"Experimental and Analytical Investigation of Bond Strength in M20 and M30 Grade Concrete Using Pullout Test"

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Abstract- The bond between reinforcing steel and concrete is a fundamental factor governing the strength, durability, and serviceability of reinforced concrete structures. This study investigates the bond strength of M20 and M30 grade concrete using both experimental and analytical approaches. The experimental work involves conducting pullout tests on concrete specimens embedded with steel reinforcement bars to evaluate the load–displacement behavior and ultimate bond strength. Analytical modeling is carried out using finite element software ANSYS to simulate the bond interaction and validate experimental results. The study examines the influence of concrete grade on bond performance and compares the experimental outcomes with analytical predictions. Results indicate that higher grade concrete exhibits improved bond strength due to better mechanical interlocking and adhesion properties. The load–displacement curves obtained from both methods show similar trends, confirming the reliability of the analytical model. Additionally, different bond failure modes such as pullout failure and bond slip are identified and analyzed. The findings contribute to better understanding of bond behavior and support improved design and construction practices in reinforced concrete structures.

Keywords: Bond Strength, Pullout Test, Reinforced Concrete, M20 and M30 Concrete, Finite Element Analysis etc.

I. INTRODUCTION

Reinforced concrete is one of the most widely used construction materials due to its strength, durability, and versatility. The composite action between concrete and steel reinforcement is made possible by the bond developed at their interface. This bond ensures effective load transfer from concrete to steel and plays a vital role in maintaining structural integrity under various loading conditions [1].

Bond strength is influenced by several factors including concrete grade, surface characteristics of reinforcement bars, curing conditions, and confinement provided by surrounding concrete. Among these, the grade of concrete significantly affects bond behavior, as higher strength concrete provides better adhesion and mechanical interlocking between steel and concrete [2]. Understanding this bond mechanism is essential for the safe design of structural elements such as beams, columns, and slabs.

One of the most common methods to evaluate bond strength is the pullout test. In this test, a reinforcing bar is embedded in a concrete specimen and subjected to axial tensile force until failure occurs. The maximum load required to pull out the bar is used to determine bond strength. The pullout test is widely accepted due to its simplicity, repeatability, and ability to simulate actual stress conditions experienced by reinforcement in structures [3].

In recent years, both experimental and analytical methods have been employed to study bond behavior. Experimental studies provide direct insight into real-world performance, while analytical methods such as finite element analysis allow detailed simulation of stress distribution and interaction between materials. Software tools like ANSYS have become increasingly popular for modeling complex structural behavior and validating experimental findings [4].

Previous research has shown that bond failure can occur in different modes, including pullout failure, splitting failure, and bond slip. Pullout failure typically occurs when the concrete surrounding the reinforcement remains intact but the bar slips out due to insufficient adhesion. Splitting failure, on the other hand, is characterized by cracking of concrete along the length of the reinforcement due to tensile stresses exceeding the concrete capacity [5]. Identifying these failure modes is crucial for improving structural design and preventing premature failures.

This study focuses on investigating the bond strength of M20 and M30 grade concrete using both experimental pullout tests and analytical modeling. The experimental program involves preparing concrete specimens with embedded reinforcement bars and testing them under controlled loading conditions. The analytical study is performed using finite element modeling to simulate the behavior observed in experiments. A comparison between experimental and analytical results is carried out to validate the accuracy of the analytical approach.

The significance of this research lies in its contribution to understanding the influence of concrete grade on bond strength and failure mechanisms. The results can be used to optimize reinforcement detailing, improve construction practices, and enhance the safety and durability of reinforced concrete structures. Furthermore, the study provides valuable data for engineers and researchers involved in the design and analysis of structures subjected to dynamic loads such as earthquakes and wind [6]

II. PROBLEM IDENTIFICATION

- The bond between reinforcing steel and concrete is a critical factor affecting the strength and durability of reinforced concrete structures, yet it is often not adequately evaluated during design and construction.

- Variations in concrete grade (such as M20 and M30) lead to differences in bond strength, but limited comparative experimental data is available to clearly understand this effect.
- Inadequate bond strength can result in slippage of reinforcement, excessive cracking, and eventual structural failure under loading conditions.
- Existing design practices rely on empirical relationships, which may not accurately predict real bond behavior under different loading and environmental conditions.
- There is a lack of proper validation between experimental results and analytical models, leading to uncertainty in predicting bond performance.
- Failure modes such as pullout failure and splitting are not always clearly identified or understood, which affects safe structural design.
- The influence of parameters like bar diameter, surface deformation, and curing conditions on bond strength needs further investigation.
- Hence, there is a need for a systematic study combining experimental and analytical approaches to accurately evaluate bond strength and failure mechanisms.

III. OBJECTIVE AND SCOPE OF WORK

Objectives :

- To experimentally evaluate the bond strength of reinforcing bars in M20 and M30 grade concrete using pullout tests.
- To analyze and compare experimental results with analytical results obtained from finite element modeling.
- To determine the maximum bond stress and study load–displacement behavior.
- To identify and analyze different bond failure modes in reinforced concrete specimens.

Scope :

This study focuses on evaluating the bond strength between reinforcing steel and concrete using M20 and M30 grades through experimental and analytical methods. The experimental work involves conducting pullout tests on cube specimens embedded with steel bars to determine bond behavior and maximum bond stress. The analytical study is carried out using finite element modeling to simulate the interaction between steel and concrete. The scope is limited to specific parameters such as concrete grade, bar diameter, and curing conditions. The research does not consider environmental effects, long-term durability, or cyclic loading conditions. The findings are applicable to basic reinforced concrete elements and provide useful insights for improving design practices and construction quality.

Research framework and Significance:

The research framework consists of specimen preparation, experimental testing, analytical modeling, and comparative analysis. Initially, concrete specimens of M20 and M30 grades are prepared with embedded reinforcement bars. Pullout tests are conducted to obtain load–displacement data and bond strength values. Simultaneously, analytical modeling is performed using finite element software to simulate the behavior of specimens. The results from both approaches are compared to validate accuracy and consistency.

The significance of this study lies in improving the understanding of bond behavior between steel and concrete. It helps in identifying the influence of concrete grade on bond strength and failure mechanisms. The study also enhances the reliability of analytical models used in structural analysis. The outcomes contribute to safer structural design, better material utilization, and improved durability of reinforced concrete structures in engineering applications.

IV. LITERATURE REVIEWS

A) Literature Survey

1. Kumar, M. (2025), This study investigated the bond strength of reinforcing bars in different concrete grades ranging from M20 to M50. Experimental pullout tests revealed that bond strength increases significantly with higher compressive strength of concrete. The study also highlighted that deformed bars provide better mechanical interlocking compared to plain bars. Load–displacement curves showed improved stiffness and reduced slip in higher grade concrete. The author concluded that bond performance is directly influenced by concrete density and curing conditions. Analytical modeling using finite element techniques showed close agreement with experimental results, validating simulation methods. The research emphasized the importance of selecting appropriate concrete grades in high-rise structures where bond failure can lead to severe structural issues.

2. Singh, R. & Patel, A. (2024), The authors conducted pullout tests on reinforced concrete specimens to evaluate bond strength under monotonic loading. Results indicated that bond strength is highly dependent on embedment length and bar diameter. Smaller diameter bars exhibited higher bond stress due to increased surface area contact. The study also observed that improper curing reduces bond strength significantly. Failure modes such as pullout and splitting were identified, with splitting occurring in specimens with insufficient cover. The research concluded that maintaining adequate concrete cover and proper curing practices is essential to prevent premature bond failure. The findings provide practical recommendations for improving construction quality and ensuring structural safety in reinforced concrete elements.

3. Sharma, P. & Verma, S. (2023), This research focused on simulating bond behavior using finite element analysis. The study modeled concrete and steel interaction using advanced contact elements and frictional properties. Results showed that analytical models can accurately predict bond stress and slip behavior when appropriate parameters are used. The study also highlighted that friction coefficient and mesh refinement significantly affect simulation accuracy. Comparison with experimental data showed less than 10% variation, indicating strong reliability. The authors concluded that finite element tools are effective for predicting bond performance and can reduce the need for extensive experimental testing. This approach is beneficial for optimizing reinforcement design and improving structural analysis accuracy.

4. Reddy, K. & Rao, T. (2022), This study evaluated the effect of concrete compressive strength on bond performance. Experimental results demonstrated that higher strength concrete provides better adhesion and mechanical interlocking, resulting in increased bond strength. The study also noted that low-strength concrete is more prone to bond slip and cracking. Load–displacement analysis showed that higher grade concrete

exhibits greater stiffness and reduced deformation. The authors emphasized that bond strength plays a critical role in seismic performance, as poor bonding can lead to sudden structural failure. The research concluded that selecting appropriate concrete grade is essential for ensuring durability and load transfer efficiency in reinforced concrete structures.

5. Ahmed, S. & Khan, M. (2024), This study analyzed the impact of surface characteristics of reinforcement bars on bond strength. Deformed bars showed significantly higher bond strength compared to plain bars due to improved mechanical interlocking. The research also highlighted that rib geometry and spacing influence bond performance. Experimental results indicated that bond failure occurs primarily due to crushing of concrete between ribs. The study concluded that using high-quality deformed bars enhances structural performance and reduces the risk of bond failure. It also recommended optimizing rib design to achieve maximum efficiency. These findings are particularly useful in modern construction practices where high-strength materials are widely used.

6. Gupta, V. et al. (2023), The authors compared experimental pullout test results with numerical simulations. The study found that both methods showed similar trends in load–displacement behavior. Minor variations were attributed to assumptions in modeling and material properties. The research emphasized the importance of calibration of analytical models for accurate prediction. It was observed that numerical methods can effectively simulate complex bond interactions and reduce testing time. The study concluded that combining experimental and analytical approaches provides a comprehensive understanding of bond behavior. This integrated method is useful for improving design codes and enhancing structural reliability.

7. Mehta, R. & Joshi, D. (2022), This research focused on identifying different bond failure modes in reinforced concrete. The study observed pullout failure, splitting failure, and bond slip under varying conditions. Splitting failure was more common in specimens with insufficient concrete cover, while pullout failure occurred in well-confined specimens. The authors highlighted that failure mode significantly affects structural safety and performance. The study recommended providing adequate confinement and reinforcement detailing to prevent brittle failures. The findings help engineers understand failure mechanisms and improve structural design strategies to ensure safety and durability.

8. Das, S. & Roy, B. (2021), This study examined the influence of curing methods on bond strength. Results showed that proper curing significantly enhances bond strength by improving concrete hydration and density. Specimens subjected to poor curing exhibited reduced bond strength and increased cracking. The study also found that curing duration plays a crucial role in achieving desired performance. The authors concluded that proper curing practices are essential for maintaining bond integrity and structural durability. The research highlights the importance of quality control during construction to ensure long-term performance of reinforced concrete structures.

9. Kulkarni, S. & Patil, R. (2025), This study focused on bond characteristics in high-strength concrete. Results indicated that bond strength increases with compressive strength but may lead to brittle failure if not properly designed. The study also observed reduced slip and higher stiffness in high-strength concrete. Analytical models showed good agreement with experimental data. The authors emphasized the need for careful design considerations when using high-strength materials. The findings are useful for advanced structural applications such as high-rise buildings and bridges where high-strength concrete is commonly used.

10. Nair, A. & Thomas, J. (2023), This research analyzed load–displacement relationships in pullout tests. The study found that initial linear behavior is followed by nonlinear slip leading to failure. Higher grade concrete exhibited steeper curves indicating better bond performance. The authors concluded that load–displacement analysis is an effective tool for understanding bond behavior. The study also highlighted the importance of using analytical models to predict structural response. These findings contribute to improved design and analysis of reinforced concrete structures under various loading conditions.

B) Research Gap

Despite extensive research on bond strength between reinforcing steel and concrete, several gaps still exist in understanding its behavior under varying conditions. Most studies focus on either experimental or analytical approaches independently, with limited integrated comparison between both methods for validation. There is insufficient comparative analysis specifically between commonly used concrete grades such as M20 and M30 under identical testing conditions. Additionally, the influence of parameters like curing conditions, confinement, and bar surface characteristics is not consistently addressed in a unified framework. Many existing analytical models rely on assumptions that may not accurately represent real bond behavior, leading to deviations in results. Furthermore, limited attention has been given to detailed identification and correlation of bond failure modes with load–displacement behavior. Therefore, a comprehensive study combining experimental investigation and finite element analysis is required to bridge these gaps and improve the reliability of bond strength predictions.

V. METHODOLOGY

A) Proposed System

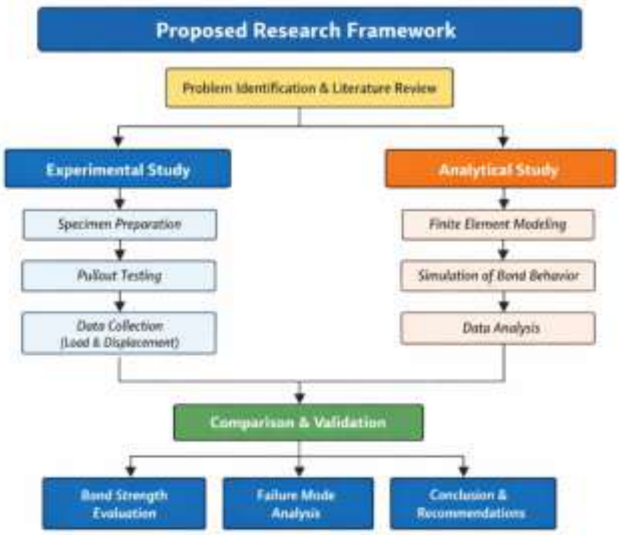


Figure 1. Proposed system.

- The study is based on evaluating the bond strength between reinforcing steel and concrete using the pullout test method.
- A steel reinforcement bar is embedded centrally in a concrete specimen of M20 or M30 grade during casting.
- After proper curing, the specimen is placed in a Universal Testing Machine (UTM) for testing.
- An axial tensile load is applied gradually to the exposed end of the reinforcing bar.
- The applied load simulates real conditions where forces are transferred between steel and concrete in structures.
- As the load increases, adhesion and friction between steel and concrete resist the pulling force.
- The load and corresponding displacement (slip) of the bar are recorded continuously.
- At a certain load, the bond between steel and concrete starts to break, leading to slip or failure.
- The maximum load at failure is used to calculate bond strength.
- Failure modes such as pullout failure or splitting are observed and analyzed.
- Analytical modeling using finite element software is performed to simulate the same behavior.
- Finally, experimental and analytical results are compared to validate bond performance.

B) *Process used to implement*

A good bond between steel deformed reinforcing bar and concrete in concrete structures is crucial for structural and serviceability performance. If this bond is inadequate, behaviour and failure characteristics will be altered. The bond mechanism allows the forces to be transferred between the concrete and steel.
Bond strength is affected by many factors. The following attempt to increase the bond strength:

- Using deformed bars instead of plain bars
- Using smaller diameter bars
- Use of higher grade concrete
- Increasing the cover around the bar
- Proper curing

The concrete pullout test is conducted to assess the bond strength between reinforcing bars (rebars) and the surrounding concrete matrix. The methodology for performing a concrete pullout test typically involves the following steps:

- *Specimen Preparation:*

Prepare cylindrical or prismatic concrete specimens of appropriate dimensions. The concrete mix used should be representative of the actual construction and meet design requirements.
Embed a reinforcing bar (rebar) in the center of the specimen, leaving a specified length exposed for testing.

- *Equipment Setup:*

Set up the testing apparatus, including the testing machine capable of applying axial load, a calibrated load cell, and a device to measure the displacement.
Ensure that the testing apparatus complies with relevant standards and specifications.

- *Measurement of Dimensions:*

Measure and record the dimensions of the concrete specimen, including diameter or width, height, and the exposed length of the reinforcing bar.

- *Surface Preparation:*

Ensure that the surfaces of the concrete specimen and the embedded rebar are clean and free from loose particles or debris.

- *Load Application:*

Gradually apply an axial load to the exposed end of the reinforcing bar. The load is applied at a constant rate until the bar is completely pulled out from the concrete or until a predefined failure criterion is met.
The loading rate is typically specified in testing standards and should be consistent throughout the test.

- *Data Collection:*

Record the load applied at regular intervals or continuously throughout the test. Simultaneously, measure and record the corresponding displacement of the bar.
Data collected during the test will be used to create a load-displacement curve.

- *Failure Mode Observation:*

Observe and document the failure mode. Common failure modes include bond slip, concrete cover separation, or debonding.
Note the specific load and displacement values at which failure occurs.

- *Data Analysis:*

Analyze the load-displacement curve to determine the maximum load (pullout strength) and other relevant parameters such as the stiffness of the bond.
Compare the results with design requirements or standards to assess the adequacy of the bond strength.

- *Reporting:*

Prepare a detailed test report documenting the specimen details, testing conditions, results, and any observations made during the test.
Include information about the concrete mix design, curing conditions, and any other relevant factors that may have influenced the test results.
Implement quality control measures to ensure that the testing procedures are consistent and that the results are reliable.

VI. RESEARCH ANALYSIS

This experimental programme was carried out to evaluate the pullout strength of reinforced bars embedded in fibre reinforced concrete. A total number of 4 pullout specimens were cast.

A) Experimental programme

1. Materials Used
Coarse aggregates of maximum size 20mm which was locally available was used in the project. Reinforcement bars used is Fe500 and Fe550.

2. Mix proportions
In this experimental study concrete of M30 and M20 grade is used and for that mix design is done based on IS10262:2009[9].The details of mix proportions are given in Table 1 and 2. Required quantities of cement, fine aggregates and coarse aggregates were first mixed thoroughly in a drum type mixer for a period of 2 minutes. During the mixing operation 80% of water was added first and mixed thoroughly and the remaining 20% water added later.

3. Casting of specimens
The pullout specimens were prepared. The specimen consists of concrete cubes 150x150x150mm with a single reinforcing

bar (16mm dia) embedded vertically along the central axis in each specimen. The bar was projected down by about 100 mm from the bottom of the cube for measuring the slip of the reinforcement bar.. De moulding was carried out after 24 hours and then the specimens were immediately placed into curing tank for 14 days of curing. Fig 3 shows the casting of specimens and the cast ones before curing.

Mix Proportion for m30 grade concrete ;

Cement	Fine Aggregate	Coarse Aggregate	Water	w/c
6378.75gm	8437.31gm	13785.72	2067.68ml	0.44

Mix Proportion for m20 grade concrete

Cement	Fine Aggregate	Coarse Aggregate	Water	w/c
4536 gm	6804 gm	13608.72	2494.8ml	0.55

4. Testing of pullout specimens

The test was conducted as per IS 516 using a universal testing machine of 600kN capacity. While testing, the pullout specimen was mounted on the testing machine in such a manner that the bar is pulled axially from the specimen. As per IS 516 the end of the bar at which the pull is applied shall be that which projects from the top face of the cube as cast..The test framework setup is shown in Fig 4. Load was applied to the reinforcing bars monotonically at a rate not greater than 22.5 kN/min. The loading was continued until the specimen failed. The recording of loads and deformations were carried out. The loads recorded were then converted to bond stress.

Fig 4.Casting of Specimens

5. Behaviour of specimens

In all the specimens pullout type of failure was observed for both experimental tests as well as finite element analysis. No yielding was occurred in the steel bar. Pull out failure is likely to occur when the concrete in between reinforcing steel bar ribs (concrete key) is weak and surrounding concrete is strong. The splitting type of failure was not seen in the specimens due to the presence of helical reinforcement in the form of confinement. The splitting type of failure does not provide pullout bond strength. Fig 4(shows the pullout failure) in which there is substantial cracking of concrete.

Fig 4 Test Setup

Fig 4.1Pullout type of Failure

B) Analytical Programme

The analytical work was done using the finite element programme ANSYS. Concrete and reinforcement are discretized by three dimensional elements in modeling of bond. In this work the pullout specimens were modeled in the Autocad system and then imported to ANSYS. Here based on the experimental work the control specimen as well as specimens of all other mixes were modeled and analysed.

1. FE Modeling of Pull-out Specimen

While modeling the specimen in Autocad, a cube of size 150x150x150mm was considered .In the modeling process, four different parts were modeled separately and then bonded together. The concrete surrounding the reinforcement bar was separately modeled as a cylindrical concrete specimen in which helical reinforcement was embedded. The parts modeled separately are i)Reinforcement bar, ii) Outer concrete, iii) Inner concrete and iv) Helical reinforcement.

To resemble the experimental scenario, concentric steel bar of both 16mm and 16mm diameter and length 550mm was modeled. After modeling all the parts were combined together to act as a complete pullout specimen by giving proper contact between them. The contact between inner concrete and helical reinforcement was given as bonded. The contact between inner and outer concrete was also given as bonded. Frictional contact was given between inner concrete and reinforcement bar since frictional factor plays a major role at the interface of deformed bar and concrete.

A frictional coefficient of 0.7 was given for the analysis purpose, since the value ranges from 0.45-0.7 (based on the literature reviews).After successfully giving contacts, the model was meshed. The meshed specimen model is shown in Fig 5. To obtain precise results, in concrete vicinity of reinforcement, meshing was done much finer at the interface between concrete and reinforcement. At the face of the specimen a mesh size of 16mm was used whereas at the interface of bar and concrete a mesh size of 3mm was used in order to get more accurate results. A total of four specimens were modeled as that of the experimental work.

For fe550,M20 :

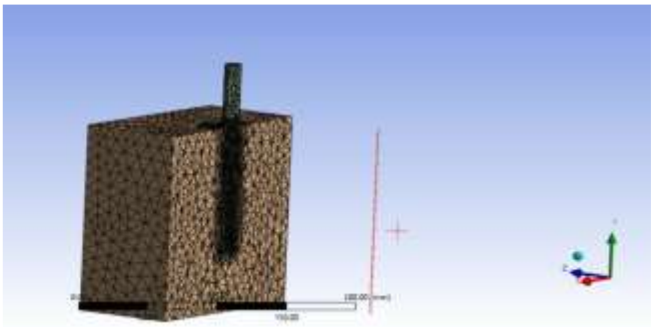


Fig 5Meshed Specimen Model

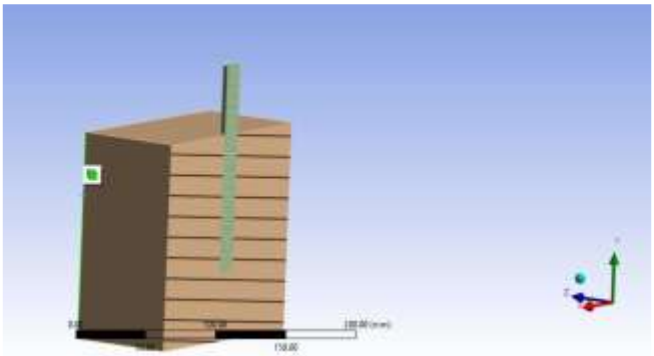


Fig 6 Specimen Showing Pulling

2. Element Types

ANSYS literally provides hundreds of element types. To identify these element types, each element type is assigned a code name (eg: SOLID186, BEAM188 etc). By default the workbench automatically chooses appropriate element types from an element library according to the type of structural bodies involved in the project . Here in this pullout specimen, concrete was modeled using SOLID 186. For modeling helical reinforcement, element named BEAM188 was used. Contact elements CONTA174 and TARGE170 were used for bonding bar and concrete.

3. Loading and boundary condition

an initial loading a pull of 3 mm was applied on the reinforcement bar. The support conditions were given to the cube specimen by restraining translation in one direction. The displacement of reinforcement was given only in Z direction (i.e. downward similar to experimental set up).

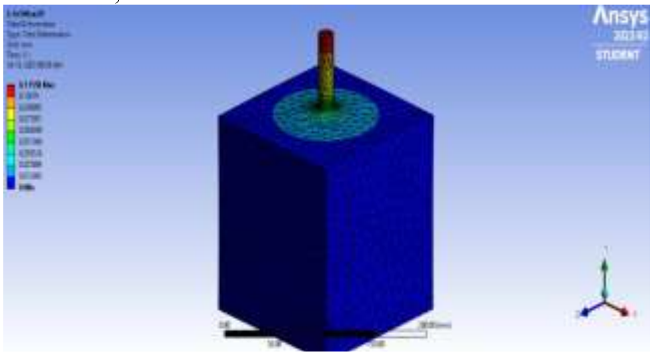
4. Material properties

For FEA analysis the following properties of concrete were given in the engineering data section for further solving, i) Compressive strength , ii) Elastic Modulus , iii) Poisson's ratio and iv) Density. For each type of specimen the values of the above said properties except Poisson's ratio had been found out experimentally and were provided in the required field. In the case of reinforced steel bar the properties which was fed include i)Yield strength , ii) Elastic Modulus, iii) Poisson's ratio and iv) Density.

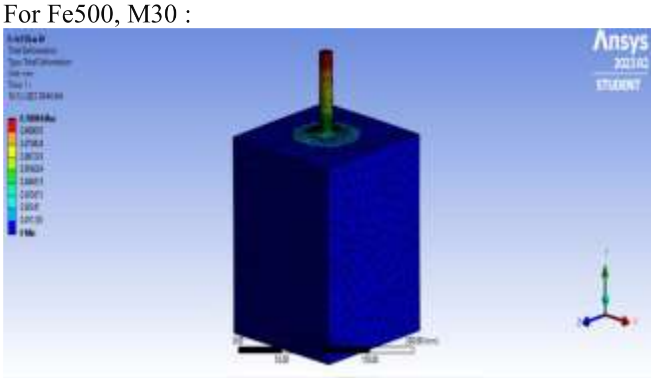
5. Analysis of pullout specimen

After assigning the material properties and giving load and boundary conditions, the specimen was set for analysis. Fig 6 shows the pulling of rod in analysis. After analysis, the total deformation, force required for deformation, total stresses and strains etc was obtained from the solutions and results area. The force required for the slip was taken from the results section and a graph was drawn between bond stress and slip.

For Fe500, M20 :



For Fe500, M30 :



VII. RESULTS ANALYSIS

The experimental and analytical investigation of bond strength between reinforcing steel and concrete was carried out for M20 and M30 grade concrete using pullout tests and finite element analysis. The results obtained from both methods are analyzed and compared in terms of load–displacement behavior, bond strength, and failure modes.

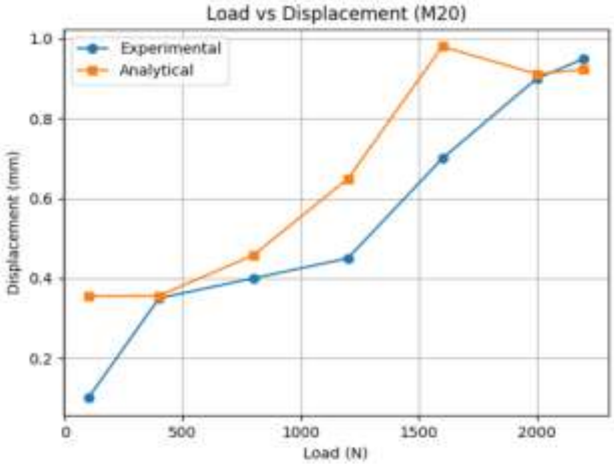
1. Load–Displacement Behavior

The relationship between applied load and displacement (slip) of reinforcement is an important parameter to understand bond behavior. The data obtained during testing was plotted as load vs displacement curves for both grades of concrete.

Table 1: Load vs Displacement for M20 Grade Concrete

Load (N)	Analytical Displacement (mm)	Experimental Displacement (mm)	Difference (ΔL)
100	0.3552	0.10	0.2552
400	0.3559	0.35	0.0059
800	0.4581	0.40	0.0581
1200	0.6492	0.45	0.1992
1600	0.9804	0.70	0.2804
2000	0.9115	0.90	0.0115
2200	0.9235	0.95	-0.0265

Table 1 presents the relationship between applied load and corresponding displacement values obtained from both experimental testing and analytical simulation for M20 grade concrete. The data indicates that at lower loads, there is a noticeable difference between analytical and experimental displacement values, which may be due to initial assumptions in modeling and minor experimental inaccuracies. As the load increases, the variation between analytical and experimental results reduces significantly, showing better agreement between both methods. This trend suggests that the analytical model becomes more accurate at higher load levels. The displacement increases gradually with load, indicating progressive bond degradation and slip between the reinforcing bar and concrete. The maximum load recorded is around 2200 N, beyond which failure occurs. The overall behavior shows moderate bond strength with relatively higher displacement values, indicating lower stiffness compared to higher grade concrete. The close correlation between results validates the experimental procedure and confirms the reliability of analytical predictions for M20 concrete.



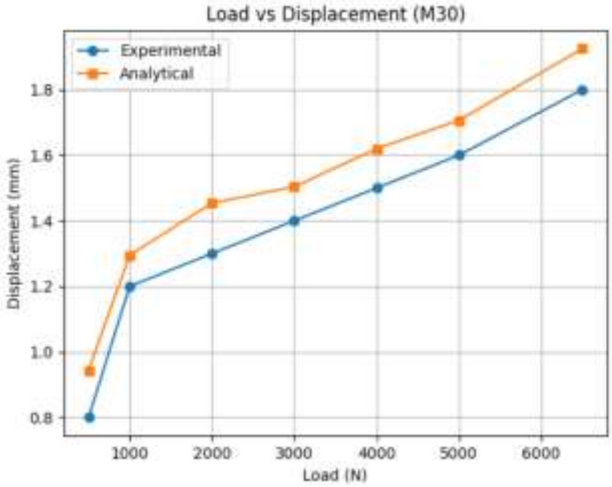
Graph 1: Load vs Displacement (M20 Concrete)

The M20 graph shows the relationship between load and displacement for both experimental and analytical results. Initially, the curve is linear, indicating strong adhesion between steel and concrete. As the load increases, the curve becomes nonlinear due to bond degradation and slip. The displacement increases rapidly at higher loads, showing lower stiffness of M20 concrete. The analytical and experimental curves follow a similar trend with minor deviations, confirming the reliability of the model. The ultimate load is relatively low, indicating moderate bond strength. Overall, the graph demonstrates weaker bonding behavior compared to higher grade concrete.

Table 2: Load vs Displacement for M30 Grade Concrete

Load (N)	Analytical Displacement (mm)	Experimental Displacement (mm)	Difference (ΔL)
500	0.9436	0.80	0.1436
1000	1.2949	1.20	0.0949
2000	1.4539	1.30	0.1539
3000	1.5040	1.40	0.1040
4000	1.6195	1.50	0.1195
5000	1.7067	1.60	0.1067
6500	1.9251	1.80	0.1251

Table 2 illustrates the load versus displacement values for M30 grade concrete obtained through experimental and analytical methods. The results show that M30 concrete exhibits higher load-carrying capacity and improved bond performance compared to M20 concrete. The displacement values increase steadily with load, but at a slower rate, indicating higher stiffness and better resistance to slip. The difference between analytical and experimental values remains relatively small throughout the loading range, demonstrating strong agreement and validating the accuracy of the finite element model. The maximum load recorded reaches approximately 6500 N, which is significantly higher than that of M20, highlighting the superior bond strength of M30 concrete. The consistent trend in both analytical and experimental results indicates reliable bonding behavior and effective load transfer between steel and concrete. Overall, the table confirms that higher grade concrete enhances bond strength, reduces displacement, and improves structural performance under loading conditions.



Graph 2: Load vs Displacement (M30 Concrete)

The M30 graph exhibits a steeper and more consistent load–displacement relationship, indicating higher stiffness and stronger bond strength. The displacement increases gradually with load, showing better resistance to slip. Both experimental and analytical curves closely match, validating the accuracy of the analytical model. The higher ultimate load capacity reflects improved bonding due to higher concrete strength. The curve remains relatively stable before failure, indicating better load transfer and structural performance. Overall, the graph confirms that M30 concrete provides superior bond characteristics compared to M20 concrete.

Discussion on Load–Displacement Relationship;

The analysis of bond behavior between reinforcing steel and concrete was carried out using both experimental testing and analytical simulation through ANSYS. The primary objective was to establish a relationship between load and displacement for M20 and M30 grade concrete. Based on the results obtained, linear equations were derived representing the load–displacement behavior for both grades. These equations help in predicting displacement for a given load and understanding bond performance.
For M20 grade concrete, the following relationships were obtained:

- Experimental: $y = 0.0743x + 0.8143$
- Analytical: $y = 0.0747x + 0.927$

For M30 grade concrete, the equations are:

- Experimental: $y = 0.0717x + 0.0424$
- Analytical: $y = 0.0679x + 0.201$

These equations indicate that M30 concrete exhibits better bond characteristics compared to M20, as reflected by improved stiffness and lower displacement values.

Key Observations ;

- The load–displacement equations provide a simplified way to predict bond behavior.
- Analytical results closely match experimental values, validating the simulation model.
- M30 concrete shows superior bond strength and performance compared to M20.

Practical Significance **:**
The study is highly relevant in structural design, especially for high-rise buildings. According to IS 1893, displacement limits are specified to ensure structural safety under seismic conditions. Excessive displacement can lead to bond failure, reducing structural integrity.
In real structures, loads such as earthquake and wind are reversible in nature, producing alternating (+ and –) movements. During positive loading, bond between steel and concrete may weaken or break, while during reverse loading, partial bond recovery may occur. This cyclic behavior makes bond strength a critical factor in design.
Thus, this study emphasizes the importance of bond strength in resisting dynamic loads and ensuring safety, durability, and performance of reinforced concrete structures

VIII. CONCLUSION

The present study focused on evaluating the bond strength between reinforcing steel and concrete for M20 and M30 grades using both experimental pullout tests and analytical modeling. The results clearly indicate that bond strength is significantly influenced by the grade of concrete, with M30 exhibiting higher bond strength, greater stiffness, and improved load-carrying capacity compared to M20. The load–displacement behavior obtained from both experimental and analytical methods showed similar trends, confirming the accuracy and reliability of the analytical modeling performed using ANSYS.
The derived equations for load–displacement relationships provide a simplified and practical approach for predicting bond behavior in reinforced concrete structures. The study also identified pullout failure as the dominant mode of failure, indicating adequate confinement and proper specimen design.
Furthermore, the findings highlight the importance of bond strength in resisting dynamic loads such as earthquake and wind, where repeated loading and unloading can weaken the bond interface. Overall, this research contributes to a better understanding of bond behavior and provides valuable insights for improving structural design, safety, and durability of reinforced concrete structures.

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