conditions, and loading arrangement. The beam is modelled as a layered section in which different concrete grades are assigned to individual layers along the depth, allowing realistic representation of material variation.

Concrete behaviour is defined using nonlinear material models to capture cracking in tension and crushing in compression. The Concrete Damage Plasticity (CDP) model is adopted to represent the inelastic behaviour of concrete, including stiffness degradation and damage evolution under increasing load. Reinforcement is modelled as an embedded region within the concrete, assuming perfect bond between steel and concrete. All material parameters used in the numerical model are selected based on experimental data and standard code provisions.

Boundary conditions and loading are applied to simulate simply supported conditions with monotonic loading. The analysis is performed under displacement-controlled loading to obtain stable convergence and accurate load–deflection response. The numerical results obtained from ABAQUS, including load–deflection curves, stress distribution, and cracking patterns, are compared with experimental results to validate the modelling approach. This Abaqus-based numerical framework provides a reliable tool for understanding the structural behaviour of conventional layered concrete beams.

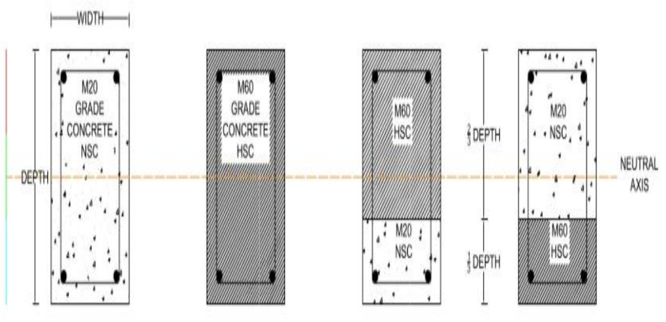

Figure – 3.1 Combinations of 2-layered Beam

3.1 Geometry modelling

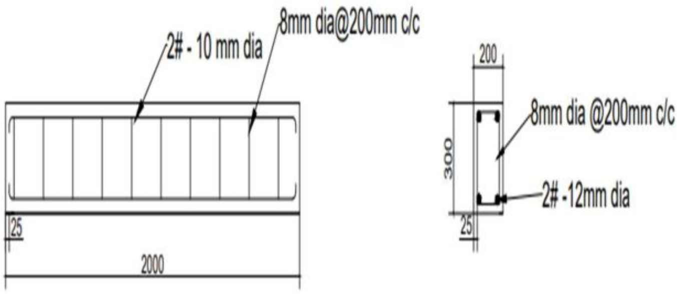

Figure – 3.2 modeling of simply supported beam

The geometry of the beam was modelled to match the experimental specimen dimensions. The beam cross-section was divided into two distinct concrete layers representing the 2-layered configuration. Each layer was assigned its respective thickness and material properties. Reinforcement bars were modelled separately and positioned accurately within the beam according to the experimental detailing. A perfect bond between concrete and steel reinforcement was assumed in the model.stacked along the height (depth) of the beam.

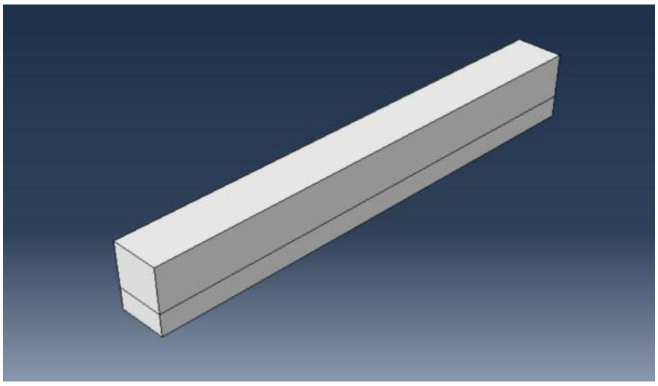

Figure – 3.3 modeling of 2-layered Beam

3.2 Material modelling

Concrete was modelled using the Concrete Damage Plasticity (CDP) model available in Abaqus, which is suitable for representing nonlinear behaviour, cracking in tension, and crushing in compression. Material properties such as elastic modulus, Poisson's ratio, and compressive strength, tensile strength, and damage parameters were defined separately for each concrete layer. Steel reinforcement was modelled as an elastic–plastic material with isotropic hardening based on standard stress–strain relationships.

Table 3.1 Young's Modulus of concrete

Grade of concrete	Youngs modulus(MPa)
M10	15811
M20	22360
M60	38729

Table 3.2 Material Properties

Density of steel	7850 kg/m^3
Density of concrete	2400 kg/m^3
Poisson ratio of concrete	0.2
Poisson ratio of steel	0.3
Modulus of elasticity steel	2.1x10^{5}N/mm^2..

3.3 Interaction and Interface Modelling

A tie constraint was used between the two concrete layers to ensure proper load transfer and composite action, assuming perfect interlayer bonding. The interaction between reinforcement and concrete was defined using embedded region constraints, which allowed the reinforcement to follow the deformation of the surrounding concrete without relative slip

3.4 Boundary Conditions and Loading

The beam was modelled as **simply supported**, consistent with the experimental setup. One end of the beam was restrained against vertical and longitudinal displacements, while the other end was allowed longitudinal movement to avoid axial restraint. Monotonic load was applied in the form of displacement-controlled loading at the loading points to capture the complete load–deflection response up to failure.

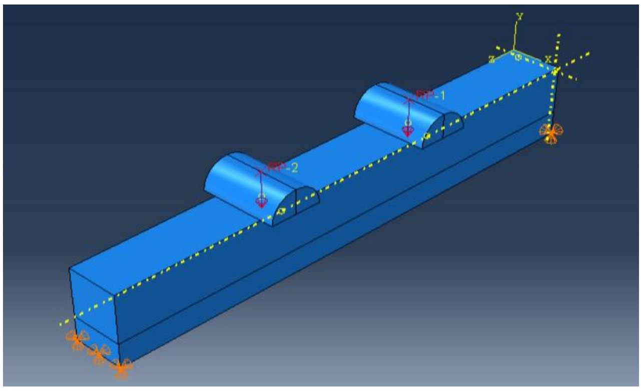

Fig 3.4 2- point loading in 2 layered beam

3.5 Meshing

A structured meshing approach was adopted for the concrete beam using three-dimensional solid elements. A finer mesh was provided in regions of high stress concentration, particularly near the loading points and mid-span. Reinforcement bars were discretized using appropriate truss or beam elements. Mesh sensitivity was checked to ensure accuracy without excessive computational cost.

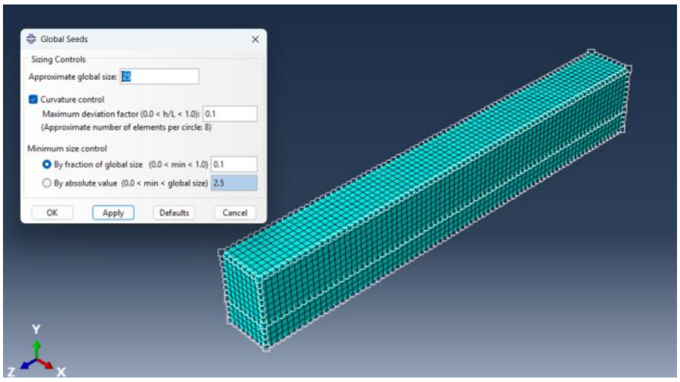

Fig. 3.5 Meshing of 2 lYERED BEAM

3.6 Output parameters and Validation

The FEM results were evaluated in terms of load–deflection behaviour, stress distribution, crack initiation, and damage patterns. The numerical results were compared with experimental data to assess the accuracy of the model. A close agreement was observed between FEM and experimental responses, with variations within acceptable limits, confirming the reliability of the developed finite element model for analysing 2-layered conventional concrete beams

4. RESULTS AND DISCUSSION

This section presents and discusses the experimental and finite element analysis results of the 2-layered conventional reinforced concrete beam subjected to flexural loading. The behaviour of the beam is evaluated in terms of load–deflection response, cracking characteristics, stress distribution, and failure mode. The numerical results obtained from Abaqus are compared with experimental observations to validate the accuracy of the finite element model.

4.1 Stress Distribution

The stress distribution obtained from FEM analysis indicates a more uniform stress transfer across the depth of the 2-layered beam. Higher compressive stresses were concentrated in the top concrete layer, while tensile stresses were predominantly resisted by reinforcement in the bottom region. This confirms the efficient utilization of different concrete layers based on stress demand.

The transition of stresses across the interface of the two concrete layers was smooth, indicating proper composite action and effective load transfer. No significant stress discontinuity was observed at the layer interface.

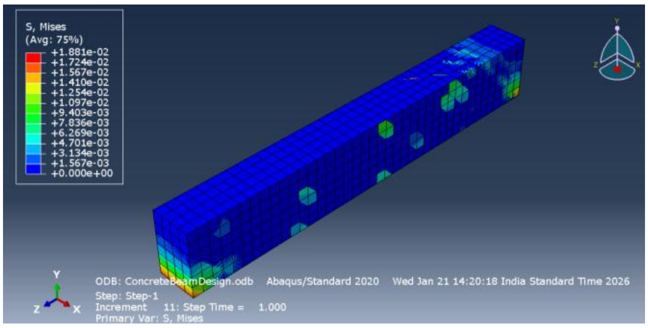

Fig 4.1 Stress distribution in 2 layered beam

4.2 Displacement

The displacement behaviour of the 2-layered conventional reinforced concrete beam was evaluated using mid-span deflection obtained from both experimental testing and finite element analysis. Displacement is a key parameter for assessing serviceability performance and stiffness characteristics of flexural members.

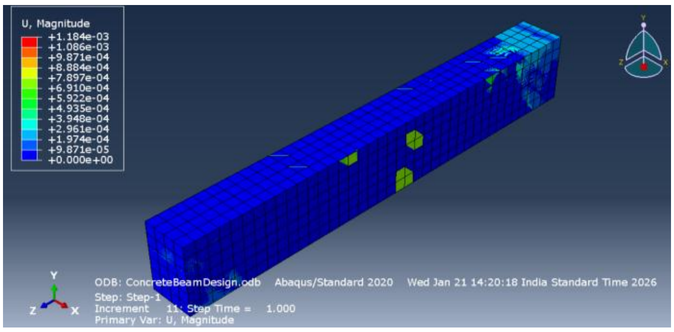

Fig 4.2 Displacement in 2 layered beam

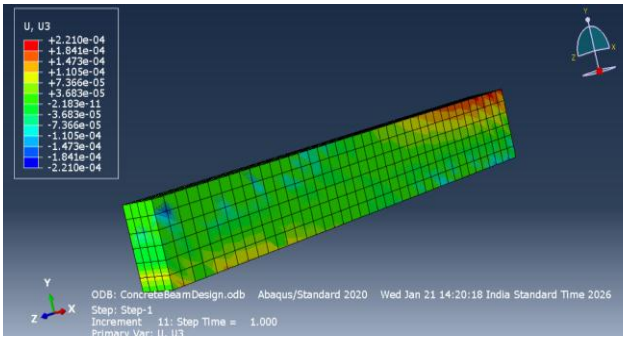

Fig 4.3 Displacement in 2 layered beam

4.3 Reaction Force

The reaction force behaviour of the 2-layered conventional concrete beam showed a linear increase with applied load during the initial elastic stage. Nearly equal reaction forces were observed at both supports due to symmetric loading and simply supported conditions. After crack initiation, slight nonlinearity occurred because of stiffness degradation in the tension zone. FEM results from Abaqus closely matched the experimental reaction forces with only minor variations. At ultimate load, stable reaction forces confirmed effective load transfer and ductile behaviour of the beam.

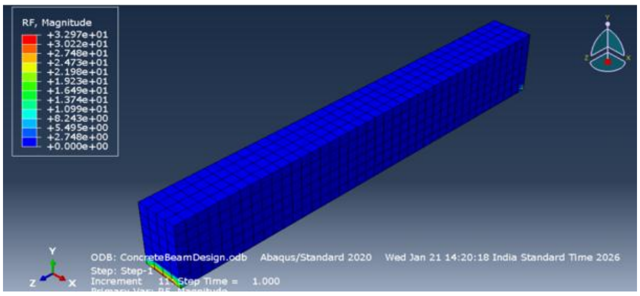

Fig 4.4 Reaction Force in 2 layered beam

3. CONCLUSIONS

1. The 2-layered beam exhibited improved flexural performance compared to conventional single-layer beams, demonstrating better utilization of concrete based on stress demand.
2. The load–deflection behaviour showed an initial linear response followed by nonlinear behaviour after crack initiation, indicating ductile performance under flexural loading.
3. The presence of a higher-strength concrete layer in the compression zone enhanced stiffness and reduced mid-span displacement, particularly in the pre-yield stage.
4. First crack load and ultimate load obtained from finite element analysis closely matched the experimental results, with variations within acceptable limits.
5. Stress distribution obtained from FEM analysis confirmed effective composite action between the two concrete layers, with smooth stress transfer across the interface.
6. Cracking patterns and failure modes predicted by the FEM model were consistent with experimental observations, showing predominant flexural failure.
7. The validated FEM model using Abaqus proved to be reliable for predicting displacement, stress response, and damage behaviour of 2-layered conventional concrete beams.

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