SUSTAINABLE REHABILITATION OF FIRE-DAMAGED LOW-RISE RC STRUCTURES: ASSESSMENT, RETROFITTING, AND BAMBOO FIBER SOLUTIONS

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Abstract- Urban fires pose significant risks to structures, lives, and the environment, necessitating efficient post-fire rehabilitation methods. This paper explores the assessment, retrofitting techniques, and sustainable solutions for fire-damaged low-rise reinforced concrete (RC) structures. Understanding fire behavior and its impact on concrete integrity is crucial, with post-fire assessments playing a pivotal role in determining structural viability. Various parameters, including temperature variations and concrete conditions, are evaluated to quantify fire damage accurately. Retrofitting techniques aim to restore structural integrity, with bamboo fiber reinforcement emerging as a sustainable alternative. Bamboo fibers enhance strength and durability while reducing reliance on non-renewable materials, offering cost-effective solutions for urban infrastructure repair. This research emphasizes the importance of sustainable rehabilitation practices to mitigate the impact of fires on urban infrastructure.

Keywords- Assessment, Bamboo fibers, Retrofitting techniques, Sustainable solutions, Urban fires.

1 Introduction

Urban fires cause significant property damage and loss of life. Rehabilitating fire-damaged concrete structures must consider structural integrity, safety, and sustainability. Sustainable rehabilitation methods are crucial for mitigating the impact on urban infrastructure, especially in underdeveloped nations where fire disasters are common [1]. To address the sustainability and effectiveness of bamboo fibers in post-fire retrofitting, a summary of research studies and their findings is provided in Table 1. This compilation highlights the benefits and applications of bamboo fibers in enhancing the structural integrity of fire-damaged concrete structures. Fire-damaged RC structures worldwide showcase the resilience of reinforced concrete. Despite intense flames, these buildings often retain their integrity and avoid collapse, demonstrating recovery potential from fire disasters [1]. Studies of rare events like fires triggered by earthquakes highlight various risks to buildings, including natural and human-induced causes such as hurricanes and explosions, which can lead to structural failure [2]. Fires exceeding 1000°C weaken construction materials, threatening stability and increasing the risk of collapse [3-6].

Understanding fire behavior from pre-flashover to post-flashover stages is crucial [7]. During the pre-flashover phase, toxic gases like carbon monoxide, hydrogen cyanide, and phosgene pose severe health risks. Combustion smoke irritates and obstructs escape routes, heightening the risk of toxic gas inhalation and burns. Oxygen depletion during fires escalates these hazards, posing a significant threat to personal safety [8-9]. Fire-related incidents result in billions of dollars in losses globally, emphasizing the need for efficient prevention and mitigation strategies [7]. Combustion, firefighting, and hazardous substance releases contribute to environmental pollution. They worsen air and water contamination and cause significant environmental deterioration [10]. It's vital to engineer structures to withstand various risks, including fire, ensuring human safety and environmental sustainability throughout their lifecycle [2].

Table – 1 Research summary on Bamboo Fibers in post-fire retrofitting of concrete structures

No.	Authors	Focus	Key Findings and Benefits	Ref.
1	Ni & Gernay (2020)	Residual deformations in RC structures post-fire	Bamboo fibers reduce residual deformations, enhancing structural stability.	[1]
2	Kodur et al. (2019)	Fire hazards and safety strategies	Bamboo fibers improve fire resistance and recovery, boosting fire resilience.	[2]
3	Buchanan & Abu (2001)	Structural design for fire safety	Bamboo fibers enhance fire resistance and structural integrity.	[3]
4	Khan et al. (2021)	Mechanical properties of hybrid fiber concrete	Bamboo fibers strengthen concrete, enhancing durability.	[4]
5	Xie et al. (2021a)	Testing methods for fiber-reinforced composites	Bamboo fibers provide superior fracture properties post-fire, leading to enhanced crack resistance.	[5]
6	Xie et al. (2021b)	Structural failure prediction with hybrid fibers	Bamboo fibers delay failure under fire conditions, extending structural lifespan.	[6]
7	Awoyera et al. (2024)	Structural performance of fire-damaged beams	Bamboo fiber laminates increase strength and performance of fire-damaged beams.	[22]
8	Cuce et al. (2024)	Energy efficiency and thermal resistance	Bamboo-reinforced briquettes enhance thermal performance and sustainability.	[23]
9	Bala & Gupta (2023)	Sustainable building materials	Bamboo-reinforced concrete is sustainable building material that support eco-friendly construction.	[24]
10	Awoyera et al. (2024)	Green retrofitting materials	Bamboo fibers offer sustainable repair solutions for fire-damaged RC buildings.	[25]

Fire significantly impacts reinforced concrete (RC) structures, reducing their load-bearing capacity. Assessing post-fire strength is crucial for effective repairs, with research focusing on concrete flexural strength under fire conditions [11]. Although concrete is non-combustible, high temperatures weaken its integrity, necessitating robust assessment frameworks for fire damage. Rehabilitating fire-damaged concrete structures is essential for safety and functionality. Integrating bamboo fibers into concrete offers a sustainable solution, enhancing fire resilience, reducing residual deformations, and improving post-fire strength and durability [1-6, 22-25]. This review highlights the novel use of bamboo fibers in post-fire rehabilitation, promoting eco-friendly practices in mitigating structural damage.

2 Quantification of fire damage in low-rise RC structures

Fires pose significant risks to lives, RC structures, and the environment. This article focuses on fire-related issues in RC buildings and low-rise structures, examining fire damage using petrographic techniques. It identifies firefighting system deficiencies and safety measures. Visual inspection is crucial for evaluating RC elements' quality, cracks, and bond condition, while surface examination assesses color change, crazing, and cracking. Table 2 provides data on temperature variations, color changes, appearance alterations, and concrete conditions [18]. For assessing fire damage in low-rise RC structures, various techniques are used based on fire intensity. At early stages (0 to 300°C), visual and surface inspections detect initial cracks and color changes. For moderate exposure (300 to 600°C), petrographic analysis and infrared thermography reveal internal damage. In severe conditions (600 to 950°C), ultrasonic testing and core sampling assess internal and reinforcement damage. For extreme fires (>950°C), carbonation depth and rebound hammer tests evaluate penetration and surface strength. These techniques ensure thorough assessment and effective repair.

Table – 2 Color variations in concrete occur across different temperature ranges [18]

Temperature variation	Color modification	RC Structure appearance	Status of concrete
0 to 300°C	Unchanged	Normal	Unaffected
300 to 600°C	Pink to red	Cracking	Stable but with reduced strength
600 to 950°C	Whitish grey	Spalling steel exposed & powder existence	Weak
> 950°C	Buff	Severe Spalling	Intense/Severe

3 Post-fire Assessment and Retrofitting Techniques

RC buildings generally withstand fires well, but post-fire assessments are essential to evaluate concrete conditions, as fire often affects only the surface layer [12]. Due to their superior fire resistance compared to materials like stainless steel and wood, RC structures are extensively studied [11]. Thicker concrete covers help insulate reinforcement, preserving load capacity, though high-strength concrete is less fire-resistant than lightweight concrete. RC beams and slabs near ceilings are particularly vulnerable to heat currents during fires [13]. While RC structures retain some residual strength post-fire, heat degradation can cause irreversible damage, necessitating thorough evaluations for future use and repair [14]. Figure 1 shows fire-induced water evaporation in cement paste, leading to dehydration and concrete discoloration. Moderate fires can also cause spalling and surface crazing, underscoring the need for comprehensive assessment and rehabilitation to restore integrity.

a) b) c)

Figure 1: Assessment of RC structures, a. Crazing [26], b. Spalling [27], c. Color changing [27]

Assessing concrete's residual strength post-fire is critical for deciding on future use, repair, or demolition. Both laboratory and on-site tests, emphasizing compressive strength, provide detailed insights into post-fire damage severity [21]. Research on reinforced concrete structures employs various testing approaches, including standard fire tests, parametric variations, and natural fire scenarios, which offer more realistic depictions than conventional methods [15]. Post-fire assessments should determine the thickness of sections where concrete damage is severe enough to be considered destroyed [16]. Heat exposure alters thermal and mechanical properties, affecting structural toughness and resistance, and influencing compression, tension, and strain characteristics [17]. Thermal expansion of reinforcing bars during fires can crack concrete covers, especially at supports and beam bases. Structural fire engineering combines active measures like detectors and sprinklers with fire-resistant materials and design strategies. Rapid assessments of fire-damaged structures ensure safety and identify repair needs for low-rise buildings. Research on natural fibers, particularly bamboo, shows significant strength improvements in reinforced and retrofitted RC beams [19, 20].

4 Sustainable solutions

Concrete structures degrade in high heat, requiring effective repair methods. Traditional approaches, like replacing damaged sections or using non-renewable materials, are resource-intensive and harmful to the environment. Bamboo fiber reinforcement offers a sustainable alternative, improving strength and durability post-fire. Bamboo, a quickly renewable resource, has minimal environmental impact compared to steel or synthetics. Studies show bamboo fiber composite plates can boost retrofitted concrete beam strength by 10-21%. Affordable and accessible, bamboo fibers are ideal for widespread use, especially in fire-prone regions. Their use reduces reliance on non-renewables and cuts concrete's carbon footprint. Bamboo fiber reinforcement enhances structural integrity. It provides significant environmental benefits. This method offers a sustainable and cost-effective solution for urban infrastructure repair.

5 Conclusion

In conclusion, the research underscores the significance of sustainable rehabilitation methods in mitigating the impact of urban fires on infrastructure. By prioritizing sustainability, researchers can address the following key points:

1. Understanding the resilience of reinforced concrete (RC) structures in fire disasters highlights the possibility of recovery and emphasizes the importance of sustainable rehabilitation approaches.

2. Thorough post-fire assessment techniques are vital for evaluating concrete conditions and determining suitable retrofitting techniques to regain structural integrity.
3. Bamboo fiber reinforcement emerges as a sustainable alternative, offering improved strength and durability post-fire while reducing reliance on non-renewable resources and cutting concrete's carbon footprint.
4. Implementing bamboo fiber reinforcement in concrete repair not only enhances structural integrity but also provides significant environmental benefits, offering a cost-effective solution for fire-prone regions.

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