Non-destructive detection of bond slip failure in fiber reinforced concrete using piezo sensors

Ramesh Gomasa [0000-0001-9258-2826], Anil Kumar Mangalampalli [0009-0009-9881-9025], Visalakshi Talakokula \*[0000-0002-1791-7830], Sri Kalyana Rama Jyosyula [0000-0003-4945 4161], Mounika Battula, Sathwika Chellam

Department of Civil Engineering, École Centrale School Engineering, Mahindra University, Hyderabad 500043, India

\*Corresponding author: [basavishali@gmail.com](mailto:basavishali@gmail.com)

**Abstract.** Bond slip failure in fiber-reinforced concrete (FRC) is a critical issue that compromises structural performance. This study presents a non-destructive method for identifying bond slip failure of dog bone-shaped polypropylene fiber (PPF) and steel fiber (SF) concrete specimens with varying fiber dosages of 1%, 1.5% and 2% of volume using piezo sensors. The PPF and SF concrete specimens are subjected to a controlled rate of loading under displacement control using a universal tensile testing machine. The electro-mechanical impedance (EMI) technique is employed to acquire data from the piezo sensors. Additionally, root mean square deviation (RMSD) method is used to quantify the progression of bond slip damage from the EMI data. The experimental results shown a significant reduction in bond slip, with a load increase of 63.58% for 1.5% SF and 107.24% for 2% SF compared to the 1% SF dosage. For PPF, there is a substantial load increase of 54% for 1.5% and 18.40% for 2% compared to the 1% PPF dosage. This highlights the critical need for optimizing fiber dosages, and potentially incorporating hybrid fibers, to enhance structural performance and achieve more consistent improvements in bond slip reduction. The study concludes that piezo sensors are effective in providing early detection and continuous monitoring of bond slip failure in FRC, thereby contributing to improved structural performance.

**Keywords:** Steel fiber; Polypropylene fiber; Bond slip failure; Piezo sensor; EMI technique.

# Introduction

Fiber-reinforced concrete (FRC) has gained significant attention in the construction industry due to its enhanced mechanical properties, including increased tensile strength, toughness, and impact resistance 1. The addition of fibers such as steel fibers (SF) and polypropylene fibers (PPF) into the concrete matrix improves its ability to resist crack propagation and enhances its post-cracking behavior 23. These fibers act as reinforcement, bridging the cracks that develop under stress and providing additional load-bearing capacity 4. Consequently, FRC is widely used in various applications, including pavements, bridge decks, tunnels, industrial floors, and earthquake-resistant structures 5. The effectiveness of fiber reinforcement heavily relies on the bond between the fibers and the concrete matrix. Bond slip failure occurs when the bond between fiber and concrete matrix fails during mechanical loading, leading to a loss of composite action 67. This type of failure is particularly critical in structures subjected to cyclic or dynamic loading, such as bridges, high-rise buildings, and offshore platforms, where bond slip can compromise structural integrity and reduce the service life of the concrete 8.

Traditional methods for assessing bond slip, such as pull-out tests and microscopic observations, are inherently destructive, labor-intensive, and not feasible for real-time monitoring or continuous evaluation of a structure’s health. Additionally, these methods do not provide early detection of damage, which is crucial for timely maintenance and repair 9. Non-destructive testing (NDT) methods are therefore needed to detect bond slip in FRC efficiently and effectively 1011. Existing NDT techniques, such as ultrasonic pulse velocity (UPV) and ground-penetrating radar (GPR), have limitations in detecting subtle bond slip failures, particularly in complex structures 12. These techniques may require extensive surface preparation and may lack the sensitivity to detect early-stage bond degradation. The electro-mechanical impedance (EMI) technique, utilizing piezo sensors, offers a promising solution for non-destructive detection and monitoring of bond slip failure in FRC 1314. Piezo sensors are highly sensitive to mechanical strain and can detect minute changes in the structural properties of materials 1516. These sensors were attached or embedded in the structure to capture changes in the impedance response, thereby identifying any damage 171819. The objective of this study is to develop a non-destructive method for detecting bond slip failure in fiber-reinforced concrete using piezo sensors and the EMI technique. This research investigates the influence of different fiber dosages (1%, 1.5%, and 2% by volume) on bond slip performance and determines the optimal dosage for minimizing bond slip failures. The study also provides a comparative analysis of the effectiveness of steel and polypropylene fibers in mitigating bond slip failure and assesses the capability of piezo sensors to detect bond slip failure in concrete specimens reinforced with these fibers.

# Materials and methods

The FRC specimens were prepared according to the mix proportions provided in Table 1. The mix designed to achieve a high-strength concrete matrix incorporating various fibers to enhance its mechanical properties and performance. The matrix included a combination of ordinary Portland cement (OPC), ground granulated blast furnace slag (GGBS), silica fume, manufactured sand (M-Sand), water and a superplasticizer (SP) to improve workability. Fibers such as steel and polypropylene were incorporated in FRC to enhance crack resistance and toughness. Table 2 shows the properties of the polypropylene and steel fibers used in this study.

Table 1 Mix Proportioning of FRC

|  |  |
| --- | --- |
| Materials | Quantity (kg/m3) |
| OPC | 650 |
| GGBS | 330 |
| Silica fume | 140 |
| Water | 207 |
| M-Sand | 950 |
| SP | 12.8 |

Table 2 Properties of polypropylene and steel fibers

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Fiber Type | Density  (kg/m3) | Tensile Strength (MPa) | Elastic modulus (GPa) | Diameter (mm) | Length(mm) |
| Steel | 7850 | 2100 | 205 | 0.8 | 60 |
| Polypropylene | 910 | 450 | 120 | 0.05 | 20 |

# Preparation of FRC specimens

The mix proportions outlined in Table 1 were used to prepare briquette-shaped specimens. Six sets of concrete mixes were prepared, each with different dosages of fibers (1%, 1.5%, and 2% by volume for both steel and polypropylene fibers). The mixing process started with dry materials (OPC, GGBS, silica fume, and M-sand) blended in a mortar mixer for two minutes to achieve a uniform dry mix. Water and the SP were gradually added to the dry mix, and mixing continued for an additional three minutes. Fibers were then added to the mix, carefully sprinkled into the mortar mixer to ensure even distribution. Mixing continued for another five minutes to achieve a homogeneous concrete mix with evenly dispersed fibers. The concrete was then transferred into briquette-shaped molds pre-coated with a lubricate agent to facilitate easy demolding. The molds were filled in two layers, each compacted using a vibrating table to eliminate air voids and ensure a dense specimen. The top surface of the molds was leveled and finished with a trowel to achieve a smooth finish. The specimens were left in the molds for 24 hours under ambient conditions to set as shown in Fig. 1. After hardening, the specimens were demolded and subjected to saturated lime water curing for six days to promote early strength gain.



Fig. 1 Dog bone-shaped PPF and SF concrete specimens

Once the specimens were cured and dried, piezo sensors were bonded to the surface of each briquette-shaped specimen. A thin layer of high-strength epoxy adhesive was applied to the prepared surface of the concrete specimen, and the piezo sensor was carefully positioned onto the adhesive layer, pressed gently to ensure full contact with the concrete surface. Fig. 2 shows electrode connections of the piezo sensors using coaxial wires after hardening of adhesive.



Fig. 2 Specimens with piezo sensors for bond slip testing

# Experimental program

After installing the piezo sensors, the FRC specimens were subjected to the direct pullout test. Each specimen was clamped between the upper and lower chucks of a universal tensile testing machine (UTM) configured to apply tensile forces in a displacement-controlled mode. The piezo sensors were connected to an LCR meter, which measures the electrical admittance of the specimens during the test. The LCR meter and VEE pro software were used as a data acquisition system to record the admittance signatures. The tensile tests were performed on the FRC specimens under displacement control at a constant displacement rate until failure. The healthy state and damaged state data is acquired from the LCR meter to monitor the bond slip failure. Fig. 3 shows experimental set-up for bond slip identification of FRC specimens.

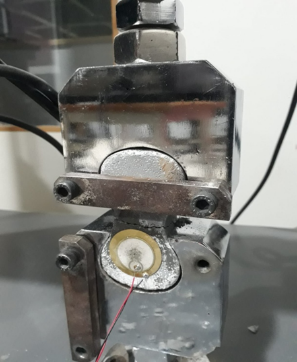
 

Fig. 3 Experimental set-up for bond slip testing

# Results and discussion

# Mechanical performance of FRC

The compressive strength (CS) and tensile strength (TS) results for the different FRC specimens with varying fiber dosages, as shown in Fig. 4, indicate that both SF and PPF significantly enhance the mechanical properties of concrete. For SF concrete specimens, increasing the dosage from 1% to 2% resulted in significant improvements in both tensile and compressive strength. The experimental results show a significant reduction in bond slip, with a load increase of 63.58% for 1.5% SF and 107.24% for 2% SF compared to the 1% SF dosage. For PPF concrete specimens, the optimal dosage for maximizing tensile strength was found to be 1.5%. Beyond this dosage, performance did not improve due to fiber clustering and reduced fiber-matrix bonding associated with the high fiber content 202122. The results further demonstrate a substantial load increase of 54% for 1.5% PPF and 18.40% for 2% PPF compared to the 1% PPF dosage.

Fig. 4 Compressive strength and tensile strength of PPF and SF concrete

**5.2** **Conductance signature analysis of PPF concrete**

The conductance signature analysis for PPF concrete as shown in Fig. 5 demonstrates that increasing the fiber dosage improves the bond strength between the fibers and the concrete matrix, thereby delaying the bond slip failure. At 1.5% fiber dosage appears to be the most effective in enhancing bond strength, as indicated by the minimal shift in conductance signatures under loading. However, beyond this dosage, the benefits may start to diminish due to fiber dispersion and bonding efficiency. The results suggest that an optimal fiber dosage exists for PPF concrete, beyond which the effectiveness in mitigating bond slip failure may not increase correspondingly.

Fig. 5 Conductance signature analysis of PPF concrete

**5.3 Conductance signature analysis of SF concrete**

The conductance signatures obtained using the EMI technique reveal that correlate with the bond slip failure in SF concrete. Reduced shifts as shown in Fig. 6 in SF concrete suggest that increased fiber content enhances bond strength and delays the bond slip failure. The superior performance of SF concrete, especially at a 2% dosage, aligns with the higher mechanical properties of steel fibers, which contribute to better load transfer and reduced micro-cracking at the fiber-matrix interface.

Fig. 6 Conductance signature analysis of SF concrete

The conductance signature shifts in the EMI data reflects the degree of bond slip failure within the FR concrete. The reduced shifts in specimens with higher fiber dosages, particularly with steel fibers, suggest that increased fiber content enhances bond strength and delays the bond slip failure. The superior performance of SF concrete, especially at a 2% dosage, aligns with the higher mechanical properties of steel fibers, including higher modulus of elasticity and tensile strength, which contribute to better load transfer and reduced micro-cracking at the fiber-matrix interface. The moderate performance at a 2% PPF dosage further supports the idea of an optimal fiber content, beyond which the bond slip or resistance decreases.

**5.4 Quantification of bond slip using RMSD analysis**

The RMSD analysis quantified the bond slip damage as shown in Fig. 7. The results show a significant decrease in RMSD with increasing fiber dosages, particularly for steel fibers, indicating enhanced bond strength and reduced bond slip failure. The decrease in RMSD up to a 2% SF concrete dosage suggests that higher fiber dosages provide greater reinforcement effectiveness. In contrast, PPF concrete showed optimal performance at a 1.5% dosage, with a slight increase in RMSD at higher dosages due to potential fiber clustering.

Fig. 7 Quantification of bond slip using RMSD

1. **Conclusion**

This study presents a non-destructive technique for detecting bond slip failure in PPF concrete and SF concrete with varying fiber dosages of 1%, 1.5% and 2% using piezo sensors. The results from both the mechanical tests and the conductance signature analysis confirm that type of fiber and dosage significantly affect the bond slip performance of FRC. SF concrete provide superior reinforcement compared to PPF concrete, particularly at higher dosages, enhancing both tensile and compressive strengths and bond slip resistance. The RMSD analysis effectively quantifies the bond slip failure in PPF concrete and SF concrete, highlighting the importance of selecting appropriate fiber types and dosages to optimize structural performance. These findings highlight the need to consider both material properties and optimal fiber content when designing FRC for specific structural applications, ensuring enhanced performance under loading conditions.

# References

1. Yoo DY, Banthia N. Mechanical and structural behaviors of ultra-high-performance fiber-reinforced concrete subjected to impact and blast. *Constr Build Mater*. 2017;149:416-431. doi:10.1016/j.conbuildmat.2017.05.136

2. Wang W, Zhang Y, Mo Z, Chouw N, Jayaraman K, Xu Z dong. A critical review on the properties of natural fibre reinforced concrete composites subjected to impact loading. *J Build Eng*. 2023;77(June):107497. doi:10.1016/j.jobe.2023.107497

3. Ahmad J, Zhou Z. Mechanical Properties of Natural as well as Synthetic Fiber Reinforced Concrete: A Review. *Constr Build Mater*. 2022;333(March):127353. doi:10.1016/j.conbuildmat.2022.127353

4. Yoo DY, Banthia N. Mechanical properties of ultra-high-performance fiber-reinforced concrete: A review. *Cem Concr Compos*. 2016;73:267-280. doi:10.1016/j.cemconcomp.2016.08.001

5. Zhao C, Wang Z, Zhu Z, Guo Q, Wu X, Zhao R. Research on different types of fiber reinforced concrete in recent years: An overview. *Constr Build Mater*. 2023;365(December 2022):130075. doi:10.1016/j.conbuildmat.2022.130075

6. Deng Y, Zhang Z, Shi C, Wu Z, Zhang C. Steel Fiber–Matrix Interfacial Bond in Ultra-High Performance Concrete: A Review. *Engineering*. 2023;22:215-232. doi:10.1016/j.eng.2021.11.019

7. Zheng Y, Fan C, Ma J, Wang S. Review of research on Bond–Slip of reinforced concrete structures. *Constr Build Mater*. 2023;385(March):131437. doi:10.1016/j.conbuildmat.2023.131437

8. Tatar J, Milev S. Durability of externally bonded fiber-reinforced polymer composites in concrete structures: A critical review. *Polymers (Basel)*. 2021;13(5):1-26. doi:10.3390/polym13050765

9. Huo L, Cheng H, Kong Q, Chen X. Bond-slip monitoring of concrete structures using smart sensors—A review. *Sensors (Switzerland)*. 2019;19(5). doi:10.3390/s19051231

10. Chen H, Nie X, Gan S, Zhao Y, Qiu H. Interfacial imperfection detection for steel-concrete composite structures using NDT techniques: A state-of-the-art review. *Eng Struct*. 2021;245(June):112778. doi:10.1016/j.engstruct.2021.112778

11. Shan W, Liu J, Ding Y, Mao W, Jiao Y. Assessment of bond-slip behavior of hybrid fiber reinforced engineered cementitious composites (ECC) and deformed rebar via AE monitoring. *Cem Concr Compos*. 2021;118(December 2020). doi:10.1016/j.cemconcomp.2021.103961

12. Purnomo H, Chalid M, Pamudji G, Arrifian TW. Bond–Slip Relationship between Sand-Coated Polypropylene Coarse Aggregate Concrete and Plain Rebar. *Materials (Basel)*. 2022;15(7). doi:10.3390/ma15072643

13. Dugnani R, Zhuang Y, Kopsaftopoulos F, Chang FK. Adhesive bond-line degradation detection via a cross-correlation electromechanical impedance–based approach. *Struct Heal Monit*. 2016;15(6):650-667. doi:10.1177/1475921716655498

14. Zapris AG, Naoum MC, Kytinou VK, Sapidis GM, Chalioris CE. Fiber Reinforced Polymer Debonding Failure Identification Using Smart Materials in Strengthened T-Shaped Reinforced Concrete Beams. *Polymers (Basel)*. 2023;15(2). doi:10.3390/polym15020278

15. Ju M, Dou Z, Li JW, et al. Piezoelectric Materials and Sensors for Structural Health Monitoring: Fundamental Aspects, Current Status, and Future Perspectives. *Sensors*. 2023;23(1). doi:10.3390/s23010543

16. Parida L, Moharana S, Ferreira VM, Giri SK, Ascensão G. A Novel CNN-LSTM Hybrid Model for Prediction of Electro-Mechanical Impedance Signal Based Bond Strength Monitoring. *Sensors*. 2022;22(24). doi:10.3390/s22249920

17. Jiao P, Egbe KJI, Xie Y, Nazar AM, Alavi AH. Piezoelectric sensing techniques in structural health monitoring: A state-of-the-art review. *Sensors (Switzerland)*. 2020;20(13):1-21. doi:10.3390/s20133730

18. Gomasa R, Talakokula V, Kalyana S, Jyosyula R, Bansal T. A review on health monitoring of concrete structures using embedded piezoelectric sensor. *Constr Build Mater*. 2023;405(August):133179. doi:10.1016/j.conbuildmat.2023.133179

19. Ai D, Zhu H, Luo H, Wang C. Mechanical impedance based embedded piezoelectric transducer for reinforced concrete structural impact damage detection: A comparative study. *Constr Build Mater*. 2018;165:472-483. doi:10.1016/j.conbuildmat.2018.01.039

20. Sudhir A, Talreja R. Simulation of manufacturing induced fiber clustering and matrix voids and their effect on transverse crack formation in unidirectional composites. *Compos Part A Appl Sci Manuf*. 2019;127(June):105620. doi:10.1016/j.compositesa.2019.105620

21. Li J, Yang L, Xie H, et al. Experimental investigation on interfacial bonding performance between cluster basalt fiber and cement mortar. *Constr Build Mater*. 2024;411(November 2023):134215. doi:10.1016/j.conbuildmat.2023.134215

22. Zhuang L, Pupurs A, Varna J, Ayadi Z. Fiber/matrix debond growth from fiber break in unidirectional composite with local hexagonal fiber clustering. *Compos Part B Eng*. 2016;101:124-131. doi:10.1016/j.compositesb.2016.07.005