Investigation of Crack Depth by Numerical Analysis and NDT Technique

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***Abstract*— This project investigates the behavior of cracks in reinforced concrete beams through a combination of experimental testing, numerical simulations, and non-destructive testing (NDT). Reinforced concrete beams were subjected to flexural tests under two-point loading conditions, and the resulting load-deflection behavior was recorded. Numerical simulations using ABAQUS software were performed to model the experimental setup and predict crack initiation and propagation. The numerical models were validated against the experimental data, showing good agreement in load-deflection curves and crack patterns. The Pundit Ultrasonic Pulse Velocity tester was employed as an NDT method to measure crack depth indirectly, providing accurate and non-invasive assessment of internal damage. The integration of these methods offered a comprehensive understanding of crack behavior, highlighting the effectiveness of combining physical testing, computational modelling, and NDT techniques. This multi-faceted approach not only enhances the accuracy of structural assessments but also contributes to improved design, maintenance, and safety of reinforced concrete structures.**

***Index Terms*— Crack depth, NDT, ABAQUS**

I. INTRODUCTION

Cracks in reinforced concrete (RC) structures are a critical concern in civil engineering due to their potential to undermine structural integrity and longevity. Understanding the formation, propagation, and depth of these cracks is essential for ensuring the safety and durability of RC structures. This study integrates experimental, numerical, and non-destructive testing (NDT) methods to provide a comprehensive analysis of crack behavior in RC beams. Experimental methods play a crucial role in understanding the real-world behavior of RC structures under various loading conditions. In this study, flexural tests are conducted on RC beams with dimensions of 150 mm in breadth, 250 mm in depth, and 2200 mm in length. The beams are reinforced with Fe500 steel, including 2 nos of 12 mm diameter bars at the bottom, 2 nos of 10 mm diameter bars at the top, and 8 mm diameter stirrups spaced at 150 mm intervals. The beams are subjected to static live loads under two-point loading conditions in a simply supported setup. These tests capture load-deflection behavior and identify critical failure modes, providing valuable data for validating numerical models.

Numerical modeling using ABAQUS involves creating a detailed finite element model to simulate the behavior of RC beams under specified conditions. The process begins with defining the beam's geometry and assigning material properties for concrete and steel reinforcement. The reinforcement layout is modeled accurately, and a finite element mesh is created. Boundary conditions and static live loads are applied to simulate the experimental setup. Crack modeling is performed using the Extended Finite Element Method (XFEM), which allows for the simulation of crack initiation and propagation. The numerical results are compared with experimental data to ensure accuracy and reliability.

Non-destructive testing (NDT) methods are employed to detect and monitor cracks in RC structures without causing any damage. One of the key techniques used in this study is ultrasonic testing with the Pundit device, which uses ultrasonic waves to measure crack depth and assess internal damage. This method provides a non-invasive means of evaluating the structural health of RC beams. Additionally, smart sensor technologies are explored for real-time monitoring of crack development. These sensors can detect changes in structural integrity and provide continuous data on crack growth, enhancing the ability to perform predictive maintenance.

The combination of experimental testing, numerical simulations, and NDT methods offers a robust framework for understanding and mitigating cracks in RC structures. This integrated approach not only provides a comprehensive analysis of crack behavior but also highlights the practical benefits of combining physical testing, computational modeling, and advanced monitoring techniques. The findings from this study aim to improve design guidelines, construction practices, and maintenance strategies for RC structures, contributing significantly to the field of structural engineering. Through a detailed study of crack behavior, this work seeks to enhance structural safety, durability, and performance.

II. NUMERICAL MODELLING

Numerical modelling in ABAQUS involves creating a finite element model that represents the RC beam's geometry, material properties, and loading conditions. This approach allows for a detailed simulation of crack initiation and propagation, providing insights that can validate analytical and experimental findings. The following sections outline the steps and methodologies used in ABAQUS for modelling RC beams with specified dimensions and reinforcement details.

a. Model Definition and Geometry

The RC beams modeled in this study have a breadth of 150 mm, a depth of 250 mm, and a length of 2200 mm. The reinforcement details include Fe500 steel with 2 nos of 12 mm diameter bars at the bottom, 2 nos of 10 mm diameter bars at the top, and 8 mm diameter stirrups spaced at 150 mm intervals. These geometric and material properties are defined in ABAQUS to create an accurate digital representation of the physical beam.

b. Material Properties

The concrete used is M25 grade, and its material properties are defined using a concrete damage plasticity model. This model accounts for the nonlinear behavior of concrete under different loading conditions. The reinforcement steel properties are defined according to the characteristics of Fe500, with appropriate stress-strain relationships to capture the elastic and plastic behavior of the steel bars.

c. Meshing

A crucial aspect of numerical modeling is the creation of an appropriate finite element mesh. The beam is discretized into smaller elements, with finer meshing around areas expected to experience higher stress concentrations, such as near the supports and the loading points. A balance is struck between computational efficiency and accuracy by refining the mesh sufficiently to capture detailed stress and strain distributions without excessively increasing computational time.

d. Boundary Conditions and Loading

The boundary conditions replicate the simply supported setup used in experimental tests. These supports allow rotation but prevent translation at the support points. Static live loads are applied through two-point loading conditions, mirroring the experimental procedure. This involves applying load increments to the beam until failure occurs, allowing the observation of load-deflection behavior and crack development.

e. Crack Modeling with XFEM

To simulate crack initiation and propagation, the Extended Finite Element Method (XFEM) is used. XFEM allows the modeling of discontinuities, such as cracks, without the need for re-meshing, which can be computationally expensive. By incorporating XFEM, the model can simulate the initiation of flexural cracks, their growth, and their interaction with the reinforcement. This method is particularly effective for capturing the complex crack patterns observed in RC beams under flexural loads.

III. EXPERIMENTAL STUDY

a. Mix proportion:

M25 grade concrete is formulated according to the guidelines specified in IS 10262:2019, a standard by the Bureau of Indian Standards. This grade is widely utilized in various construction projects and is defined by its target compressive strength of 25 MPa (megapascals) after a 28-day curing period. Achieving the desired strength and durability for M25 concrete involves precise mix proportioning and careful selection of materials. The mix proportioning shown in Table 1.

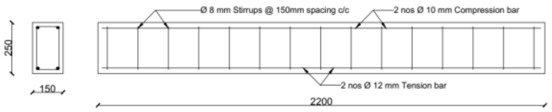
Table 1. Mix proportioning of Concrete

Material	Water (liters)	Cement kg	FA kg	CA kg
Per m^3	197	402	681	1220
Ratio	0.49	1	1.69	3.03

b. Formwork and casting:

The shape of the casting for a concrete beam with dimensions 2200mm x 150mm x 250mm is typically rectangular. Precision in casting a concrete beam is achieved through plywood formwork. The rectangular mold, meticulously shaped by plywood sheets, ensures accurate dimensions during pouring and curing. This synergy of formwork precision and plywood choice guarantees the creation of high – quality concrete beams. Cross section of beam shown in figure 1.

Figure.1. Cross section of Reinforced Beam.



c. Flexural Test

The beams were subjected to simply supported boundary conditions with static live loads applied through two-point loading. This setup was chosen to induce flexural stress in the mid-span region of the beam, where maximum bending moment occurs. During the test, load was incrementally applied using actuators, and the resulting deflection at various points along the beam was recorded using Linear Variable Differential Transformers (LVDT) placed at strategic locations.

The load-deflection behavior was closely monitored, focusing on the formation and growth of flexural cracks. Initial cracking was observed at lower load levels, progressing to more significant cracks as the load increased. The experimental results provided critical data on the beams' performance, highlighting the relationship between applied load, deflection, and crack development. This data served as a benchmark for validating numerical models and understanding the mechanics of crack propagation in reinforced concrete beams under flexural loading conditions. Flexural beam test Setup Shown in figure 2.

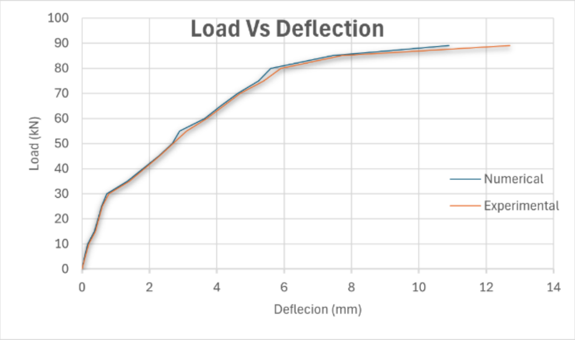
Figure.2. Flexural test on concrete specimen.

IV. RESULTS

a. Load-Deflection Behaviour

Initial linear behaviour corresponding to the uncracked stage of the concrete. The First crack occurred at approximately 15 kN, indicating the transition from elastic to inelastic behaviour. Post-cracking stage showed a reduced stiffness with a more gradual slope in the load-deflection curve. Ultimate load was reached at 89 kN with a corresponding deflection of 12.7 mm. The load-deflection curves from both the experimental tests and the numerical simulations show a good correlation. The initial linear behaviour and the onset of cracking are captured accurately by the numerical model. The post-cracking behaviour, ultimate load, and corresponding deflection are in close agreement, validating the numerical model's accuracy. Minor discrepancies can be attributed to assumptions and simplifications in the numerical model, such as the exact material properties and the idealization of boundary conditions. Comparison of Load deflection Curve-Experimental and Numerical shown in Figure 3.

Figure.3. Load Deflection Curve-Experimental and Numerical.

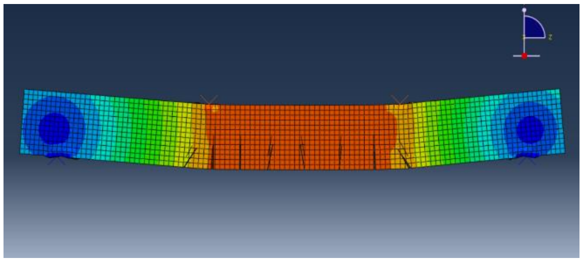


b. Crack Patterns

Initial hairline cracks appeared at the bottom of the beam near the mid-span, corresponding to the maximum bending moment region. The load increased, cracks propagated vertically and increased in width, indicating the beam's progression into the inelastic range. Secondary cracks developed at locations closer to the supports but remained relatively smaller in length and width. The final failure was characterized by a wide and prominent crack near mid-span, leading to the separation of the beam into two segments. Experimental and Numerical Crack patterns after loading Shown in Figure 4 and Figure 5.

Figure.4. Crack pattern after loading Experimental

Figure.5. Crack pattern observed Numerical Analysis (ABAQUS)



c. Crack depth by NDT

The Pundit ultrasonic testing device, using the indirect method, effectively measured the depth of the selected crack. The consistency of the crack depth measurements validates the reliability of the method for assessing internal damage in concrete structures. For a selected crack, the first set of measurements was taken with the transducer and receiver placed a distance ‘b’ from the crack on each side, and the pulse velocity time t_1 was recorded. A second set of measurements was taken with the transducer and receiver placed a distance 2b from the same crack, and the pulse velocity time t_2 was recorded. NDT Crack measurements and Numerical analysis values shown in Table 2. Crack depth measurement by NDT is shown in figure 6.

Table 2. Comparison of Experimental and Numerical Analysis

Crack No	Experimental (NDT)	Numerical (ABAQUS)	Percentage Variation
1	0.055	0.040	27
2	0.084	0.065	23
3	0.092	0.070	24

Figure.6 Crack depth Measurement by NDT

V. CONCLUSION

In conclusion, the comprehensive study of crack behaviour in reinforced concrete beams successfully integrated experimental testing, numerical simulations, and non-destructive testing (NDT) to provide a thorough understanding of crack formation and propagation. Experimental flexural tests captured the load-deflection behaviour and identified the critical failure modes, while the validated numerical models in ABAQUS software accurately predicted these experimental results, demonstrating their reliability for predictive analysis. The use of Pundit ultrasonic testing as an NDT method effectively measured crack depth and provided a non-invasive means of assessing internal damage. The integration of these methods not only offered a robust analysis of crack behaviour but also highlighted the practical benefits of combining physical testing, computational modelling, and NDT techniques.

The findings from this project lay the groundwork for future advancements in structural health monitoring and the development of more durable and resilient concrete infrastructures

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