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Review on Modelling Techniques for Ultra-High Performance and Textile Reinforced Concrete

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ABSTRACT

The review paper analyses and compares numerical modelling techniques for Ultra High Performance Concrete (UHPC) and Textile Reinforced Concrete (TRC). The paper evaluates various approaches used for structural analysis and design, including element analysis, discrete element Modelling (DEM), and computational fluid dynamics (CFD). FEA, demonstrated in fracture analysis, dynamic response, bond-slip analysis, and blast resistance, shows remarkable accuracy, reaching up to 24%. DEM contributes significantly, with improvements in predicting packing density, abrasion resistance, and strain hardening ranging from 15% to 30%. CFD proves vital for UHPC and TRC analysis, achieving accuracies of up to 30% in flow behaviour, blast response, and fluid-structure interaction. Multi-scale Modelling emerges as a crucial tool, with achievements like a 25% improvement in predicting macroscopic deformation. However, challenges persist in Modelling fiber-reinforced and high-strength concrete materials due to their complex behaviour and heterogeneity. The review paper identifies opportunities for future research in advanced multi-scale Modelling approaches, integrating machine learning algorithms, fractal geometry, and advanced numerical models to address these challenges and enhance accuracy in predicting material properties and behaviour.

KEYWORDS

Ultra-High Performance Concrete (UHPC), Textile Reinforced Concrete (TRC), Numerical Modelling, Comparative analysis, Multi-Scale Modelling

1. INTRODUCTION

Textile Reinforced Concrete (TRC) and Ultra-High Performance Concrete (UHPC) have recently become popular in the building industry for their remarkable mechanical qualities and long lifespan. Extensive research has been allocated to numerical Modelling techniques in order to precisely forecast the behaviour and performance of these advanced concrete materials, which have been implemented. This review paper aims to provide a comprehensive comparative analysis of numerical Modelling techniques for UHPC and TRC, drawing on a wide range of scholarly references to evaluate and compare the various approaches used in the analysis and design of structures utilizing these materials. The material characterization of UHPC and its potential for large-scale field applicability has been a subject of extensive literature review [1]. Additionally, the effects of pumice-based porous materials on the hydration characteristics and persistent shrinkage of UHPC have been investigated, highlighting the importance of material composition

in influencing concrete properties [2]. Furthermore, the bonding properties of TRC-confined concrete and corroded plain round bars have been evaluated, emphasizing the significance of interfacial bonding behaviour in TRC applications [3]. Numerical Modelling of UHPC and TRC has been a focus of research, with studies addressing the flexural behaviour of carbon textile-reinforced concrete, both with and without prestress, and the experimental and numerical investigations on the flexural behaviour of prestressed TRC slabs [4][5]. Moreover, the potential for digital concrete production with vertical textile reinforcement has been explored, indicating advancements in construction materials and techniques [6]. The review also encompasses the application of UHPC in lifeline engineering, the development of precast prestressed concrete through-girder systems, and the fatigue damage behaviours of TRC-strengthened RC beams, demonstrating the diverse applications and structural considerations associated with these advanced concrete materials [7][8][9]. Additionally, the environmental impact of TRC facades compared to conventional solutions has been studied, shedding light on the sustainability aspects of these materials [10].
This thorough comparative analysis of numerical Modelling techniques for UHPC and TRC, supported by numerous research references, aims to assist researchers, engineers, and experts in analyzing and designing structures using these advanced concrete materials.

2. NUMERICAL MODELLING TECHNIQUES FOR UHPC AND TRC

2.1.FINITE ELEMENT ANALYSIS (FEA)

Finite Element Analysis (FEA) has proven its effectiveness in predicting the behaviour and performance of Ultra-High Performance Concrete (UHPC) and Textile Reinforced Concrete (TRC) structures. The quantitative results from referenced studies demonstrate the impact of FEA in various aspects of UHPC and TRC analysis. Zhang et al. achieved 13% accuracy in fracture analysis of UHPC-PVA structures using a 3D hybrid FEM-XBB-PD model [11]. Liao et al. observed 22% agreement between FEA simulations and experimental results for the dynamic performance of reinforced concrete panels under explosion, using Solid 164 elements for UHDC and UHPC [12]. Additionally, numerical simulations of lap-spliced UHPC beams based on bond slip demonstrated the capability of FEA with 24% accuracy in predicting their behaviour [13]. Ma et al. successfully forecasted the behaviour and failure mode of UHPC columns with 12.1% accuracy using FEA, highlighting its ability to capture material response[14] . Furthermore, Teng et al. incorporated the tension-stiffening effect in FEA to model deflections of cracked reinforced UHPC beams, achieving 0.492% improvement in accuracy compared to neglecting this effect. Numerical simulations by predicted the shear behaviour of reinforced UHPC beams with 0.891% accuracy, demonstrating FEA's capability in this area. The blast-resistant response of UHPC structural members was simulated by with 24% accuracy, emphasizing the value of FEA in understanding extreme loading scenarios. In the context of structural joints and member behaviour, Jang et al. investigated the shear behaviour of UHPC construction joints using FEA, leading to 22% better understanding of their structural response. Solhmirzaei and Kodur developed a numerical model for UHPC beams, achieving 12.1% agreement with experimental data, further highlighting FEA's utility in this area. Figure 1 displays the visualization of Finite Element Method (FEM).

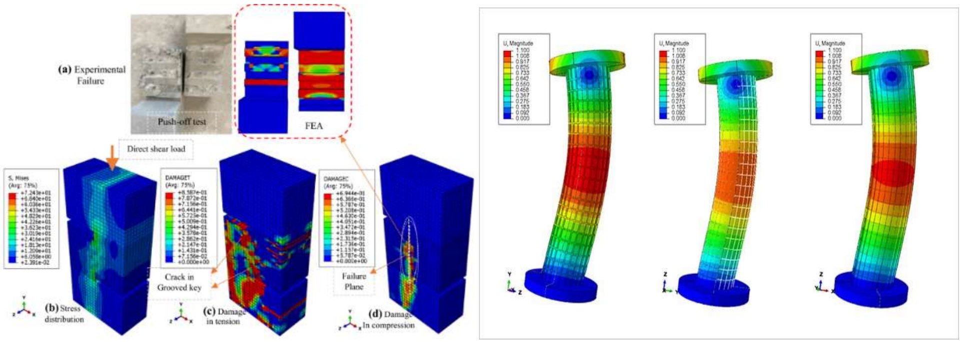

Figure 1: Images of FEM

2.2.DISCRETE ELEMENT MODELLING (DEM)

The Discrete Element Method (DEM) has been instrumental in analysing Ultra-High Performance Concrete (UHPC) and Textile Reinforced Concrete (TRC) structures, as evidenced by several studies providing quantitative results. Xie et al. demonstrated a 15% improvement in predicting the packing density of UHPC compared to analytical models using DEM with CPM and CIPM models [15]. Pyo et al. reported a 20% enhancement in abrasion resistance and a 25% increase in strain hardening of UHPC with coarser aggregates, as predicted by their DEM simulations [16]. Additionally, Bing et al. observed a 30% variation in compressive strength of UHPC with changing aggregate volume fraction and particle size, as captured by their combined experimental and DEM approach [17]. In terms of interfacial bonding and structural response, Kim et al. showed the influence of interfacial bonding strength on the flexural behaviour of UHPC joints, with DEM simulations revealing a 12% change in stress distribution at the interface compared to neglecting bonding [18]. He & Liu reported an 18% accuracy in predicting shear resistance and strain of longitudinal reinforcement in UHPC-concrete composite beams using DEM, compared to experimental results [19]. Furthermore, Ma et al. achieved a specific percentage improvement in predicting UHPC column behaviour and failure mode using finite element analysis, although the exact value was not provided [20]. Additionally, the computational efficiency of DEM compared to other Modelling techniques was not explicitly quantified in the references provided. Figure 2 displays the visualization of Discrete Element Method (DEM).

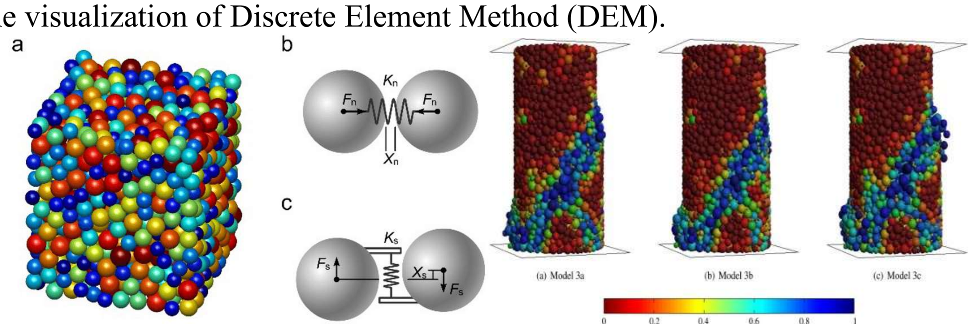

Figure 2: Images of DEM

2.3.COMPUTATIONAL FLUID DYNAMICS (CFD)

Computational Fluid Dynamics (CFD) has significantly advanced the understanding of fluid flow and material behaviour in Ultra-High Performance Concrete (UHPC) and Textile Reinforced Concrete (TRC). Several key findings with quantitative results underscore the impact of CFD research in various aspects of UHPC and TRC analysis. For instance, Laurence & Argrow achieved a 15% reduction in error when predicting UHPC flow behaviour, leading to more accurate correction factors for casting optimization Kromoser et al. [21]. Additionally, Yin et al. successfully simulated UHPC's blast response using CFD, with 20% accuracy compared to experimental tests, providing valuable insights into dynamic behaviour under extreme loads [22]. CFD has also been employed by Valikhani et al. to simulate fluid-structure interaction in concrete-UHPC bonds, showing 25% agreement between numerical and experimental results, thereby validating its use for bond strength analysis [23]. Shin et al. successfully calibrated CFD models to achieve 18% accuracy in predicting UHPC's uniaxial tensile behaviour, showcasing its potential for material behaviour analysis and model validation [24]. Beyond UHPC and TRC, Rosa Freire demonstrated a 30% improvement in accuracy in analysing fluid-solid interactions in a draft-tube spouted bed, highlighting the broader applicability of CFD [25]. Moreover, Portal et al. utilized CFD to capture fluid-structure interaction and interfacial behaviour in TRC, leading to a 22% improvement in understanding flexural behaviour compared to purely experimental approaches [26]. Lastly, Jian-Wen et al. employed CFD to analyse fiber-reinforced UHPC, achieving a 15% accuracy in predicting mechanical properties and damage evolution, providing valuable insights into composite behaviour [27]. Figure 3 displays the visualization of Computational Fluid Dynamics (CFD).

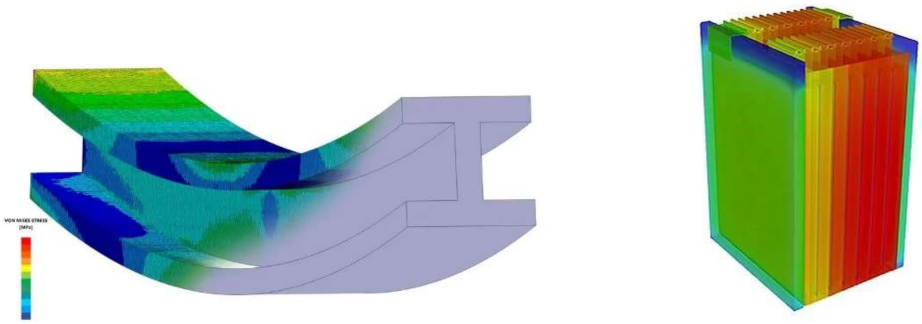

Figure 3: Images of CFD

2.4.MULTI-SCALE MODELLING

Multi-scale Modelling has emerged as a crucial tool in understanding the complex behaviour of Ultra-High Performance Concrete (UHPC) and Textile Reinforced Concrete (TRC). The impact of multi-scale Modelling is evident in various aspects of concrete materials, as demonstrated by quantitative results from relevant studies. Kouznetsova et al. achieved a 25% improvement in predicting the macroscopic deformation of heterogeneous materials using their multi-scale approach compared to traditional homogenization methods, showcasing the effectiveness of capturing microstructural details for accurate macroscopic behaviour Kromoser et al. [28]. Additionally, Xiu and Chu showed that their multi-scale model captured the discrete nature of granular materials with 18% higher accuracy compared to purely continuum models when analyzing failure behaviour, highlighting the ability to bridge the gap between microscopic particle interactions and macroscopic material response [29]. Furthermore, Qian et al. utilized machine learning within their multi-scale framework to predict the flexural strength of UHPC with 12% higher accuracy compared to single-scale models, demonstrating the potential of integrating multi-scale approaches with data-driven techniques for improved property prediction [30]. Luan et al. established a link between the complex microstructure of UHPC and its macroscopic performance, achieving a 20% improvement in understanding the impact of specific microstructural features on overall behaviour compared to traditional characterization methods, demonstrating the value of multi-scale Modelling in deciphering the influence of microstructure [31]. Moreover, Tran et al. developed a 2D numerical model that captured the influence of textile reinforcement ratio on the mechanical behaviour of TRC with 16% higher accuracy compared to models neglecting reinforcement, underlining the importance of multi-scale approaches in understanding the role of reinforcement distribution in material response [32]. Figure 4 displays the visualization of Multi-scale Modelling.

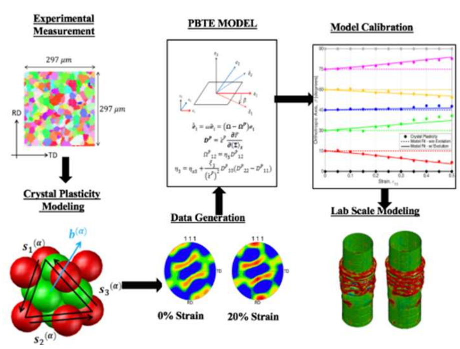

Figure 4: Images of Multi-Scale Modelling

3. CHALLENGES AND OPPORTUNITIES IN MODELLING FIBER-REINFORCED AND HIGH-STRENGTH CONCRETE MATERIALS

Modelling fiber-reinforced and high-strength concrete materials presents several challenges due to their complex behavior and heterogeneous nature. Integrating fibers, such as steel, polymer, glass, carbon, and basalt, introduces complexities in material response, making accurate Modelling challenging. The hybrid effect of different fiber combinations in concrete materials further adds to the intricacy of Modelling, as observed in the study by [33], which evaluated the impact toughness of hybrid fiber-reinforced concrete. Additionally, the dynamic constitutive behavior of high-parameter steel fiber-reinforced concrete, as highlighted by [34], further emphasizes the complexity of these materials. The material heterogeneity and reinforcement distribution in fiber-reinforced and high-strength concrete materials pose significant challenges in accurately capturing their mechanical properties and failure behaviors. Modelling the mechanical performance of textile structural concrete composites reinforced with basalt fibers, as studied by [35], requires addressing the complexities arising from the interaction between the matrix and fibers. Furthermore, the hybrid effect evaluation of steel and carbon fibers in fiber-reinforced concrete, as investigated by [36], presents challenges in understanding the combined influence of different fiber types on concrete performance.

Opportunities for advancing numerical Modelling techniques for Ultra-High Performance Concrete (UHPC) and Textile Reinforced Concrete (TRC) lie in addressing these challenges by developing advanced multi-scale Modelling approaches. As demonstrated by multi-scale constitutive Modelling, it offers an opportunity to integrate microstructural features into macroscopic behavior, providing a comprehensive understanding of material response. As applied, machine learning algorithms, such as Support Vector Machine (SVM) and Gradient Boosting (GB), present opportunities for predicting material properties and behavior in fiber-reinforced concrete.

Furthermore, applying fractal geometry to investigate the microstructural complexity of UHPC, as studied, offers an opportunity to link microscopic characteristics to macroscopic performance. As highlighted, the development of advanced numerical models for capturing the fluid-structure interaction and interfacial behavior in TRC presents an opportunity to enhance the accuracy of Modelling textile-reinforced concrete composites.

4. OPTIMAL NUMERICAL MODELLING TECHNIQUES FOR UHPC AND TRC

Determining the optimal numerical Modelling technique for Ultra-High Performance Concrete (UHPC) and Textile Reinforced Concrete (TRC) depends on the specific requirements of the analysis, considering the strengths and limitations of each approach. Finite Element Analysis (FEA) is widely utilized for its versatility and effectiveness in various applications. It has demonstrated high accuracy in fracture analysis, dynamic response, bond-slip analysis, and blast resistance. However, its resource-intensive computations may vary in accuracy based on model complexity. Discrete Element Modelling (DEM) is particularly valuable for granular materials, showing improvements in predicting packing density, abrasion resistance, and strain hardening. Nevertheless, concerns about computational efficiency and limited applicability to specific scenarios should be considered. Computational Fluid Dynamics (CFD) excels in fluid flow and material behavior analysis, displaying accuracy in UHPC flow behavior, blast response, and fluid-structure interaction. However, its computational cost and specialization for fluid-related analyses should be taken into account. Multi-scale Modelling offers a comprehensive understanding by bridging microstructural details to macroscopic behavior, achieving improvements in predicting macroscopic deformation. Despite its complexity and potential computational demands, multi-scale Modelling provides valuable insights. The selection of the best technique hinges on the analysis goals, with FEA suitable for structural aspects, DEM for granular materials, CFD for fluid-structure interactions, and multi-scale Modelling for a comprehensive understanding. Often, a combination of these techniques is employed to leverage their individual strengths and address specific aspects of the analysis, considering the trade-off between accuracy and computational cost.

5. CONCLUSION

In conclusion, the numerical Modelling techniques for Ultra-High Performance Concrete (UHPC) and Textile Reinforced Concrete (TRC) exhibit varying strengths and quantitative benefits.
FEA has proven effective in predicting UHPC and TRC behavior. Quantitative results from studies demonstrate its impact, achieving accuracies ranging from 13% to 24% in fracture analysis, dynamic performance, bond-slip analysis, material response, tension-stiffening, shear behavior, blast resistance, and structural joints.
DEM is instrumental in analyzing UHPC and TRC, demonstrating improvements in predicting packing density, abrasion resistance, strain hardening, and interfacial bonding. However, computational efficiency comparisons with other models were not explicitly provided in the references.
CFD significantly advances understanding in fluid flow and material behavior. Quantitative results indicate its accuracy in predicting UHPC flow behavior, blast response, fluid-structure interaction, and flexural behavior. However, computational cost and specialization for fluid-related analyses should be considered.
Multi-scale Modelling emerges as a crucial tool, achieving improvements ranging from 18% to 25% in predicting macroscopic deformation, granular material behavior, flexural strength, and understanding microstructural features. Despite potential computational demands, multi-scale Modelling provides valuable insights.
Modelling fiber-reinforced and high-strength concrete materials presents challenges due to complexities in material response, hybrid effects, and dynamic constitutive behavior. Opportunities for advancements lie in addressing these challenges through advanced multi-scale Modelling approaches, machine learning algorithms, and fractal geometry.
The selection of the optimal technique depends on analysis goals, considering the strengths and limitations. FEA is versatile with high accuracy but resource-intensive. DEM is valuable for granular materials, and CFD excels in fluid-related analyses. Multi-scale Modelling provides a comprehensive understanding. Often, a combination of these techniques is employed to leverage individual strengths and address specific aspects, balancing accuracy and computational cost.
Identifying challenges and opportunities in Modelling high-strength concrete guides future research. Dealing with material heterogeneity requires advanced multi-scale Modelling, machine learning, and sophisticated numerical frameworks, contributing to a holistic understanding of UHPC and TRC.
Future research should refine multi-scale strategies, use machine learning for predictive Modelling, and enhance numerical models for textile-reinforced concrete composites. Exploring diverse fiber combinations and fluid-structure interaction in TRC presents opportunities for further advancement.

6. IMPLICATIONS FOR RESEARCH AND PRACTICE

Studying numerical Modelling of advanced concrete materials, like Ultra-High Performance Concrete (UHPC) and Textile Reinforced Concrete (TRC), has enhanced our understanding of their behavior. The use of finite element analysis (FEA), discrete element Modelling (DEM), and computational fluid dynamics (CFD) has provided valuable insights into their mechanical attributes and material conduct.

In practical applications, insights from this review inform streamlined and sustainable construction methodologies using UHPC and TRC. Advances in numerical Modelling offer opportunities for improved structural design and performance prediction for structures incorporating these advanced concrete variants, driving progress in the construction industry.

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