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COMPREHENSIVE REVIEW ON ADVANCES IN ARTIFICIAL INTELLIGENCE FOR PREDICTION OF BOND STRENGTH BETWEEN REINFORCEMENT AND CONCRETE

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Abstract:
This study provides a detailed analysis of current advances in Artificial Intelligence (AI) applied to forecasting bond strength between reinforcement and concrete in civil engineering. The bond strength at the interface between reinforcement bars and concrete is a critical characteristic impacting reinforced concrete constructions' structural stability and durability. Traditional approaches for calculating bond strength frequently rely on empirical formulae and considerable laboratory testing, which may be time-consuming and costly. In this paper, the authors demonstrate how machine learning algorithms, neural networks, and deep learning models have advanced bond strength prediction. The author also looks at how AI may be used with non- destructive testing techniques and sensor data to monitor and evaluate bond strength in real-time and on the spot. Moreover, the author addresses the difficulties in implementing AI, such as data quality and model interpretability. The combination of AI with bond strength prediction has the potential to advance reinforced concrete structure design and construction, eventually boosting safety and durability. This paper sheds light on the potential for AI to alter how we evaluate and optimize the bond strength between reinforcement and concrete, making it an invaluable resource for academics, engineers, and practitioners in civil engineering.

Key words: Artificial Intelligence, Bond Strength, Concrete-Steel composite, Prediction, Sustainability

1. Introduction

The built environment has been significantly shaped by reinforced concrete, frequently referred to as the foundation of contemporary buildings. Reinforced concrete structures have shown to be remarkably resilient, long-lasting, and adaptable throughout the past century by combining the compressive strength of concrete with the tensile strength of steel reinforcement. Along with expanding architectural options, reinforced concrete technology has tackled essential problems in structural engineering, sustainability, and urban development [1-3]. The performance and stability of different civil engineering structures, such as buildings, bridges, and dams, depend significantly on the bond strength between steel and concrete, a critical structural engineering component. The bond strength between reinforcement and concrete is crucial when designing and evaluating reinforced concrete buildings [4]. It directly impacts the structural integrity, load-carrying capacity, and durability of these structures, making it a critical concern for civil engineers and researchers. Accurate bond strength prediction and optimization have long been essential goals in structural design and construction, driven by the requirement to assure the safety and performance of concrete components subjected to varying environmental and loading conditions [5]. In the past, bond strength prediction has depended on empirical models and laboratory testing methods that give valuable but limited insights into the intricate interactions between reinforcement and concrete [6]. These traditional methodologies have inherent limitations, frequently failing to capture the whole range of parameters that impact bond strength, such as concrete composition, surface conditions, and environmental variables. As a result, there is an increasing desire for creative approaches that may give more exact and complete forecasts of bond strength, eventually leading to more efficient and accurate structural designs.

Artificial intelligence (AI) has provided a dramatic paradigm change in structural engineering in recent years [7-9]. The ability of AI to analyze enormous amounts of data, discern detailed patterns, and build predictive models has given bond strength prediction a new lease of life. This in-depth analysis of the cutting-edge tools and methodologies altering the sector aims to traverse the landscape of AI developments in predicting bond strength between reinforcement and concrete [10]. The implications of AI for bond strength prediction go far beyond its ability to supplement structural engineers' skills. The capacity to precisely predict bond strength allows for the optimization of structural designs, material selection, and building procedures, eventually improving the safety and sustainability of civil infrastructure. Furthermore, AI's contribution to bond strength prediction is set to aid in creating more robust and cost-effective building procedures, resulting in a more resilient built environment [11].
In this review, the author embarks on a complete study through the integration of AI into bond strength prediction, beginning with a basic explanation of the parameters determining bond strength in reinforced concrete buildings. The author then delves into the traditional methodologies for assessing bond strength, emphasizing its limitations and drawbacks. Following that, authors examine a wide range of AI technologies, such as machine learning algorithms, neural networks, deep learning models, and evolutionary optimization algorithms, stressing their potential to transform bond strength prediction. To demonstrate the practical importance of these breakthroughs, real-world case studies and practical applications of AI in this context are provided. To ensure a comprehensive understanding of the difficulties and opportunities presented by this revolutionary technology, researchers also address critical factors like data quality, model interpretability, and the deployment of AI predictions in the field as we navigate this multidisciplinary landscape. By doing this, the authors want to shed some light on the way forward and provide an understanding of how artificial intelligence might enable structural engineers to push the frontiers of reinforced concrete design and construction, ushering in a new era of robust and sustainable civil infrastructure.

2. Research Significance

The need to thoroughly study improvements in artificial intelligence (AI) for forecasting bond strength between reinforcement and concrete cannot be emphasized. This finding has enormous ramifications for civil engineering and AI development, as well as for the construction sector and infrastructure sustainability. Bond strength is essential to consider when designing and building reinforced concrete buildings. A thorough analysis in this area will assist engineers and construction experts make informed judgments, resulting in safer and more solid structures and infrastructure. By applying AI, researchers can better comprehend and forecast bond strength fluctuations under diverse scenarios, lowering the risk of structural failures. Predicting bond strength properly enables material utilization optimization in construction. This can save cost since engineers can choose the best reinforcement and concrete kinds, thicknesses, and installation strategies. AI-powered forecasts allow resource-efficient designs, which contribute to sustainable building practices. Artificial intelligence provides a framework for quick data analysis and model creation. Researchers may uncover cutting-edge approaches and technologies by examining the most recent AI developments in bond strength prediction, speeding the development of revolutionary building materials and processes. This can result in more durable, resilient, and ecologically friendly construction materials. Resilient infrastructure is critical in an era of climate change and rising environmental issues. AI may help us understand bond strength and predictability, which can lead to the construction of structures that can endure harsh weather events, earthquakes, and other natural calamities. This study helps to construct more resilient communities. Developments of AI in predicting bond strength between reinforcement and concrete are crucial because they can improve structural safety, optimize material utilization, speed R&D, increase resilience, promote sustainability, and advance AI in engineering. This study can potentially change how we design and build buildings and infrastructure, resulting in safer, more sustainable, and resilient structures that benefit society and the environment.

3. Statistics of Published work

In recent years, there has been a substantial increase in research on predicting bond strength between reinforcement and concrete in artificial intelligence (AI). A comprehensive survey of published work on this topic demonstrates an increasing interest in and awareness of the potential of AI in enhancing our knowledge and prediction capacities in civil engineering. Fig.1 shows types of documents on AI for Prediction of Bond Strength between steel and concrete research. The orientations of this research categorized as (a) Articles (b) Review paper (c) Book chapters (d) Conferences. It has been seen that majority of publications belongs to articles indicating the popularity of this research. Fig.2 depicts the number of documents publishes in subsequent 3years interval. As per the data, there has been a significant increase in articles focusing on AI applications in bond strength prediction. These papers cover various artificial intelligence approaches, such as machine learning algorithms, neural networks, deep learning models, and evolutionary optimization algorithms. This variety demonstrates AI's adaptability in tackling the multiple issues related to bond strength prediction. Furthermore, a review of published work highlights AI's practical importance in this sector, with multiple case studies and real-world applications confirming its efficacy in improving the accuracy and efficiency of bond strength forecasts. Engineers and academics increasingly turn to artificial intelligence (AI) to optimize the design and construction of reinforced concrete buildings, recognizing the technology's potential to increase structural integrity and lifespan.

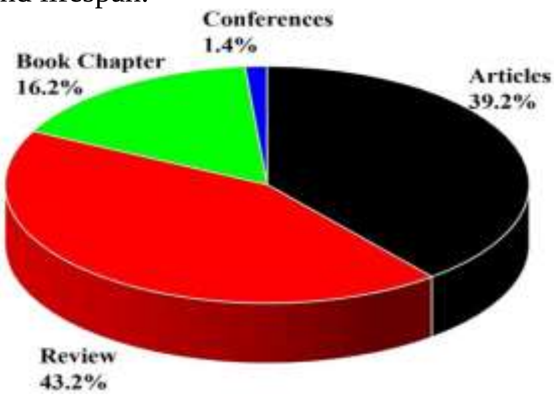

Fig.1. Document type on AI for Prediction of Bond Strength research (Scopus)

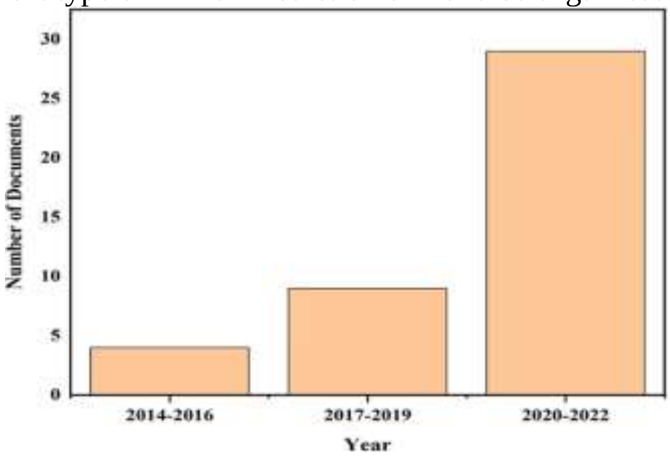

Fig.2. Number of documents in every 3-year interval(Scopus)

4. Critical factors for Bond Strength between Reinforcement and Concrete

The bond strength between steel and concrete is a critical factor in the design and construction of reinforced concrete structures. The bond between steel and concrete ensures that the steel reinforcement is effectively integrated into the concrete, thereby enhancing the strength and durability of the structure. As the demand for sustainable construction continues to increase, it is important to identify the critical factors that influence bond strength between steel and concrete. This state of the art review aims to highlight the latest research findings on the critical factors for bond strength between steel and concrete for a sustainable future. The literature review will explore the effects of concrete composition, steel surface conditions, curing conditions, and environmental conditions on bond strength.

4.1 Concrete Composition:

Concrete composition is a critical factor affecting the bond strength between steel and concrete. Researchers have identified that the strength and durability of the bond are influenced by the water-to-cement ratio, aggregate type, and aggregate size [12-14]. Studies have shown that a lower water-to-cement ratio increases bond strength. The use of coarse aggregates is also beneficial in enhancing bond strength as the rough surface of the aggregates increases the surface area of contact between the steel and concrete. Moreover, using lightweight aggregates has been found to reduce bond strength.

4.2 Steel Surface Conditions:

The surface condition of steel reinforcement is a crucial factor in determining bond strength. Researchers have identified that rust, mill scale, and oil on the surface of steel reinforcement can negatively impact bond strength [15,16]. Studies have shown that removing rust and mill scale from the surface of the steel reinforcement using abrasive blasting, wire brushing, or grinding can enhance bond strength. Oil-free steel reinforcement has also been found to improve bond strength.

4.3 Curing Conditions:

Curing conditions are another critical factor affecting steel and concrete's bond strength. The curing process influences the strength and durability of the bond. Studies have shown that proper curing methods such as moist, steam, and curing compounds can enhance bond strength [17,18]. Wet curing involves keeping the concrete surface moist for a specific period, while steam curing involves applying steam to the concrete surface. The use of curing compounds also helps to maintain moisture in the concrete and promote proper curing.

4.4 Environmental Conditions:

Environmental conditions such as temperature, humidity, and chemical exposure can affect steel and concrete's bond strength. Aggressive chemicals such as chlorides and sulfates can cause corrosion of steel reinforcement and weaken the bond. Studies have shown that corrosion inhibitors and epoxy coatings can help protect steel reinforcement from decay and enhance bond strength [19,20]. Also, using sealers and coatings can protect concrete from chemical exposure and improve bond strength.

In summary, the critical factors for bond strength between steel and concrete for a sustainable future include concrete composition, steel surface conditions, curing conditions, and environmental conditions. The use of appropriate measures to address these factors can enhance bond strength and promote the durability and sustainability of reinforced concrete structures. Designers and contractors must consider these critical factors to ensure that reinforced concrete structures are designed and constructed to meet the increasing demand for sustainable construction. Corrosion, exposure to high temperatures, and loading cycles are the most significant factors that can degrade the bond strength between steel and concrete.

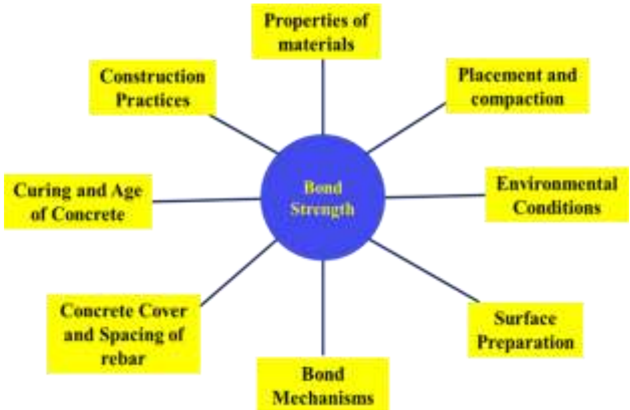

Fig.3. Factors affecting Bond Strength

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5. Conventional studies on Bond strength

The bond strength between steel and concrete is an essential feature of the performance and safety of reinforced concrete structures. Fig.4 shows typical diagram for bond strength between steel and concrete. Traditional research in this field has concentrated on understanding the elements that influence this relationship and establishing tools to measure its strength. As seen in Fig. 5, frictional, adhesive, and shear bonding are frequently used in reinforced concrete infrastructure systems. The magnitude of the bond hindrance for distorted bars is principally controlled by the mechanical interlocking mechanism. These main findings and techniques includes:

Fig.4. Typical bond between concrete and steel

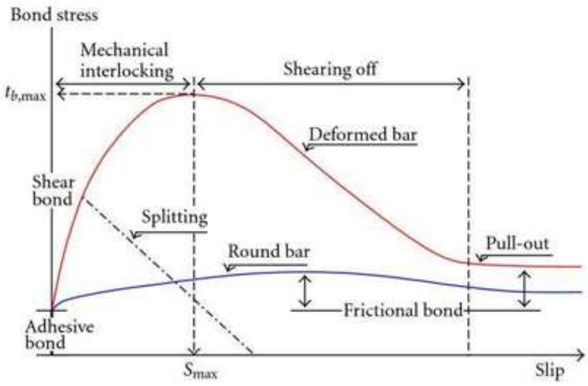

Fig.5. Bond stress and slip relationship [21]

5.1 Surface Preparation

Surface preparation is critical in reinforcing the bond strength between steel and concrete in reinforced constructions [22]. The approach used for surface preparation significantly impacts the adhesive characteristics of these materials. Mechanical procedures such as abrasive cleaning, grinding, and scarification leave the steel with a rough surface profile, which improves mechanical interlocking with the concrete. Surface adhesion is enhanced by chemical treatments such as phosphating and acid etching, which remove impurities and promote chemical bonding [23]. Bonding agents such as epoxy and cementitious materials are added to the steel surface to improve the bond. Adequate surface preparation increases reinforced concrete structures' longevity and overall performance, ensuring their long-term integrity and safety. Researchers explored the significance of good surface preparation of steel reinforcement bars (rebar) to establish an effective bond with concrete. Techniques such as wire brushing, abrasive blasting, and chemical treatments have been investigated to improve surface roughness and cleanliness, enabling better adherence.

5.2 Concrete Composition

Concrete composition is critical in influencing the binding strength between steel and concrete. Cement, aggregates, water, and optional additives are the most common components of concrete [24]. These components' quality and quantities directly influence the binding between steel reinforcement and concrete. Several studies have investigated the impact of concrete parameters such as compressive strength, water-cement ratio, and aggregate type on the bond between steel and concrete [25]. According to conventional belief, increased concrete strength frequently leads to enhanced bond performance. A well-designed concrete mix with the optimum water-cement ratio, workability, and curing can improve bond strength. High-quality aggregates, such as clean and well-graded materials, promote a stronger connection. Furthermore, additives such as superplasticizers can increase workability while maintaining bond strength. A suitable concrete composition ensures that the hardened concrete effectively envelops the steel reinforcement, forming a strong mechanical and chemical connection and contributing to reinforced concrete structures' structural integrity and durability.

5.3 Rebar Configuration

The placement of reinforcing bars (rebar) within concrete buildings influences the bond strength between steel and concrete. The design of the rebar determines how well concrete encases and connects with the steel [26]. Straight bars, curved bars, and stirrups or ties to maintain spacing are all standard rebar arrangements. Straight bars produce a direct and continuous connection with the concrete, resulting in a relatively high bond strength. On the other hand, bending bars or hooks improve bond strength by increasing the surface area of contact between the steel and the concrete, hence boosting load transfer capacity. Researchers have examined how rebar spacing, diameter, and orientation affect the bond strength [27,28]. Proper spacing and alignment are essential for the transmission of forces between steel and concrete to be successful. Furthermore, the use of stirrups or ties in reinforced concrete columns and beams aids in maintaining optimum rebar spacing and alignment, which is crucial for dispersing loads and optimizing bond strength. Rebar arrangement and placement must be carefully considered to ensure that the concrete adequately surrounds and binds with the steel, thus improving reinforced concrete buildings' structural integrity and performance.

5.4 Bond Testing Methods

In reinforced concrete constructions, bond testing methods are crucial for measuring the strength of the link between steel reinforcement and concrete. These processes assess the integrity of the bond interface, ensuring structural safety and performance. Pull-out tests, pull-off tests, and strain gauge bond stress measurements are all common bond testing techniques [29,30]. Pull-out tests include gradually increasing the axial force applied to a steel bar embedded in concrete to measure its pull-out resistance. When applying a perpendicular force to the concrete surface, pull-off tests assess the adhesion between concrete and steel. Bond stress measurements using strain gauges or other equipment provide information about the stress distribution at the bond contact. These testing procedures are critical for quality control during construction and analyzing the state of existing structures, assisting engineers in making informed decisions about maintenance, repair, or reinforcement.

5.5 Effects of Environmental Factors

Environmental conditions have a considerable impact on the strength of the bond between steel and concrete. The strength and efficiency of the bond may be impacted by changes in temperature, humidity, and exposure to corrosive materials [31]. High humidity levels can hasten the corrosion of steel reinforcement, which, over time, decreases bond strength. Thermal pressures brought on by large temperature swings may degrade the bond. In addition, contact with substances like salts or acids can erode the steel surface, reducing the steel's ability to adhere to concrete. Due to their significant role in maintaining the bond strength and long-term performance of these essential materials, it is imperative to consider local environmental factors when planning and building reinforced concrete buildings. Studies have examined how the environment, including exposure to moisture, changes in temperature, and chemical assault, affects bond strength [32]. These investigations aid in comprehending how prolonged exposure impacts the strength and efficiency of the connection between steel and concrete.

5.6 Corrosion and Deterioration

The bond strength in reinforced concrete structures is severely weakened by corrosion and degradation [33]. The volumetric expansion as steel corrodes can cause the nearby concrete to fracture and spill. The link between the steel and concrete is disrupted in addition to weakening the steel due to this degradation. Traditional research has focused on the link between corrosion- induced steel expansion and bond strength, highlighting the need for corrosion prevention methods to preserve bond integrity [34]. By-products of rust and corrosion take up crucial bonding space, lowering the available surface area for adhesion. The corrosion-induced cracking can open passageways for moisture and hostile substances to enter the structure deeper, hastening the degradation process. The long-term durability and structural integrity of reinforced concrete elements are guaranteed by correct surface preparation, corrosion-resistant coatings, and routine maintenance. These measures help to reduce these effects and preserve bond strength.

6. State of Art on Artificial intelligence in Bond strength prediction

Artificial intelligence (AI) has emerged as a potent technique for forecasting steel-concrete bond strength. AI can create accurate predictions about bond strength by analyzing a large variety of data, including material parameters, surface preparation processes, ambient conditions, and historical performance data, using machine learning algorithms. Engineers and construction professionals may use this predictive capacity to optimize reinforcement design, choose suitable surface preparation processes, and ensure the structural integrity of concrete parts. AI improves productivity and makes construction safer and more cost-effective by offering insights that enable proactive decision-making and the prevention of possible structural difficulties [35]. Table 1 shows detail difference between conventional and artificial intelligence based bond strength between steel and concrete. These advanced methods use machine learning algorithms and deep learning models to improve accuracy and efficiency in bond strength prediction. Here is a brief description of the current state of the art in this field:

Table 1. Conventional and AI based bond strength between steel and concrete

Aspect	**Conventional**	**Artificial Intelligence**
Data input	Rely on datasets from mathematical and empirical formulas.	Utilizes extensive Sensor data, historical dataset.
Accuracy and Precision	Although it can provide good predictions, it is restricted by assumptions and the quality of actual data.	Has the potential to provide greater precision and accuracy owing to its capacity to learn from a variety of data sources and adjust to changing environmental circumstances.
Training and Validation	Empirical and Analytical validation	Trained on historical data and verified using variousmethods, including cross-validation or testing on fictitious data.

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Model Complexity	Simplified equations and assumptions	Employ sophisticated deep learning models, machine learning algorithms, or complicated neural networks that can handle complex interactions and nonlinearities.
Training Data Requirements	Need empirical testing data to calibrate the model.	Building accurate AI models, relies on a large amount of high-quality training data.

Table 2. Advantages and disadvantages of AI based bond strength

Aspect	**Advantages**	**Disadvantages**
Data preprocessing	Handle large dataset	Need for high quality data for training and validation
Accuracy	Precise prediction	Depends on quality of data
Cost Efficiency	Reduce testing costs	Initial investment is high
Speed	Saving time	Model training time consuming
Interpretability	AI can offer information on bond strength factors.	The interpretability of AI models can be complicated

6.1 Machine Learning Algorithms

Machine learning algorithms have emerged as reliable methods for forecasting steel-concrete bond strength [36]. These algorithms use enormous datasets containing numerous characteristics such as surface preparation processes, concrete mix qualities, environmental conditions, and more to predict the intricate link between these elements and bond strength. Engineers can create accurate predictions and improve structural designs using techniques like regression, decision trees, random forests, and neural networks [37]. Machine learning enhances forecast accuracy while providing insights into the most critical aspects of bond strength [38]. Consequently, data-driven decision- making and optimization play a crucial role in modernizing the construction industry by assuring the safety and endurance of reinforced concrete buildings. Fig.6 illustrates typical machine learning models for prediction and evaluations of bond strength. Artificial Neural Networks (ANNs) have considered as powerful tools for strength evaluations and predictions. Fig.7 shows typical structure of ANN models.

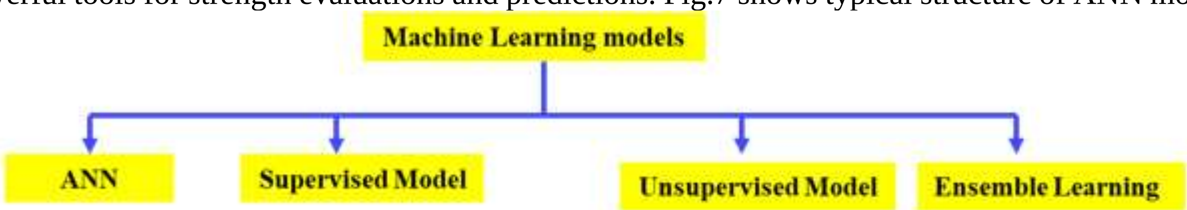

Fig.6. ML models

Fig.7. Typical structure of ANN model

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6.2 Deep Learning Models

Deep learning models have grown in popularity in recent years due to their capacity to anticipate complicated correlations in various industries, including civil engineering [39]. Deep learning models offer a robust tool for analyzing enormous datasets in the context of bond strength prediction between steel and concrete, encompassing aspects such as surface preparation procedures, material characteristics, ambient conditions, and structural geometry [40]. Frequently built on neural networks, these algorithms may learn and extract detailed patterns from previous data, offering more accurate bond strength estimates. Engineers and researchers may improve safety and structural integrity by employing deep learning skills to optimize surface preparation processes and build reinforced concrete buildings more confidently [41]. However, these models must be trained on relevant and varied datasets to ensure accuracy and applicability in real-world applications. Fig.8. illustrates the structure of Deep learning where input datasets were passed through deep learning models for strength evaluation and predictions.

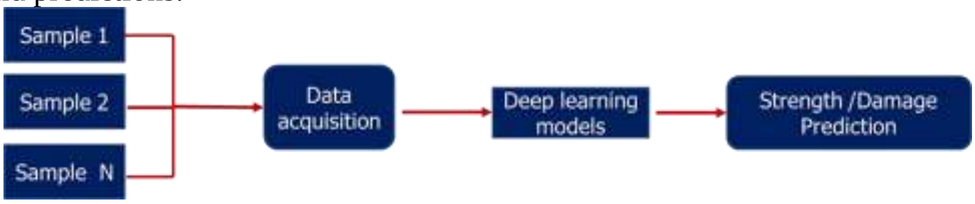

Fig.8. Structure of Deep learning

6.3 Data-Driven Approaches

Data-driven techniques have gained traction in estimating steel-concrete bond strength. These methods use the power of data driven algorithms and vast datasets to investigate the subtle interactions between many parameters, such as surface preparation procedures, material qualities, and ambient conditions, and their impact on bond strength [42]. These systems can give accurate estimations of bond strength by putting historical data into prediction models and assisting engineers and building contractors in making educated judgments. This data-driven method improves the precision of bond strength predictions [43]. It enables the discovery of critical elements influencing the bond, resulting in more effective surface preparation procedures and enhanced structural design. Data-driven techniques are poised to play an increasingly important role in improving the performance and lifetime of reinforced concrete structures as technology and data-gathering methods progress.

6.4 Hybrid Models

In predicting steel-concrete bond strength, hybrid models provide a comprehensive method that combines the capabilities of multiple modeling approaches to generate more precise and dependable findings [44,45]. Typically, these models combine empirical data with machine learning methods or finite element analysis. By using both experimental data and computational methodologies, hybrid models may represent the intricate relationships between parameters impacting bond strength, such as surface preparation, concrete qualities, and steel features [46]. This method improves the accuracy of bond strength forecasts, allowing engineers and researchers to optimize structural designs while also assuring the safety and longevity of reinforced concrete structures. Hybrid models are becoming more critical in the construction industry, providing a potent tool for enhancing knowledge and predicting bond behavior in real-world situations.

7. Challenges

There are numerous challenges involved in integrating AI for bond strength prediction in civil engineering. To begin with, data quality still needs to improve. AI models rely primarily on high-quality and diverse information, and gathering such data for bond strength prediction can be difficult due to the complexity of building sites and the requirement for lengthy testing. It is critical to ensure data correctness, reliability, and consistency. Furthermore, model interpretability is a critical challenge. While AI and deep learning models have shown potential in predicting bond strength, it is frequently challenging to grasp the logic behind their forecasts. The capacity to evaluate and trust AI-driven predictions is critical in civil engineering, where safety and stability are significant. The development of transparent and interpretable AI models is a continuous problem. Moreover, integrating AI with non-destructive testing procedures and sensor data for real-time bond strength monitoring introduces additional challenges. These approaches need robust hardware, data synchronization, and calibration, which can be costly and technically challenging to execute on building sites. It is critical for practical use to ensure that AI is seamlessly integrated with these technologies.

8. Summery and Conclusions

The present article explores the most recent advances in using Artificial Intelligence (AI) in civil engineering for forecasting bond strength between reinforcement and concrete. Bond strength significantly impacts the structural stability and durability of reinforced concrete structures. Traditional bond strength calculation techniques rely on empirical calculations and considerable laboratory testing, which may be time-consuming and costly. The authors show how machine learning algorithms, neural networks, and deep learning models have changed bond strength prediction in this study. Moreover, this study also investigates the integration of AI with non- destructive testing procedures and sensor data for real-time bond strength monitoring and assessment. Furthermore, the paper covers implementation problems such as data quality and model interpretability. AI and bond strength prediction working together have the potential to revolutionize the design and construction of reinforced concrete buildings, eventually improving safety and durability.
In conclusion, this research highlights Artificial Intelligence's transformational potential in civil engineering, especially in forecasting bond strength between reinforcement and concrete. AI provides a more efficient and cost-effective alternative to traditional bond strength measurement methods by utilizing machine learning algorithms and exploiting real-time data from non- destructive tests and sensors. While there are problems such as data quality and model interpretability, the advantages of AI in enhancing structural stability and durability cannot be emphasized. This study is a significant resource for civil engineering academics, engineers, and practitioners, outlining the route to rethinking how bond strength is measured and maximized, eventually contributing to safer and more lasting reinforced concrete buildings.

9. Future Research

The outcomes of this study provide promising new opportunities in artificial intelligence (AI) and civil engineering. The application of AI to bond strength prediction is set to advance much further as it develops. Researchers and professionals can investigate the creation of more complex AI models that can consider a wider variety of variables and aspects impacting bond strength. Additionally, using AI in real-time bond strength monitoring and evaluation allows predictive maintenance and early structural issue diagnosis, improving the safety and robustness of reinforced concrete structures. Further research can address data quality and interpretability of the model difficulties, ultimately leading to more robust and trustworthy AI solutions for bond strength prediction. Interdisciplinary cooperation between AI specialists and civil engineers can create novel methods and solutions for sustainable infrastructure practices. AI has the potential to transform not only bond strength evaluation but also numerous elements of civil engineering design, building, and maintenance, opening the way for safer and more robust infrastructure.

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