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Durability Assessment of CFRP-Strengthened RC Structures under Thermal Exposure and Material Deterioration

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Abstract

Purpose: This study quantitatively investigates the synergistic effects of deterioration depth and temperature changes on the durability and structural behavior of reinforced concrete (RC) structures strengthened with Carbon Fiber Reinforced Polymer (CFRP) sheets. It provides empirical evidence to address the limitations of current design standards that primarily focus on newly constructed structures. **Research design, data and methodology:** Experimental data from global literature were systematically reinterpreted to analyze correlations between deterioration depth, load-carrying capacity, temperature-dependent epoxy adhesion, and CFRP-concrete interfacial behavior. Regression analysis was employed to derive prediction models for strength reduction rates and to review failure mode transitions at various deterioration stages. **Results:** Structural performance decreased nonlinearly as deterioration depth increased; yield strength dropped by up to 35% in the 10–30 mm range. A quadratic regression model ($R^2=0.997$) demonstrated higher explanatory power than a linear model ($R^2=0.989$), confirming accelerated degradation. Beyond 30 mm of deterioration, interfacial debonding became the dominant failure mode. Furthermore, epoxy adhesion weakened sharply between 80–100°C, effectively nullifying the CFRP strengthening effect. In combined environments, performance degradation appeared as a synergistic rather than a simple additive effect. **Conclusions:** CFRP strengthening design must quantitatively incorporate deterioration depth, thermal impacts, and interface-oriented approaches. This study establishes a quantitative evaluation framework to improve durability assessment and design standards for aging structures.

Keywords : CFRP, Deterioration Depth, Temperature Effect, Interfacial Debonding, RC Structure

JEL Classification Code : L52, L74, N60

1. Introduction

1.1. Background and Necessity

The rapid deterioration of domestic architectural and civil infrastructure has raised serious concerns regarding the structural safety of reinforced concrete (RC) systems. According to the facility safety survey conducted by the Ministry of Land, Infrastructure and Transport (2023),

more than 30% of RC structures in Korea are over 30 years old, and this proportion is expected to exceed 50% within the next decade. The increasing number of aging structures has led to a sharp rise in repair and strengthening demands, creating an urgent need for economical and efficient strengthening technologies.

The externally bonded strengthening method using Carbon Fiber-Reinforced Polymer (CFRP) sheets has been widely adopted for flexural and shear enhancement

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of RC structures due to advantages such as light weight, high strength, excellent constructability, and superior corrosion resistance (Na, 2002; Jeon, 2004; Kim, 2012). In particular, CFRP offers significant benefits for strengthening existing aging structures because it does not require enlargement of the original concrete cross-section. However, the effectiveness of CFRP systems depends heavily on the performance of epoxy adhesives, which exhibit inherent vulnerability to temperature variations and environmental conditions.

When epoxy is exposed to elevated temperatures beyond its typical glass transition temperature (T_g), approximately 60–80°C for common thermosetting resins, a substantial loss of bonding strength occurs, leading to a direct reduction or complete failure of the strengthening system. This issue is especially critical for outdoor structures, where surface temperatures can reach or exceed this range during summer due to direct solar radiation, making quantitative evaluation essential.

Furthermore, many structures requiring strengthening are already in a deteriorated state due to carbonation, chloride attack, wet–dry cycling, and other environmental actions. Current design standards, including KDS 14 20 66 and ACI 440.2R, mainly focus on the material properties of the strengthening system. However, they do not adequately account for variations in strengthening efficiency caused by deterioration depth or the interface behavior under combined environmental conditions, highlighting a significant limitation in existing design practices.

1.2. Limitations of Previous Studies

Previous studies on CFRP strengthening have primarily focused on parameters such as the amount of reinforcement, bonding conditions, and improvements in flexural and shear performance (Lee, 2012; Kim, 2012). Although some research has examined the effects of temperature (Kim, 2010; Cho, 2024) and deterioration (Park, 2022), studies that integratively analyze the long-term behavior of real structures where these two factors act simultaneously are extremely limited. Despite the close interrelationship among the thermal property changes of epoxy resin, the progression of concrete deterioration depth, and the debonding or brittle failure characteristics at the interface, existing studies have tended to treat these factors as independent variables. This approach poses the risk of overestimating the strengthening efficiency of CFRP systems under combined environmental conditions, potentially compromising structural safety.

In addition, many previous studies have treated deterioration depth as a simple categorical variable or have

failed to propose quantitative predictive models that can be directly applied to strengthening design due to limited experimental conditions. Comprehensive analyses of time-dependent phenomena—such as interfacial creep behavior (Park, 2007) and epoxy softening under wet or humid environments—also remain insufficient.

1.3. Research Objectives and Scope

The purpose of this study is to identify deterioration depth and temperature variation as key factors affecting the durability of CFRP-strengthened reinforced concrete (RC) structures and to quantitatively analyze the combined influence of these two parameters on structural behavior. To achieve this, experimental data from previous domestic and international studies were systematically reinterpreted to quantify the relationship between deterioration depth and strength reduction, while evaluating temperature-dependent mechanical changes in epoxy resin and the transition of failure modes across different deterioration levels.

Ultimately, this study aims to comprehensively assess the performance of CFRP strengthening under practical conditions where thermal effects and material deterioration act simultaneously, and to contribute to the enhancement of current design guidelines by proposing refinement measures—such as the incorporation of correction factors that reflect the characteristics of aging structures—to improve the accuracy and reliability of strengthening design in engineering practice.

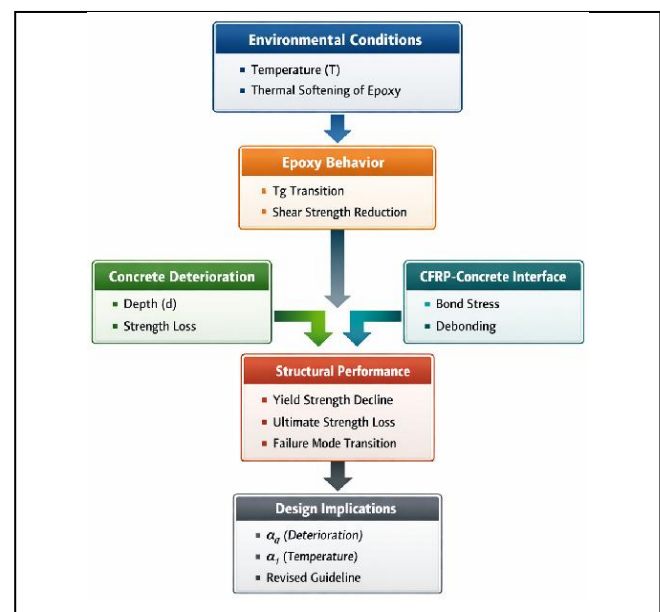


Figure 1: Research framework of CFRP-strengthened RC structures considering thermal and deterioration effects.

Figure 1 presents an integrated research framework that summarizes the interactions among deterioration depth, temperature variation, interface behavior, and structural performance considered in this study.

2. Theoretical Background

2.1. Mechanisms of Strength Degradation in Deteriorated Concrete

The durability deterioration of concrete structures is caused by various physical and chemical degradation mechanisms, including carbonation, chloride penetration, freeze–thaw cycles, and alkali–aggregate reactions (Korea Occupational Safety and Health Agency (KOSHA), 2022). Among these, carbonation is a process in which atmospheric CO₂ reacts with Ca(OH)₂ in the pore solution of concrete to form CaCO₃, progressively advancing from the surface toward the interior and resulting in the loss of alkalinity. The depth of carbonation progresses proportionally to the square root of time and is governed by the carbonation coefficient (K), which is determined by factors such as the water–cement ratio (W/C) and environmental exposure conditions.

$$C=Kt$$

(C: carbonation depth (mm), K: carbonation coefficient, t: exposure period (years))

The average progression of carbonation depth over time under typical urban atmospheric conditions (based on a water–cement ratio of 50–60%) is summarized in Table 1.

Table 1 : Predicted Carbonation Depth of Concrete Over Time (Conservative Estimate)

Elapsed Time (Years)	Carbonation Depth Range (mm)	Major Conditions and Effects
10 years	5-12	Increased likelihood of surface micro-cracking
20 years	12-22	Onset of carbonation reaching the reinforcing cover
30 years	22-35	Rebar corrosion reaches critical depth (advanced deterioration)
50 years	35-55	Cover spalling and accelerated structural strength reduction

When deterioration progresses in the surface layer of concrete, a reduction in elastic modulus, a decrease in compressive strength, and the formation and widening of microcracks occur (Mi-So Park, 2022). These changes directly weaken the stress transfer path of the strengthening material. In particular, when the

deterioration depth reaches approximately 20–50 mm, the reduction in the member's yield strength increases significantly, and the risk of CFRP–concrete interface debonding rises sharply. This indicates that quantitatively incorporating deterioration depth into strength correction is an essential requirement for accurate strengthening design.

2.2. Material Properties and Strengthening Mechanism of CFRP Sheets

In CFRP strengthening systems, the key medium that transfers the performance of the strengthening material to the concrete substrate is the epoxy resin. Epoxy resin is a thermosetting polymer whose physical properties change abruptly beyond a certain temperature, a behavior governed by its glass transition temperature (T_g). For construction-grade epoxy resins typically used in CFRP applications, the T_g generally ranges from approximately 60 to 80°C. The relationship between epoxy state transitions and strengthening efficiency can be summarized as follows:

[1]. Glassy State (< 60°C):

In this stage, the epoxy maintains high stiffness and strong adhesion, enabling efficient transfer of tensile forces from the CFRP sheet to the concrete.

[2]. Transition State (60–80°C):

Molecular mobility within the resin increases, and stiffness begins to decline rapidly. Experimental results indicate that the interfacial shear strength in this temperature range can decrease to approximately 40–60% of its value at room temperature.

[3] Rubbery State (> 80°C):

The resin becomes flexible and loses its adhesive capability. In this state, premature debonding between the CFRP sheet and concrete becomes the dominant failure mode, and the strengthening effectiveness may drop to less than 20% of the theoretical capacity.

These thermal characteristics indicate that temperature increases caused by summer solar exposure or by early-stage fire conditions have a direct effect on the safety of CFRP-strengthened structures. Therefore, this study incorporates thermal variations relative to the epoxy's T_g as a key variable to quantitatively evaluate the degradation in durability under elevated temperatures.

2.3. Failure Mechanism of CFRP-Reinforced Members

The failure modes observed in externally bonded CFRP-strengthened members can be broadly classified into three categories. First, interfacial debonding failure occurs at either the concrete–epoxy interface or the epoxy–CFRP interface and is the most frequently observed failure mode in deteriorated members. Theoretically, the effective bond strength of CFRP is directly governed by the tensile strength f_{ct} and compressive strength f_{ck} of the substrate concrete. In general, the interfacial shear strength is known to develop at approximately 1.5–2.0 times the concrete tensile strength. However, when surface strength decreases by approximately 20–30% due to deterioration, the maximum transferable bond stress at the interface does not decrease linearly; instead, it drops rapidly in a nonlinear manner.

Table 2 : Theoretical Bond Performance Variations According to Concrete Surface Condition and Strength

Concrete Condition	Surface Tensile Strength (f_{ct} , MPa)	Predicted Interfacial Shear Strength (τ_{max})	Remarks (Failure Mode)
Sound (New Construction)	2.5 – 3.5	4.0 – 6.0	CFRP rupture or internal concrete failure
Moderately Deteriorated	1.5 – 2.5	2.5 – 4.0	End debonding or mixed failure
Severely Deteriorated	less than 1.5	less than 2.5	Interface debonding dominant (brittle failure)

Kim(2012) confirmed that stress concentration at the laminate end is a major cause of debonding failure and reported that tapering or increasing the bonded length is effective in preventing such failures. Second, brittle concrete shear failure occurs when severe surface deterioration leads to the early formation of shear cracks, thereby limiting the strengthening effectiveness. Third, CFRP rupture is an ideal failure mode that primarily appears in newly constructed members with good bonding conditions. In deteriorated structures, however, the reduction in concrete surface strength causes the first or second failure mode to dominate, resulting in insufficient utilization of the tensile capacity of the CFRP sheet and a significant reduction in strengthening efficiency.

2.4. Limitations of Current Strengthening Design Standards

Major strengthening design guidelines, such as ACI 440.2R and the Korea Concrete Institute (KCI) standards,

primarily provide performance calculation formulas for new structures or standard environmental conditions. However, these codes have significant limitations in reflecting the actual physical state of aged structures where concrete surfaces have already undergone substantial carbonation or degradation.

While correction factors for temperature variations are available, there is a distinct lack of clear design guidelines regarding the complex interactions that occur when the strength of the substrate concrete degrades due to aging while the epoxy adhesive simultaneously softens in high-temperature environments.

Therefore, it is essential to quantitatively evaluate CFRP (Carbon Fiber Reinforced Polymer) strengthening performance under combined conditions involving both the degradation depth of aged concrete and thermal environments. This necessitates an integrated analysis through the systematic reinterpretation of existing experimental data and literature.

3. Research Methodology

3.1. Data Collection and Selection Criteria

In this study, experimental research on CFRP-strengthened RC structures published in domestic and international journals and dissertations was systematically screened. The selection criteria were strictly limited to studies that satisfied all of the following three requirements: inclusion of aging effects (degradation depth) or thermal environments (temperature) as primary experimental variables; quantitative reporting of yield strength or ultimate load capacity; and explicit identification of failure modes.

The primary literature selected based on these criteria is summarized in Table 3. This study performed an integrated analysis by reinterpreting quantitative data extracted from more than 10 core publications.

Table 3 : Current Status of Key Previous Research and Analytical Variables for Integrated Data Analysis

Classification	Primary Author (Year)	Key Analytical Variables (Independent Variables)	Analysis Data Type
Degradation/ Aging	Park (2022)	Concrete degradation depth (0–40mm)	Strength reduction rate, failure mode
Degradation/ Aging	Na (2002)	Strengthening performance evaluation of aged RC members	Structural behavior, ductility index

Classification	Primary Author (Year)	Key Analytical Variables (Independent Variables)	Analysis Data Type
Thermal Environment (Temperature)	Cho (2024)	Thermal properties of epoxy resin and temperature changes	Bond strength variation (Tg)
Thermal Environment (Temperature)	Kim (2010)	Incorporation of high-strength fibers in high-temperature environments	Fire resistance, residual strength
Interface/Bond	Kim (2012)	Analysis of bond parameters of CFRP sheets	Interfacial stress, debonding load
Interface/Bond	Park (2007)	Creep and temperature effects of the adhesive layer	Interfacial shear deformation

3.2. Analysis Methodology

Linear and non-linear (quadratic) regression analyses were performed to identify the quantitative relationship between degradation depth and the reduction rate of structural capacity. The median values of the reduction rate ranges presented at each degradation stage were utilized as dependent variables, and the explanatory power of the models was evaluated using the coefficient of determination (R^2).

The temperature-dependent mechanical property changes of the epoxy were analyzed focusing on the experimental results of Cho (2024), specifically examining the shear strength variation rate, viscoelastic behavior characteristics, and the patterns of adhesion degradation upon exceeding the glass transition temperature (T_g).

The failure mode transition characteristics were investigated by technically considering the occurrence trends of primary failure types and changes in energy dissipation capacity at each degradation stage. Furthermore, the combined effects of aging and temperature were compared with single-factor analysis results to derive the characteristics of their interaction.

4. Experimental Results and Analysis

4.1. Changes in Structural Behavior According to Aging (Deterioration Depth)

4.1.1. Yield Strength Reduction Trends and Regression Analysis

Reinterpreting the experimental results of Park (2022), the yield strength according to the increase in degradation depth exhibits distinct non-linear reduction characteristics.

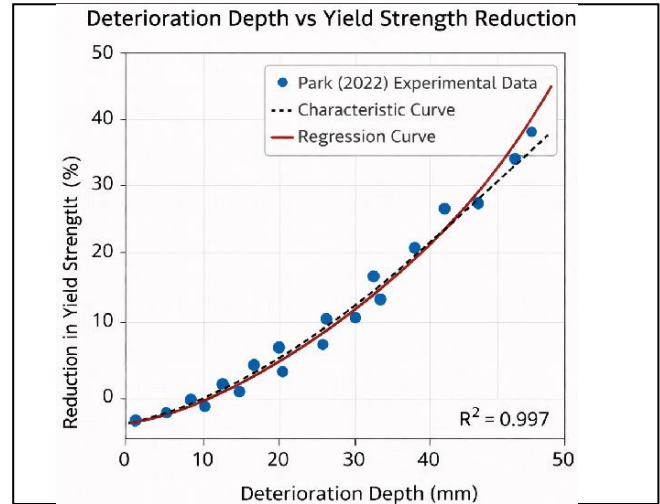


Figure 2: Effect of Deterioration Depth on Yield Strength Reduction

The reduction trends in yield strength according to the degradation depth are visually presented in Figure 2.

As confirmed in Table 4, the yield strength decreased by approximately 8–15%, 18–25%, and 25–35% compared to the control specimen under degradation conditions of 10 mm, 20 mm, and 30 mm, respectively. This reduction is the result of a combined effect of the decrease in surface layer compressive strength and the shift of the neutral axis due to crack concentration. In particular, a tendency for the magnitude of strength degradation to increase sharply was prominently observed at degradation stages of 20 mm or more. This suggests that when applying strengthening to aged structures, a degradation depth of 20 mm should be established as a critical threshold and a conservative design approach should be implemented.

Table 4 : Changes in Yield and Ultimate Strength with Deterioration Depth

Degradation Depth (mm)	Yield Strength Reduction Rate(%)	Ultimate strength reduction rate(%)	Key Behavioral Characteristics
0 (Control)	0	0	Normal bond, Flexure-critical
10	8–15	10–18	Initiation of local compressive degradation
20	18–25	20–28	Combined shear-flexure, increased edge stress
30	25–35	25–30	Frequent interfacial debonding, reduced CFRP

Degradation Depth (mm)	Yield Strength Reduction Rate(%)	Ultimate strength reduction rate(%)	Key Behavioral Characteristics
			effectiveness
≥40	≥35	≥30	Interfacial failure dominance, sharp decline in strengthening efficiency

As a result of deriving the quantitative relationship between the deterioration depth (d, mm) and the yield strength reduction rate (Yy,%) by regression analysis, the linear regression equation was calculated as follows.

$$Yy = -0.30 + 0.96d \quad (R^2 = 0.989) \dots (1)$$

This equation means that when the deterioration depth increases by 1 mm, the yield strength decreases by an average of 0.96% and shows high explanatory power (R²=0.989). However, the results of applying the second-order regression model to more accurately reflect the nonlinear behavior are as follows.

$$Yy = 0.012d^2 + 0.56d \quad (R^2 = 0.997) \dots (2)$$

The quadratic regression model showed higher explanatory power (R²=0.997) than the linear model, statistically proving that the strength reduction proceeds not linearly but accelerated after a deterioration depth of 20 mm. On the other hand, the linear regression equation for the maximum strength reduction rate (Yu,%) was derived as follows.

$$Yu = 1.25 + 0.72d \quad (R^2 = 0.962) \dots (3)$$

The slope (0.72) of the maximum strength reduction rate tends to be somewhat gentle compared to the yield strength (0.96), which can be explained by the mechanism by which early destruction due to concrete deterioration occurs even when the tensile performance of CFRP is exhibited to some extent. In other words, even if deterioration proceeds, the material strength of CFRP itself is maintained, but its performance is not fully utilized due to the weakening of the stress transfer path.

4.1.2. Ultimate Strength Reduction and Characteristics by Degradation Stage

The reduction in ultimate strength also exhibited distinct sensitivity to the degradation depth. When the degradation depth exceeded 30 mm, the ultimate strength

decreased by 25–30% compared to the control, which is attributed to the rapid reduction of the effective concrete cross-section. In cases where degradation progressed beyond 40 mm, the strength reduction rate reached over 30%, and at this level, the structural contribution of the CFRP strengthening system is significantly limited. These results demonstrate the necessity of applying differentiated strengthening strategies depending on the degradation stage. They further suggest that for highly degraded structures, repairing the concrete substrate itself prior to CFRP strengthening is essential to ensure strengthening efficiency.

4.2. Behavioral Changes of Epoxy and CFRP According to Temperature Variations

4.2.1. Temperature-Dependent Mechanical Properties of Epoxy Adhesive Layers

According to the study by Cho (2024), epoxy resins exhibit significantly different mechanical properties depending on the temperature range. As confirmed in Table 5, a normal bond state is maintained in the ambient temperature range (20–40°C). However, upon entering the 50–60°C range, as the temperature approaches the glass transition temperature, viscoelastic behavior begins to increase and the shear strength decreases by 5–10% compared to the control. In the 80–100°C range, as the epoxy completely exceeds the glass transition temperature (T_g), the mobility of the molecular chains increases significantly, and the shear strength drops sharply by 20–50%, reaching a level where the CFRP strengthening effect virtually disappears.

Table 5 : Mechanical Performance of Epoxy Adhesive Layers According to Temperature

Temperature (°C)	Shear Strength Change	Viscoelastic Behavior	T _g (Glass Transition Temp) Effect	Key Characteristics
20–40	Maintains control level	Very low	No significant effect	Maintains normal bond state
50–60	5–10% reduction	Begins to increase	Approaching T _g	Increased deformation; potential micro-debonding
80–100	20–50% reduction	Increases rapidly	Exceeds T _g	Sharp drop in adhesion; strengthening effect vanishes

This high-temperature vulnerability of epoxy empirically demonstrates that the effectiveness of CFRP strengthening can be significantly limited when structures

are subjected to long-term direct sunlight (where surface temperatures can reach 60–80°C), fire exposure, or industrial high-temperature environments. In particular, for bridge superstructures or industrial factory structures exposed to direct sunlight during summer, the surface temperature is highly likely to exceed design expectations, causing the CFRP strengthening efficiency to fall significantly below the intended design values.

4.2.2. Reduction in CFRP Strengthening Efficiency under High-Temperature Conditions

In the fire resistance tests conducted by Kim (2010), it was confirmed that CFRP materials lose a significant portion of their structural integrity under high-temperature conditions exceeding 300°C due to direct thermal damage. The failure sequence was observed as: 'adhesive layer degradation → loss of bond strength → CFRP debonding → abrupt decline in structural performance.' This indicates that the effectiveness of CFRP strengthening can be neutralized within a short duration during a structural fire. Consequently, for structures with expected fire loads, substantial strengthening effects are difficult to achieve without dedicated fire protection measures; otherwise, the degraded epoxy layer may even accelerate the deterioration of the overall structural capacity.

4.3. Analysis of CFRP-Concrete Interfacial Behavior

4.3.1. Conditions and Mechanisms of Interfacial Debonding

Summarizing the experimental data reinterpreted in this study, interfacial debonding emerged as the dominant failure mode when multiple vulnerability conditions overlapped. Specifically, debonding failure was most frequently observed when the concrete degradation depth reached 20–30 mm or more, the epoxy adhesive layer temperature reached 60°C or higher, and stress concentrations occurred at the ends due to insufficient bond length or the absence of end tapering. Upon the occurrence of interfacial debonding, stress transfer is severed before the CFRP reaches its tensile rupture, leading to a sudden loss of strength and a significant reduction in ductility. Particularly in aged members, interfacial debonding exhibits brittle failure characteristics, increasing the risk of sudden structural collapse without prior warning.

4.3.2. Effects of Humid Environment and Long-term Creep

As confirmed in the study by Park (2007), interfacial creep increases markedly when sustained loading and humid conditions are combined. In a wet environment,

moisture penetrates the epoxy resin, triggering plasticization that weakens the epoxy-concrete bond integrity. This leads to increased long-term deflections and a reduction in the interfacial shear strength. A 10–20% decrease in strength compared to the initial bond capacity was observed under sustained loading, suggesting that long-term durability may be severely compromised in aged structures strengthened after more than 30 years of service. These findings underscore the necessity of long-term performance monitoring and periodic bond integrity inspections following CFRP strengthening.

4.4. Analysis of Failure Mode Transition

The failure mode transition characteristics relative to degradation depth and temperature conditions are summarized in Table 3. In the low-degradation zone (0–10 mm), the structural efficiency of the concrete and the tensile performance of the CFRP were fully utilized, with concrete crushing or shear cracking constituting the dominant failure modes. In the intermediate-degradation zone (10–30 mm), a transition was observed characterized by combined flexural-shear behavior and increased plate-end debonding, leading to a gradual decrease in fracture energy absorption capacity. In the high-degradation zone (30 mm or more), interfacial debonding became the dominant failure mode, and structural capacity was exhausted prematurely before the tensile performance of the CFRP could be fully realized.

Table 6: Failure Mode Transition by Deterioration Stage and Temperature Condition

Category	Conditions	Primary Failure Mode	Tg Influence & Tensile Performance	Key Characteristics
Low Degradation	Depth: 0–10 mm / Ambient Temp.	Concrete crushing, Shear cracking	High– Tensile capacity fully utilized	Efficient structural behavior of concrete and CFRP
Intermediate Degradation	Depth: 10–30 mm / Ambient Temp.	Combined flexural-shear, Increased plate-end debonding	Moderate– Tensile capacity partially utilized	Transitional behavior; gradual decrease in energy absorption
High Degradation	Depth: ≥30 mm / Ambient Temp.	Dominant interfacial debonding, Brittle failure	Low– Tensile capacity unutilized	Structural behavior terminated prematurely; brittle failure
High Temperature	Ambient / Epoxy Temp. ≥80°C	Plate-end debonding, Premature shear failure	Negligible– Strengthening effect vanished	Rapid loss of bond stiffness due to epoxy softening
Combined Environment	High Degradation	Overlapping interfacial	None– Accelerated	Synergistic failure

t	n + High Temp.	failure and premature debonding	performance degradation	mechanism; total loss of reinforcement efficiency
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Regarding the failure mode transition induced by temperature elevation, it was confirmed that when the epoxy adhesive layer temperature exceeds 80°C, the CFRP sheet fails to effectively transfer loads to the concrete due to bond degradation. Consequently, the structure progresses toward a failure path characterized by plate-end debonding or premature shear failure. In particular, under combined environments involving simultaneous aging and high temperatures, a synergistic degradation phenomenon was observed. In this state, the weakening of the concrete substrate and the thermal softening of the adhesive layer interact, triggering interfacial failure significantly earlier than the degradation observed under any single environmental factor.

5. Comprehensive Analysis and Discussion

5.1. Interaction between Deterioration Degree and Epoxy Adhesive Performance

In deteriorated concrete, the reduction in surface layer strength occurs first, which directly leads to a decline in bond performance—the most critical factor in CFRP strengthening systems. As the degradation depth increases, the effective cross-section and elastic modulus of the concrete substrate decrease, while the expansion of micro-cracks increases the dominance of interfacial shear stress. Synthesizing the results of this study, it was confirmed that the degradation depth is the primary variable determining CFRP strengthening efficiency. Specifically, when the degradation depth reaches 20–30 mm or more, the reduction in bond efficiency becomes the governing factor for the overall structural performance. Interfacial debonding was the most prevalent failure mode in severely deteriorated members, characterized by the premature termination of structural behavior before the CFRP could reach its full tensile capacity. This empirically demonstrates that ensuring the quality of surface preparation (e.g., primer application, grinding, and filling of vulnerable areas) is a key determinant of strengthening performance in aged structures, and suggests the necessity of mandating pull-off tests prior to construction.

5.2. Impact of Temperature Variations on CFRP Strengthening Systems

Due to the organic nature of epoxy adhesives, the bond

layer is highly sensitive to thermal variations, with viscoelastic behavior becoming pronounced around 60°C. Beyond this threshold, the degradation of bond strength accelerates, placing the entire strengthening system under the direct influence of temperature. This implies a significant risk of reduced efficiency when structures are exposed to outdoor environments or prolonged solar radiation. Specifically, as surface temperatures of bridge superstructures or industrial facilities can reach 60–80°C during summer, the application of CFRP in such conditions necessitates dedicated thermal mitigation measures.

When high temperatures and aging effects act simultaneously, the vulnerability of the bond system is further exacerbated; it was observed that the onset of interfacial debonding under elevated temperatures occurs significantly earlier in aged members. Consequently, temperature is clearly a critical design parameter that defines the performance limits of CFRP strengthening systems and must be explicitly incorporated into current design standards.

5.3. Performance Limits and Design Implications of CFRP Strengthening in Complex Environments

In an environment where aging and temperature work together, a much accelerated reduction in strength was observed than a single factor, and it was confirmed that this was a synergistic effect by interaction, not a simple sum of the two factors. If a temperature rise occurs while the stress transfer capacity of the base concrete is reduced due to deterioration, the epoxy adhesive layer softens early and blocks load transfer, which leads to a sharp decrease in strengthening efficiency.

Based on the results of this analysis, the CFRP strengthening performance limit conditions identified in this study can be summarized as follows. When the deterioration depth reaches 30 mm or more, the CFRP strengthening effect plunges, and interfacial breakdown becomes dominant, so it is essential to reinforce the surface strengthening treatment and apply the conservative strength reduction factor. In an environment where the temperature of the epoxy adhesive layer reaches 80°C or higher, the structural performance is substantially extinguished due to loss of adhesion, so it is indispensable to combine refractory coating or heat shielding measures. In the condition where the wet environment and the long-term load are combined, long-term strength decreases due to interfacial creep, so it is necessary to increase the safety rate under long-term load conditions. In the worst environment where aging and high temperature are combined, a design that applies an interaction coefficient

rather than a simple sum of the reduction rate for each factor is required.

In order to reflect this systematically, it is necessary to explicitly introduce the CFRP attachment efficiency correction factor (α_d) and the temperature effect reduction factor (α_T) for each deterioration stage to the current design criteria, and to prepare a modified design framework that expresses the combined effect of the two coefficients as an interaction term. This framework needs to be verified in combination with future finite element analysis or reliability-based design approaches.

6. Conclusion

In this study, deterioration depth and temperature changes affecting the durability of CFRP-reinforced RC structures were set as key factors, and the following conclusions were drawn through systematic reinterpretation of existing experimental data.

First, the decrease in strength due to the increase in deterioration depth shows a nonlinear acceleration characteristic. In the deterioration 10-30 mm section, the yield and maximum strength decreased by 8-35% compared to the standard, and the quadratic regression model ($R^2=0.997$) showed higher explanatory power than the linear model ($R^2=0.989$), indicating statistically the acceleration reduction characteristics. This means that a conservative approach to strengthening design is essential from the section after 20 mm of deterioration.

Second, in the section of deterioration of 20-30 mm or more, the interfacial peeling is transferred to the dominant destruction mode. The adhesion performance of the concrete base layer acts as a primary variable determining destruction rather than the tensile capacity of the CFRP itself, and the CFRP strengthening efficiency is greatly reduced. This proves that quantitative verification of surface treatment quality should be preceded when reinforcing old structures.

Third, the epoxy adhesive layer is very sensitive to temperature, so viscoelasticity increases at around 60°C and adhesion decreases rapidly at 80-100°C, effectively losing the CFRP strengthening effect. In structures subjected to fire loads or high-temperature external environments, CFRP strengthening without separate fire and heat shielding measures may be insufficient to secure structural safety.

Fourth, in a complex environment where aging and high temperature work at the same time, the deterioration of strengthening performance shows a synergistic acceleration characteristic, not a simple sum. This clearly reveals the limitations of the current design approach that independently evaluates the effects of each factor and

supports the necessity of introducing a composite environment correction factor reflecting the interaction of the two factors.

Fifth, the deterioration-based attachment efficiency correction coefficient (α_d) and temperature effect reduction coefficient (α_T) are explicitly introduced in the current design standards, and it is urgent to prepare a revised design framework that reflects the interaction terms of the complex environment. The results of this study can be used as an empirical basis for revising such design standards.

Due to the nature of this study as a reinterpretation study based on existing experimental data, there is a limitation in directly measuring the real-time interaction of complex variables such as temperature, deterioration, wetness, and long-term loading. In the future, it will be necessary to build an interfacial strength reduction model through complex environment experiments, develop a CFRP strengthening optimization design formula for each deterioration stage, and propose a durability evaluation model considering long-term creep and repetitive loads. In particular, a follow-up study is required to quantitatively verify the reliability of the correction factor proposed in this study through finite element analysis and combination with a reliability-based design approach.

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