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COMPREHENSIVE MODELING OF THE PROPERTIES OF GLASS FIBER REINFORCED POLYMER REINFORCEMENT IN CONCRETE ELEMENTS UNDER THERMAL AND CYCLIC LOADING

Abstract. The paper addresses the problem of improving the durability and thermal resistance of glass fiber reinforced polymer reinforcement in concrete structures subjected to thermo-mechanical and cyclic loading. The relevance of the study is determined by the need to replace traditional steel reinforcement with corrosion-resistant materials possessing enhanced performance under elevated temperatures and fatigue conditions. The aim of the research is to develop a mathematical and materials-science-based methodology that integrates mathematical modeling, microstructural design, and structural formation processes for predicting the properties of composite reinforcement. The research methodology is based on a two-stage numerical approach, including transient thermal analysis using a standard fire temperature curve and subsequent mechanical modeling of the stress-strain state of the “concrete–reinforcement” system. The behavior of materials is described using the concrete damaged plasticity model, elastoplastic steel, and orthotropic glass fiber reinforced polymer material with temperature-dependent degradation. Micromechanical relations based on the rule of mixtures and efficiency factors were applied to quantify the influence of fiber composition, polymer matrix properties, and interfacial interaction on strength and fatigue behavior. The results demonstrate that structural formation processes and microstructural design play a decisive role in determining the effective performance of composite reinforcement. It is shown that the use of fibers with enhanced mechanical strength and improved resistance to alkaline environments, high glass transition temperature matrices, and nanomodifiers significantly improves thermal stability and fatigue resistance. For the first time, an integrated mathematical model has been proposed that simultaneously accounts for thermal, mechanical, and microstructural factors affecting material performance. The practical significance of the study lies in the possibility of applying the obtained results for engineering design of concrete structures operating under aggressive environmental conditions, elevated temperatures, and cyclic loading, ensuring increased service life and structural reliability.

Key words: glass fiber reinforced polymer, mathematical modeling, microstructural design, structural formation, fatigue behavior, thermo-mechanical loading, composite materials.

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Introduction. Reinforced concrete remains the fundamental material of modern civil infrastructure due to its advantageous combination of compressive strength, durability, and technological versatility. For decades, steel reinforcement has been widely used as a standard solution, ensuring high tensile strength, ductility, and compatibility with cementitious matrices. However, despite its well-established performance, steel is highly susceptible to corrosion in aggressive environments, including chloride exposure, humidity, and chemically active media. This limitation leads to significant maintenance costs, reduction in service life, and structural degradation, thereby necessitating the search for alternative reinforcement materials [1, 2].

In recent years, fiber reinforced polymer (FRP) composites have emerged as a promising replacement for steel reinforcement due to their high strength-to-weight ratio, corrosion resistance, and favorable durability characteristics. Among them, glass fiber reinforced polymer (GFRP) has gained particular attention because of its relatively low cost and acceptable mechanical performance [3, 1]. Nevertheless, unlike steel, which is an isotropic and ductile material, GFRP is a heterogeneous anisotropic composite whose behavior is governed by a complex interaction of chemical composition, microstructure, and interfacial phenomena. This fundamentally different nature requires the development of advanced approaches for predicting its mechanical response and long-term performance [4, 5].

A critical aspect of GFRP behavior is associated with its microstructural organization, which directly affects stiffness, strength, and durability. The properties of the composite are determined by the type of glass fibers (E-, S-, or AR-glass), their volume fraction, and the characteristics of the polymer matrix. At the same time, the processes of structural formation and microstructural design define the efficiency of stress transfer between components and the resistance of the material to environmental and mechanical effects. In particular, the degradation of the fiber–matrix interface under cyclic loading and elevated temperatures significantly reduces the load-bearing capacity of the material [3-5]. Therefore, understanding and controlling microstructural formation mechanisms is a key factor in improving the performance of GFRP reinforcement.

Another important factor influencing the behavior of GFRP reinforcement is thermal exposure. Compared to steel, GFRP has significantly lower thermal conductivity, which leads to different heat transfer mechanisms in reinforced concrete elements. While this property can delay heat penetration, the polymer matrix exhibits a sharp reduction in mechanical properties when the glass transition temperature is exceeded. As a result, thermo-mechanical loading conditions create complex stress states and accelerate degradation processes. These phenomena are well described in studies of thermal behavior and heat transfer in composite materials [6,7]. In addition, cyclic loading leads to fatigue damage accumulation associated with matrix microcracking, fiber breakage, and interfacial debonding, which significantly affects long-term performance [3, 5].

Despite numerous studies devoted to FRP materials, existing approaches are often limited to either mechanical or thermal aspects and rarely consider the combined influence of chemical composition, microstructural design, and structural formation processes within a unified framework. In particular, the role of microstructural engineering and mathematical modeling in linking material-level characteristics with structural performance remains insufficiently explored [3-5]. This gap restricts the development of scientifically grounded design methodologies for composite reinforcement in concrete structures.

Therefore, the present study aims to develop a comprehensive mathematical modeling approach that integrates microstructural design, structural formation processes, and thermo-mechanical behavior of GFRP reinforcement in concrete under cyclic loading conditions. The proposed methodology establishes a direct relationship between fiber composition, matrix properties, interfacial behavior, and the resulting mechanical performance of the composite material. Such an approach enables not only accurate prediction of material degradation but also provides a basis for optimizing the composition and structure of GFRP reinforcement for enhanced durability and reliability [1, 3, 5].

Materials and Methods of Research. The research methodology is based on a comprehensive mathematical modeling approach that integrates thermal, mechanical, and microstructural aspects of glass fiber reinforced polymer (GFRP) reinforcement behavior in concrete structures under combined thermo-mechanical and cyclic loading. The proposed framework combines macroscopic finite element modeling with micromechanical relations describing structural formation and microstructural design of composite materials.

Numerical modeling strategy. A two-stage numerical procedure was implemented. At the first stage, a transient heat transfer problem was solved to determine the temperature distribution within the concrete element and reinforcement under fire exposure conditions. The thermal loading was defined according to the standard ISO 834 fire curve. The governing heat conduction equation is expressed as:

$$c\frac{\partial t}{\partial T} = \nabla \cdot \left(k \nabla T\right) \tag{1}$$

where ρ is the density (kg/m³), c is the specific heat capacity (J/(kg·K)), k is the thermal conductivity (W/(m·K)), and T is the temperature (°C).

Material parameters were assigned based on literature data: thermal conductivity of concrete $k = 1.7$ W/(m·K), steel $k \approx 50$ W/(m·K), and GFRP $k = 0.3 – 0.5$ W/(m·K) [7]. These differences result in fundamentally different heat transfer mechanisms, with steel acting as a heat conductor and GFRP as a thermal insulator.

At the second stage, the obtained temperature fields were used as input data for mechanical analysis, enabling simulation of the stress–strain state of the system under compressive and cyclic loading. This sequential coupling reflects realistic operational conditions, where thermal impact precedes mechanical degradation.

Constitutive material models. The behavior of concrete was described using the Concrete Damaged Plasticity (CDP) model, which accounts for stiffness degradation, cracking, and irreversible deformations. Steel reinforcement was modeled as an elastoplastic material with yielding and strain hardening behavior.

GFRP reinforcement was modeled as an orthotropic linear-elastic material with temperature-dependent degradation of stiffness and strength. The elastic modulus of the composite in the longitudinal direction was determined using the rule of mixtures:

$$E_1 = V_f E_f + \left(1 - V_f\right) E_m \tag{2}$$

where V_f - fiber volume fraction, wt%; E_f - fiber modulus, GPa; E_m - matrix modulus, GPa.

The tensile strength of the composite was evaluated using efficiency factors:

$$\sigma_{1u} = \eta_L \eta_0 V_f \sigma_{f,u} \tag{3}$$

where η_L - length efficiency factor; η_0 - orientation factor; $\sigma_{f,u}$ - ultimate fiber strength, MPa.

Temperature-dependent degradation. The influence of temperature on material properties was described using an exponential degradation law:

$$E\left(T\right)=E_0\cdot exp\left(-\alpha\left(T-T_0\right)\right) \tag{4}$$

where E_0 - initial modulus, MPa; α - thermal softening coefficient (°C^{-1}); T - current temperature, °C; T_0 - reference temperature (20 °C).

This formulation reflects the sharp reduction in mechanical properties of polymer matrices near the glass transition temperature, which is a critical factor in composite performance under thermal loading [6, 7].

Fatigue behavior modeling. Fatigue degradation was evaluated using the S–N approach, which relates the applied cyclic stress to the number of cycles to failure:

$$\sigma_{max}^{n}=\sigma_u\cdot\left(1-\beta\cdot logN\right) \tag{5}$$

where σ_{max}^{n} - maximum cyclic stress at N cycles, MPa; σ_u - ultimate tensile stress, MPa; β - fatigue degradation coefficient.

This approach accounts for the accumulation of damage due to matrix cracking, fiber breakage, and interfacial debonding under cyclic loading conditions [3, 5].

Integrated constitutive model. To describe the combined influence of thermal, mechanical, and fatigue effects, an integrated constitutive relation was formulated:

$$\sigma_c\left(t,T\right)=\eta_b\left(T\right)\left[V_f\sigma_{f,u}+\left(1-V_f\right)\sigma_{m,u}\left(T\right)\right]\cdot\psi\left(N_f,T\right) \tag{6}$$

where $\eta_b\left(T\right)$ - bond efficiency at temperature T; V_f - fiber volume fraction, wt%; $\sigma_{f,u}$ - fiber ultimate strength, MPa; $\sigma_{m,u}\left(T\right)$ - temperature-dependent matrix strength, MPa; $\psi\left(N_f,T\right)$ - factor, describes fatigue degradation.

This relation reflects the role of microstructural design and structural formation processes in determining the effective performance of GFRP reinforcement.

Material composition and microstructural design. The material model explicitly accounts for the influence of fiber chemical composition and matrix properties. E-glass fibers (≈72 GPa) provide cost-effective reinforcement but exhibit limited chemical resistance, while S-glass fibers (≈88 GPa) offer improved stiffness and strength due to higher alumina content. AR-glass fibers, containing zirconia, are designed for enhanced durability in alkaline environments typical of concrete structures [5, 6].

The polymer matrix type (epoxy, vinyl ester, benzoxazine, or thermoplastics such as PEEK) significantly affects thermal stability and fatigue resistance. The use of high glass transition temperature matrices and nanoscale modifiers (e.g., silica, graphene) improves interfacial adhesion and fracture toughness, thereby enhancing the durability of the composite system [6,7].

Thus, the proposed methodology integrates mathematical modeling with microstructural design principles, enabling the prediction and optimization of GFRP reinforcement performance under complex service conditions.

Results and Discussion. The conducted numerical simulations made it possible to establish the relationship between thermal exposure, cyclic loading, and microstructural parameters of glass fiber reinforced polymer (GFRP) reinforcement, providing a comprehensive understanding of the material behavior under combined service conditions.

Influence of thermal loading on material properties. The results of transient thermal analysis demonstrated significant differences in heat transfer behavior between steel and GFRP reinforcement. Due to its low thermal conductivity, GFRP exhibited delayed heat penetration compared to steel, which acts as a heat conductor. However, once the temperature in the composite reached the glass transition temperature of the polymer matrix, a rapid degradation of mechanical properties was observed.

According to the applied degradation model, the elastic modulus of GFRP decreased exponentially with increasing temperature, which is consistent with experimental observations reported in the literature [6,7]. The most critical temperature range was identified between 120 and 250 °C, depending on the type of polymer matrix. In this region, the matrix softening led to a significant reduction in load transfer efficiency between fibers, resulting in a sharp decline in overall stiffness and strength.

At higher temperatures, although glass fibers retained their stiffness, the loss of interfacial adhesion caused a redistribution of stresses and initiated premature failure mechanisms. This confirms that thermal resistance of GFRP is primarily governed by matrix stability and fiber–matrix interaction rather than fiber strength alone.

Effect of microstructural design on mechanical performance. The analysis of micromechanical models showed that the effective stiffness and strength of GFRP reinforcement are strongly dependent on fiber volume fraction and chemical composition. Increasing the fiber content resulted in a proportional increase in elastic modulus according to the rule of mixtures, while the ultimate strength was influenced by efficiency factors related to fiber orientation and length.

A comparison between different fiber types revealed that S-glass fibers provided the highest stiffness and tensile strength, while AR-glass fibers ensured superior durability in alkaline environments. E-glass fibers, although cost-effective, demonstrated reduced resistance to environmental degradation. These findings are consistent with reported experimental data on composite materials [1, 3].

From the standpoint of microstructural design, it was established that optimization of fiber type, matrix composition, and interfacial properties enables significant improvement in the overall performance of GFRP reinforcement. In particular, the use of high glass transition temperature matrices and nanoscale modifiers enhances stress transfer and delays the onset of damage.

Fatigue behavior under cyclic loading. The fatigue analysis based on the S–N approach revealed a gradual degradation of strength with increasing number of loading cycles. The rate of degradation was strongly influenced by microstructural parameters, particularly fiber–matrix adhesion and matrix toughness.

The obtained results showed that fatigue damage is primarily associated with matrix microcracking, progressive fiber breakage, and interfacial debonding. These mechanisms lead to stiffness reduction and eventual failure under repeated loading conditions. The predicted fatigue trends are in agreement with experimental studies on GFRP materials [3,5].

It was also found that the incorporation of nanomodifiers and improved matrix formulations significantly reduces the fatigue degradation coefficient, thereby extending the service life of the material.

Combined thermo-mechanical-fatigue behavior. The integration of thermal, mechanical, and fatigue effects within a unified constitutive model made it possible to evaluate the effective stress capacity of GFRP reinforcement under realistic service conditions.

The results indicate that the combined influence of temperature and cyclic loading leads to accelerated degradation compared to individual effects. In particular, elevated temperatures intensify fatigue damage by reducing matrix stiffness and weakening interfacial bonding.

The proposed model demonstrated that the effective strength of GFRP reinforcement is governed by a complex interaction of factors, including fiber composition, matrix stability, and bond efficiency. This confirms that structural formation processes and microstructural design play a decisive role in determining material performance.

Engineering implications and validation. The obtained results have important implications for the design of reinforced concrete structures using GFRP reinforcement. The developed modeling framework provides a quantitative basis for selecting optimal material configurations depending on service conditions.

For example:

- in aggressive environments, AR-glass fibers with high-performance matrices should be used;

- for fatigue-critical structures, S-glass combined with improved interfacial properties ensures higher durability;
- under fire exposure conditions, hybrid or thermally stable matrices are required to maintain structural integrity.

The validity of the proposed approach is supported by consistency with published experimental data, including fatigue behavior, thermal degradation, and bond performance of GFRP reinforcement [3, 7]. Although the present study is primarily numerical, the agreement with experimental trends confirms the reliability of the developed methodology.

Conclusion

This study presents a comprehensive mathematical modeling framework for predicting the behavior of concrete elements reinforced with glass fiber reinforced polymer (GFRP) under combined thermal and cyclic loading. The proposed approach integrates thermal analysis, mechanical modeling, and micromechanical relations, enabling a multiscale description of material performance based on structural formation processes and microstructural design.

The results demonstrate that the effective mechanical properties of GFRP reinforcement are governed by a combination of fiber chemical composition, polymer matrix stability, and fiber–matrix interfacial behavior. It was established that fiber type (E-, S-, and AR-glass), volume fraction, and matrix characteristics significantly influence stiffness, strength, and durability of the composite material. In particular, S-glass fibers provide superior mechanical performance, while AR-glass fibers ensure enhanced resistance in alkaline environments typical for concrete structures.

Thermal analysis confirmed that the critical factor limiting GFRP performance is the degradation of the polymer matrix near and above the glass transition temperature. Despite the relatively stable behavior of glass fibers at elevated temperatures, the loss of interfacial adhesion leads to a rapid decrease in load-bearing capacity. This finding highlights the dominant role of matrix properties and interfacial interactions in determining thermal resistance of composite reinforcement.

Fatigue analysis based on the S–N approach revealed that cyclic loading leads to progressive degradation of material properties due to matrix microcracking, fiber damage, and interfacial debonding. The rate of degradation is strongly dependent on microstructural parameters, including matrix toughness and interfacial strength. The incorporation of high-performance matrices and nanoscale modifiers was shown to significantly improve fatigue resistance and extend service life.

The integrated constitutive model developed in this study demonstrates that the combined influence of thermal and cyclic loading leads to accelerated material degradation compared to individual loading effects. This confirms the necessity of considering coupled thermo-mechanical-fatigue processes when designing composite reinforcement systems.

The key scientific contribution of this work lies in establishing a direct relationship between material composition, microstructural design, structural formation processes, and the resulting mechanical performance of GFRP reinforcement. The proposed mathematical modeling approach provides a predictive tool for evaluating material behavior under complex service conditions.

From a practical perspective, the obtained results can be applied in the engineering design of reinforced concrete structures exposed to aggressive environments, elevated temperatures, and cyclic loading. The methodology enables rational selection of fiber type, matrix composition, and interfacial characteristics to optimize durability and structural reliability. Ultimately, the proposed approach contributes to the development of advanced composite reinforcement systems as a viable and scientifically grounded alternative to traditional steel reinforcement.

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КОМПЛЕКСНЕ МОДЕЛЮВАННЯ ВЛАСТИВОСТЕЙ СКЛОВОЛОКОННОЇ ПОЛІМЕРНОЇ АРМАТУРИ В БЕТОННИХ ЕЛЕМЕНТАХ ПРИ ТЕПЛОВОМУ ТА ЦИКЛІЧНОМУ НАВАНТАЖЕННІ

Анотація. У роботі розглянуто проблему підвищення довговічності та термостійкості скловолоконної полімерної арматури у бетонних конструкціях, що працюють в умовах термомеханічного та циклічного навантаження. Актуальність дослідження зумовлена необхідністю заміни традиційної сталевої арматури корозійностійкими матеріалами з підвищеними експлуатаційними характеристиками за умов підвищених температур і втомного навантаження. Метою роботи є розробка математико-матеріалознавчої методики, що поєднує підходи математичного моделювання, мікроструктурного конструювання та аналізу процесів структуроутворення для прогнозування властивостей композитної арматури. Методика дослідження базується на дворівневому чисельному підході, який включає нестаціонарний тепловий аналіз із використанням стандартної кривої пожежі та подальше механічне моделювання напружено-деформованого стану системи «бетон–арматура». Поведінку матеріалів описано з використанням моделі пошкоджуваної пластичності бетону, пружно-пластичної моделі сталі та ортотропної моделі скловолоконної полімерної арматури з урахуванням температурної деградації. Для оцінки впливу складу волокон, властивостей полімерної матриці та міжфазної взаємодії на міцність і втомну поведінку застосовано мікромеханічні залежності, засновані на правилі сумішей і коефіцієнтах ефективності. Результати показали, що процеси структуроутворення та мікроструктурного конструювання відіграють визначальну роль у формуванні ефективних характеристик композитної арматури. Встановлено, що використання волокон із підвищеними міцнісними характеристиками та волокон з підвищеною лужною стійкістю, матриць із підвищеною температурою склування та наномодифікаторів суттєво підвищує термостійкість і втомну довговічність матеріалу. Запропоновано інтегровану математичну модель, яка одночасно враховує термічні, механічні та мікроструктурні фактори, що впливають на поведінку матеріалу. Практична значущість дослідження полягає у можливості застосування отриманих результатів при інженерному проєктуванні бетонних конструкцій, що експлуатуються в агресивних середовищах, за підвищених температур та циклічних навантажень, забезпечуючи підвищення довговічності та надійності конструкцій.

Ключові слова: скловолоконна полімерна арматура, математичне моделювання, мікроструктурне конструювання, структуроутворення, втомна поведінка, термомеханічне навантаження, композитні матеріали.

Посилання для цитування: Пілюгін Є. Д. Комплексне моделювання властивостей скловолоконної полімерної арматури в бетонних елементах при тепловому та циклічному навантаженні. *Фундаментальні та прикладні проблеми чорної металургії*. 2026. Вип. 40. С. 226-236. https://doi.org/10.52150/2522-9117-2026-40-014

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