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Impact of Elevated Temperatures on the Mechanical Properties of GFRP Bars in RC One-Way Slab: A Review

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ABSTRACT

This study investigates the impact of elevated temperatures on the mechanical properties of Glass Fiber Reinforced Polymer (GFRP) bars as reinforcement in reinforced concrete (RC) one-way slab. GFRP bars are increasingly used in construction due to their superior corrosion resistance and strength to weight ratio, but their performance under fire exposure remains a critical concern. The study examines how temperatures above 100°C degrade the tensile strength and bond strength of GFRP with concrete, with significant losses occurring at temperatures above 300°C. The effects of fire on concrete, such as moisture loss, spalling, and strength reduction, are also discussed. Researches findings show that increased concrete cover and anchorage length improve fire resistance, with failures typically occurring at around 500°C due to GFRP bar rupture. Furthermore, GFRP-reinforced slabs exhibit better ductility and safety factors compared to steel reinforced slabs under cyclic loading, though they suffer from stiffness degradation. The review highlights the need for further research to develop advanced fire-resistant GFRP composites and better predictive models for the performance of GFRP-reinforced structures in fire-prone environments. Ultimately, GFRP bars offer promising solutions in corrosion-prone areas but require careful consideration for fire resistance and long-term performance in high-temperature applications

1. Introduction

In recent years, there has been significant research focused on the structural performance of RC slabs under fire conditions. Numerous experimental and numerical studies have been conducted to evaluate the fire performance of RC slabs [1], [2], [3], [4], [5]. However, limited studies have been conducted on the residual load capacity of RC slabs, particularly in assessing the extent of fire damage and their potential for reusability especially with GFRP reinforcement bars[6], [7], [8].

Fiber-reinforced polymer (FRP) is considered one of the hot topics in the field of civil engineering. It serves as an excellent new material for strengthening steel components, which often incur high manufacturing costs. Additionally, it can enhance strength and rigidity, or be utilized in building rehabilitation efforts [9]. The emergence and widespread use of FRP has brought about significant changes in numerous industries over the past few decades [10]. For instance, it finds application in the aviation industry due to its high strength-to-weight ratio and resistance to fatigue. Similarly, it is employed in shipbuilding for its resistance to corrosion and decay, as well as in athletic equipment due to its toughness. While the use of FRP in construction hasn't been as widespread as in other industries, some notable projects are redefining its potential in civil and architectural engineering [11]. The behaviour of FRP differs from that of steel, with one

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significant distinction being FRP's lack of ductility. Therefore, special precautions and design considerations must be taken into account, accounting for the physical properties of FRP [12].

2. Historical Overview of FRP

FRP was discovered after World War II. In the 1950s, its use in roads increased. In the early 1960s, it was studied as a material to strengthen bridge structures. By the end of the 1970s, it became commercially available as an alternative to rebar to overcome the problem of rust. In the 1980s, FRP was used in medical facilities, such as medical equipment facilities for magnetic resonance imaging (MRI), and it has become a standard material in this field [13]. The traditional materials in field construction over the past 100 years have been wood, iron, and concrete. Therefore, fiber-reinforced polymer compounds are considered relatively new materials. Approximately a quarter of the world's production of these compounds is used in the construction field. Figure 1 showing the market share of FRP compounds by field [14].

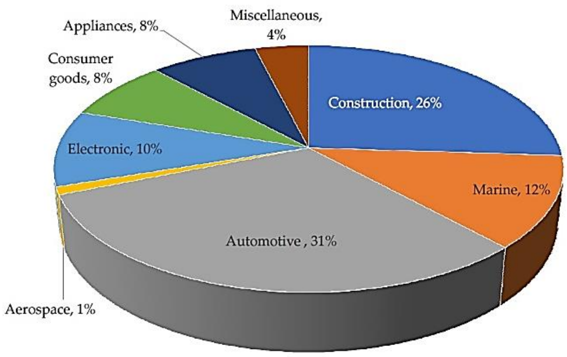

Figure 1. Market share of FRP by application [12]

3. Glass Fiber-Reinforced Polymer (GFRP) Bars

GFRP bars consist of glass fibers embedded in a thermosetting matrix, commonly phenol formaldehyde or vinyl ester, offering excellent performance for diverse industrial applications [13]

GFRP is utilized in many civil engineering applications due to its cost-effectiveness and reasonable strength properties. Glass fibers are commercially available in several types:

- **a.** Type E-glass, which is the most widely used for general purposes.
- **b.** Type S-2 glass, known for its high resistance.
- **c.** Type ECR glass (acid-resistant glass).
- **d.** Type ER glass (alkali-resistant glass), composed of alumino-lime and borosilicate. E-glass fibers predominantly serve as reinforcement for polymer composites.

GFRP bars are increasingly used as a non-corrosive alternative to steel reinforcement in concrete structures. They offer advantages such as high durability and resistance to environmental degradation, making them suitable for various applications including bridges, parking garages, and water tanks [15]. Traditional GFRP bars are manufactured by embedding continuous glass filaments within a resin matrix [16]. The choice of resin affects the bar's performance in various environmental conditions [17]. Recent advancements include the development of winding additional GFRP layers around the longitudinal fibers to enhance compressive strength and ductility. This method has shown significant improvements in compressive strength with increased winding layers [18].The diameters of glass fibers used in composite material reinforcement typically range from 9 to 23 microns [14]. Advantages of Using GFRP bars [19]

1. Lightweight; several times lighter than steel.
2. low cost.
3. excellent insulating properties.
4. Corrosion resistance; does not rust or react in acidic environments.
5. Thermal and electrical insulation capability; is the most suitable material for constructing laboratories and special buildings.
6. High strength; with a tensile strength three times that of steel, long lifespan; sustainability exceeding 100 years.

7. Easy assembly; due to its lightweight advantages, it is easier for construction work.
8. The Length; can be produced according to the required length.
9. Chemical resistance; reinforcement bars made of fiberglass are resistant to aggressive components such as acids, alkalis, or corrosion, suitable for permanent applications.
10. Transparent to magnetic fields and radio frequencies, electrically non-conductive.
11. High resistance to sunlight, UV radiation, seawater, solvents, or salts.
12. The thermal expansion coefficient does not cause cracking in concrete structures.

The process of manufacturing GFRP bars is called the Pultrusion method, which produces GFRP bars with high fiber content between 60% to 80%, and the diameter ranges of the fibers used in the manufacturing process between 10 to 45 micrometers according to the type of bars made as shown in Figure 2. Rods are produced with non-smooth surfaces to maintain the bonding strength with the concrete. This surface can achieved by wrapping a bundle of resin-dipped fibers around the rod after exiting the mould [20].

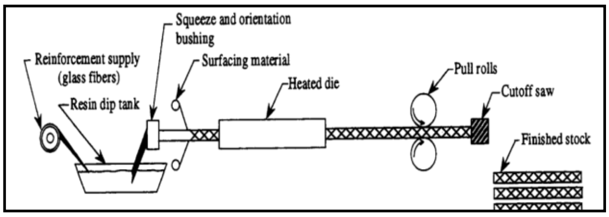

Figure 2. Pultrusion of GFRP rebar [20]

GFRP bars are used as reinforcement in concrete structures to prevent corrosion and enhance durability. They are particularly valuable in environments where steel reinforcement would be prone to corrosion [15], [16]. Due to their non-corrosive nature, GFRP bars are also used in temporary concrete structures, such as soft-eyes in tunneling works [16].

Rovira et al. (2011) [21] investigated the development and applications of GFRP bars as reinforcement in concrete structures, highlighting the corrosion issues faced by traditional steel reinforcement in aggressive environments. They emphasize GFRP's key benefits, such as high tensile strength, corrosion resistance, and lower weight, which make it suitable for structures exposed to deicing salts or moisture, like marine structures and bridges. The paper describes the manufacturing process of GFRP bars, primarily using the pultrusion method, which results in high fiber content and uniform distribution. Tensile, compression, bond, and shear tests were conducted on bars of different diameters to assess their mechanical properties, following standards like ACI 440.3R-04 [22]. The results revealed that GFRP bars exhibit linear elastic behavior until failure, lacking the yield phase typical of steel, which requires design adjustments for serviceability. It was concluded that GFRP should not be used for compression reinforcement due to its lower compressive modulus. The study advocates for more research, particularly on the use of GFRP in compression and the development of comprehensive design codes tailored to GFRP's unique properties. The study suggesting that GFRP could revolutionize concrete reinforcement, offering long-term durability and corrosion resistance, but highlights that further research is needed to optimize its use in various structural applications.

Chang and Seo (2012) [23] investigated the behavior of one-way concrete slabs reinforced with GFRP bars, aiming to compare their performance with conventional steel-reinforced slabs. The study focused on flexural and shear strength, deflection behavior, cracking patterns, ultimate capacities, and failure modes under four-point bending. The slabs, measuring 4000 × 1000 mm and with depths of 150 mm and 200 mm, were reinforced with 16 mm steel bars and 13 mm GFRP bars. The experimental program varied reinforcement ratios to simulate under-reinforced and over-reinforced conditions. Results showed that GFRP-reinforced slabs exhibited larger deflections than steel-reinforced slabs, due to GFRP’s lower modulus of elasticity. Failure modes included GFRP rupture for under-reinforced slabs and shear and concrete crushing for over-reinforced slabs. Cracking occurred earlier in GFRP-reinforced slabs, with wider cracks due to the material's lower stiffness. Deflection behavior indicated that higher reinforcement ratios led to smaller deflections post-cracking, and shear strength improved with higher reinforcement. The study suggests that existing shear design guidelines for steel reinforcement may not be fully applicable to GFRP and calls for further research into shear strength and long-term durability. It also emphasizes the need for better crack control and refined design methods for GFRP-reinforced concrete structures

Brown (2015) [24] investigated the use of GFRP bars in concrete compression members, focusing on their ability to mitigate corrosion issues seen with steel reinforcement. The study tested 24 concrete columns reinforced with either GFRP or steel, showing that GFRP columns had similar compressive capacity to steel, especially when GFRP stirrups were closely spaced. Corrosion tests revealed that GFRP bars did not corrode in saline solutions, unlike steel. While GFRP's lower modulus of elasticity resulted in slightly lower capacity, it remains a viable option when durability is a priority. The research also highlighted that closer tie spacing enhanced GFRP's performance, making it comparable to steel. Cost comparisons showed that despite higher material costs, GFRP's reduced labor time and lack of corrosion offer long-term savings. The study concludes that GFRP is a viable, durable, and cost-effective alternative to steel, especially for environments prone to corrosion, though further research is needed to optimize its use.

Elkhouly et al. (2024) [25] conducted a comparative study on the flexural behavior of concrete beams reinforced with steel and GFRP rebars. Twelve beams, categorized into two groups based on reinforcement type (steel or GFRP), were tested under four-point bending with concrete strengths of 25 MPa and 35 MPa. The study found that GFRP-reinforced beams exhibited higher failure loads compared to steel-reinforced beams, with increases of 18% and 7% for 25 MPa concrete, and 22% and 11% for 35 MPa concrete, for 0.5% and 1.0% reinforcement ratios, respectively. However, GFRP beams showed higher deflections and lower flexural rigidity due to their lack of ductility. Crack patterns indicated wider cracks in GFRP-reinforced beams compared to steel. The ductility index decreased by 9% for GFRP beams. Numerical simulations using ABAQUS confirmed the experimental results with minor variations. The study concluded that GFRP reinforcement improves load capacity but results in more brittle failures, requiring further research into its long-term durability and cost-effectiveness for practical applications.

4. Effects of Heating on Mechanical Properties of GFRP

GFRP bars when heated, rods darken, as shown in Figure 3. and at 400°C the resin fully decomposes. The tensile strength of GFRP rods was not significantly affected at temperatures below 100°C, but it decreased with increasing temperatures above 100°C, as shown in Figure 4, However, after cooling, the tensile strength of the GFRP bars was 4-56% higher than under high-temperature conditions due to partial recovery of the resin from its rubbery state. The modulus of elasticity is less impacted than tensile strength and shows minimal change at temperatures below 400°C, as the fibers primarily influence it. At temperatures below 150°C, the final strains of the GFRP bars under and after exposure to high temperatures were similar. However, at temperatures above 150°C, strain values increased due to partial recovery of the resin [26].

Figure 3. GFRP bars after exposure to elevated temperature [26]

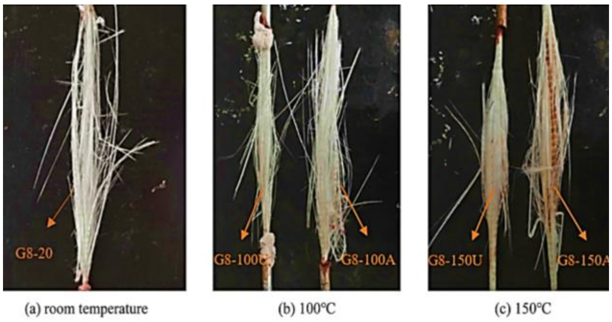

Figure 4. Tensile failure mode of specimens under and after high temperatures [26]

Robert and Benmokrane (2010) [27] examined the behavior GFRP reinforcing bars under extreme temperature conditions, crucial for their use in concrete reinforcement in harsh environments. The study investigates the mechanical properties of GFRP bars exposed to temperatures ranging from 100°C to 325°C, focusing on tensile, shear, and flexural properties as shown in Figure 5. The GFRP bars, with a nominal diameter of 12.7 mm, were tested in two series: unconditioned and water-saturated. Results showed that mechanical properties increased at lower temperatures due to the stiffness of the polymer matrix. However, above the glass transition temperature of the polymer (120°C), significant degradation in tensile strength, shear strength, and flexural modulus occurred. At temperatures above 300°C, the polymer matrix degraded further, causing a substantial loss in strength. Moisture absorption at low temperatures led to microcracks, slightly reducing mechanical properties, especially in saturated specimens. Microstructural analysis confirmed degradation of the polymer matrix, fiber/matrix debonding, and matrix cracking. While the study provides valuable insights, further research is needed to evaluate the long-term effects of high temperatures and moisture exposure in real-world conditions. The study emphasizes the need to consider temperature effects when using GFRP bars for concrete reinforcement.

Hamad et al. (2017) [28] conducted a comprehensive experimental study to assess the impact of elevated temperatures on the mechanical properties and bond characteristics of different Fiber Reinforced Polymer (FRP) rebars, specifically GFRP, BFRP, and CFRP compared to traditional steel reinforcement. Utilizing 10 mm diameter bars embedded in concrete cubes and subjecting them to temperatures ranging from 125 °C to 450 °C for 3 hours, the study revealed a critical temperature at 325 °C, beyond .

Figure 5. Tensile test at the heated chamber [27]

which FRP bars experienced significant degradation. At this threshold, FRP bars lost up to 55% of their tensile strength and 30% of their elastic modulus, with bond strength losses reaching as high as 81.5% for CFRP bars. Initial bond strengths at room temperature were recorded as 11.31 MPa for steel, followed by CFRP (8.34 MPa), BFRP (2.63 MPa), and GFRP (2.01 MPa). Post-heating bond strength dropped significantly, with GFRP and BFRP retaining only about 20.8% and 21.1% of their original bond strength, respectively, at 325 °C. Failure modes varied: GFRP and BFRP failed through shearing of the resin matrix, CFRP showed surface coating peel-off and cone failure, while steel bars exhibited splitting cracks indicative of robust bond performance. While the study offers valuable insights into thermal degradation patterns, it is limited by its focus on a single bar diameter and short-term heating exposure. Nevertheless, the work significantly advances the understanding of FRP-concrete bond behavior under fire-like conditions.

Solyom et al. (2019) [29] investigated the bond behaviour of 8-mm indented GFRP bars embedded in concrete when subjected to elevated temperatures ranging from 20 °C to 300 °C as shown in Figure 6. The study revealed that the bond strength, which was approximately 13.3 MPa at ambient temperature, decreased progressively with temperature, dropping to 8.9 MPa at 80 °C (67.4% retention), 7.1 MPa at 165 °C (53.7%), 4.1 MPa at 190 °C (31.3%), and as low as 1.1 MPa at 300 °C (7.2%). Failure modes also transitioned with temperature: at temperatures below the glass transition temperature (Tg ≈ 164–186 °C), failure occurred through shearing of the concrete lugs (P-O-C), while at higher temperatures, it shifted to shearing of the bar ribs (P-O-B). Additionally, bond stiffness and residual stress were significantly reduced at elevated temperatures. The study emphasizes that findings cannot be generalized across all FRP bar types or surface profiles. Further research is needed to assess bond behaviour with different FRP geometries and materials. The limited number of specimens per temperature group also suggests the necessity for expanded testing.

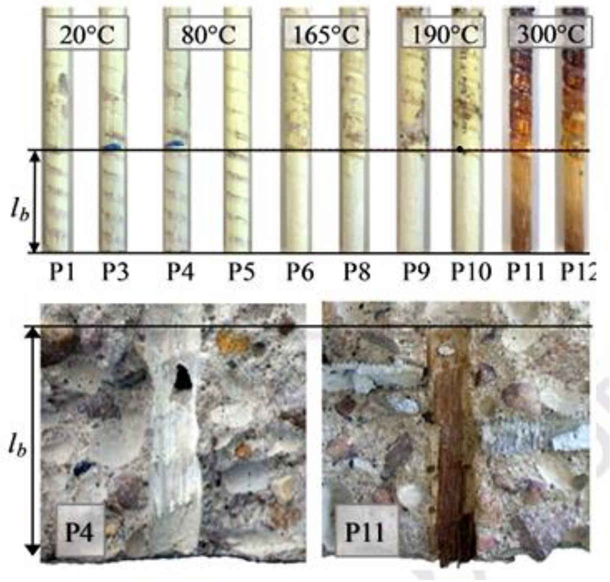

Figure 6. Conditioned GFRP bar surface (top) and concrete surface (bottom) following debonding failure [29]

Thongchom et al. (2023) [30] investigated the performance of GFRP rebars subjected to temperatures ranging from 100°C to 400°C, with a heating rate of 20°C/min for 1 hour. The study focused on how different cooling methods, specifically air versus water, impacted the tensile strength and elastic modulus of rebars in three diameters (16 mm, 20 mm, and 25 mm). The findings revealed that at 400°C, the ultimate tensile strength of the GFRP rebars decreased by up to 55%, while the ultimate strain increased by as much as 44%, regardless of the cooling method. Notably, smaller rebars (16 mm) experienced more significant reductions in tensile strength and greater increases in strain compared to larger rebars (25 mm) following exposure to high temperatures. These results underscore the importance of considering rebar size and cooling methods in the design of fire-resistant structures, as both factors greatly influence the performance of GFRP rebars under elevated temperatures.

5. Effects of Heating on Concrete

When concrete is subjected to high temperatures, the hydration process speeds up, leading to a shorter initial hardening time and the onset of surface cracks, which become more noticeable as the temperature rises. Additionally, the weight of samples exposed to high temperatures gradually decreases up to 800 degrees, after which the reduction becomes more pronounced [31], as shown in Figure 7.

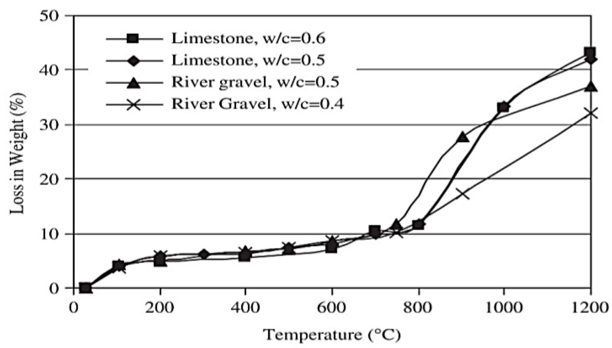

Figure 7. Weight reduction of concrete samples exposed to high temperatures [31]

The relative strength of the concrete also diminishes with increased temperatures as shown in Figure 8, particularly in concrete made with river gravel.

Chung (1985) [32] investigates the effects of high temperatures in concrete by ultrasonic pulse velocity, focusing on assessing fire damage. The study used concrete prisms measuring 100 mm x 100 mm in cross-section and 200 mm in length, made with different

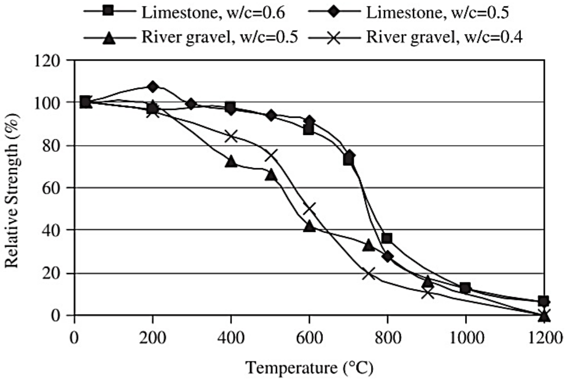

Figure 8. Relative strength of concrete mixtures following exposure to high temperatures [31]

compressive strength ranging (40-54)MPa. The specimens were heated to temperatures between 400°C and 800°C, and pulse velocity was measured before and after heating. The study found that pulse velocity decreased with increasing temperature: by 35% at 400°C, 65% at 600°C, and 85% at 800°C, due to moisture loss and microcracking. Interestingly, the decrease in pulse velocity did not directly correlate with the reduction in compressive strength. Post-heating treatment, such as quenching in water, increased pulse velocity due to moisture absorption, while air cooling resulted in lower values. The study established a correlation between residual pulse velocity and compressive strength, though moisture content and temperature distribution affected the accuracy. This method offers a non-destructive way to assess fire-damaged concrete, with potential for refinement in practical applications.

Hertz and Sørensen (2005) [33] introduced a test method to assess the risk of explosive spalling in concrete exposed to fire, focusing on the effects of moisture content and thermal stresses. The method uses a concrete cylinder (150mm diameter and 300mm height), commonly used for compressive strength testing, placed in a steel mantle as shown in Figure 9. The exposed end is heated to 800°C within 20 minutes, and spalled material is collected and weighed. The study finds that dense, moist concretes with additives like micro silica are more susceptible to spalling. However, the addition of polypropylene fibers significantly reduces the risk, even with restrained thermal expansion. Rapid temperature increases and thermal stresses are key factors in spalling, with polypropylene fibers helping mitigate spalling by facilitating microcracking. The results emphasize the effectiveness of smaller polypropylene fibers in preventing spalling. The test provides valuable insights into concrete performance under fire, but further research is needed on long-term fire exposure and the impact of different fiber types. The method is simple, cost-effective, and offers insights for fire-resistant concrete design.

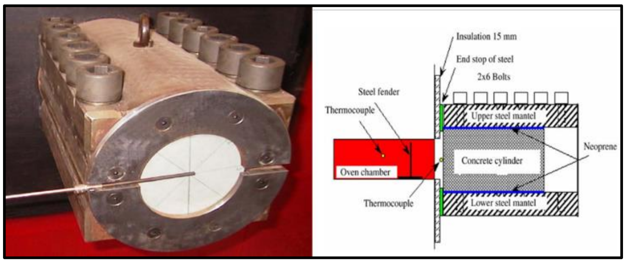

Figure 9. Steel mantle with cylinder concrete exposed to oven

Arioz (2007) [31] examined the impact of elevated temperatures on the physical and mechanical properties of concrete mixtures made with ordinary Portland cement, crushed limestone, and river gravel aggregates. Concrete specimens were cast in 70mm x 70mm x 70mm cubes, cured for 28 days, air-dried, and oven-dried before exposure to temperatures between 200°C and 1200°C for 2 hours. The specimens were then tested for weight loss, compressive strength, and surface condition, with additional differential thermal analysis (DTA) and color image analysis performed on the cement paste. The results indicated that weight loss increased with temperature, particularly beyond 800°C. Surface cracks appeared at 600°C and worsened at 800°C, with spalling observed at 1200°C as shown in Figure 10. Compressive strength significantly decreased with higher temperatures, with river gravel mixtures showing more severe strength loss than crushed limestone. The relative strength dropped sharply after 800°C, with specimens exposed to 1200°C retaining only 6% of their original strength. The study found that the type of aggregate, particularly river gravel, had a major influence on strength degradation, while the w/c ratio had a moderate effect. This study offers key insights into concrete's fire performance, highlighting the need for further research on long-term fire exposure and the role of concrete additives. Although comprehensive, the study's focus on temperatures up to 1200°C limits its applicability to more extreme fire scenarios.

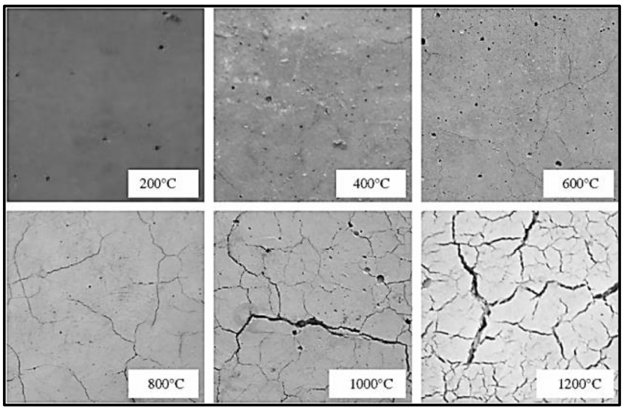

Figure 10. Texture of the concrete surface at raised temperatures [31]

Ingham (2009) [34] reviews the role of petrographic examination in assessing fire damage in concrete and masonry structures. With an increase in building fires, it is critical to evaluate fire-damaged structures for safety and plan repairs. Petrographic techniques, especially optical microscopy, provide detailed insights into microcracking, mineralogical changes, and the depth of damage in concrete and masonry materials. These techniques help decide whether to repair or demolish fire-damaged structures and ensure accurate repair specifications. The process involves visual inspection, followed by sample collection, typically through diamond drilling. Thin-section preparation allows for microscopic analysis to identify cracks, color changes, and mineralogical alterations. Petrography also helps determine the temperature exposure of concrete based on mineralogical changes and cracking, which is crucial for assessing the depth of damage, often limited to 5-30 mm after exposure to temperatures up to 600°C. The paper highlights that petrographic examination is also useful for assessing masonry, helping determine whether to repair or replace materials. However, further research is needed to explore advanced imaging techniques and automation to improve the assessment process. The paper emphasizes the value of petrography in cost-effective repair decisions, especially for historic buildings, though it may need supplementary methods for comprehensive evaluations, particularly in large-scale fires.

Kodur (2014) [35] reviewed the behavior of concrete at elevated temperatures, focusing on how fire exposure affected its thermal, mechanical, and deformation properties. Concrete’s properties, such as thermal conductivity, specific heat, and compressive strength, degraded with increasing temperature, especially above 400°C. High-strength concrete (HSC) lost strength more rapidly than normal strength concrete (NSC), and both types experienced significant reductions in tensile strength, leading to cracking and spalling. Spalling, more common in HSC due to its low permeability, occurred when pressure built up from water vapor within the concrete, causing pieces to break off, Figure 11 shows the difference between NSC and HSC in fire condition. The paper discussed how temperature, aggregate type, moisture content, and heating rate influenced fire resistance. It highlighted the need for improved models to predict concrete’s fire performance and better understanding of how different mixes and additives affected its behavior under high temperatures. While comprehensive in reviewing key properties, the paper suggested further research to enhance real-world fire resistance design and applications.

Figure 11. Spalling in NSC and HSC columns under fire conditions

Kadar (2023) [36] investigated the crack width of concrete structures reinforced with Glass rebars under high temperatures. GFRP rebars are an alternative to traditional steel reinforcement, offering corrosion resistance and lightweight properties. However, their performance under elevated temperatures, especially in fire-prone environments, is not well understood. The study aims to examine the effects of thermal stresses on crack formation and propagation in GFRP-reinforced concrete exposed to temperatures ranging from 100°C to 400°C. The methodology involved experimental testing and numerical simulations. Concrete beams reinforced with 10 mm and 12 mm GFRP rebars were cast with a compressive strength of 40 MPa at 28 days. After curing for 28 days, the beams were heated for 90 minutes at four temperature levels (100°C, 200°C, 300°C, 400°C). Crack formation was monitored using digital microscopes, crack gauges, and thermocouples embedded in the concrete and GFRP rebars. Results showed that temperatures between 100°C and 200°C caused only minor surface cracks. However, at 300°C and 400°C, cracks became more extensive, particularly at the bond interface between GFRP and concrete. Thermal stresses, combined with the degradation of GFRP's tensile strength and bond weakening, contributed to crack widening. At 400°C, bond failure was almost complete, reducing structural integrity. The study highlights the need for improved thermal properties in GFRP materials and suggests future research should focus on enhancing fire resistance. The comprehensive approach, combining experimental and numerical analysis, is a key strength, though long-term thermal exposure was not fully addressed.

6. Effects of heating on RC One-way Slabs

Upon heating to 600°C for 2 hours, RC slabs exhibited extensive map cracking and upward cambering [37]. Since fire presents a real challenge to the structure's reliability and durability, many researchers have studied fire-related problems and potential solutions.

Nigro et al. (2012) [38] conducted an in-depth investigation into the fire behavior of GFRP-reinforced concrete slabs by testing six full-scale one-way slabs with variations in geometry, loading, concrete cover, and anchorage length. The slabs were categorized into two groups: slabs S1, S2, and S3 were 3500 mm long, 1250 mm wide, and 180 mm thick, with a concrete cover of 32 mm and anchorage length of approximately 250 mm at the unexposed ends; slabs S4, S5, and S6 were 4000 mm long, 1250 mm wide, and 180 mm thick, with a greater concrete cover of 51 mm and an anchorage length of 500 mm. All slabs were reinforced with 12 mm diameter GFRP bars composed of E-glass fibers and orthophthalic polyester resin, with an average tensile strength of 1000 MPa and modulus of elasticity of 50 GPa. The slabs were tested under the ISO 834 standard [39] fire curve in a furnace, with S2, S3, S5, and S6 subjected to constant loading during exposure corresponding to 40% and 60% of their flexural capacity while S1 and S4 remained unloaded to evaluate residual strength post-fire. The results showed that increased concrete cover and anchorage length significantly improved fire performance: slabs S4–S6 achieved fire endurance of up to 190 minutes without bond failure, with failures occurring due to tensile rupture of GFRP bars at ~500 °C. In contrast, slabs S1and S3 failed between 60 and 120 minutes due to bar pull-out resulting from loss of bond after the glass transition temperature (Tg ≈ 100 °C) was reached. A simplified calculation method developed by the authors predicted fire resistance times conservatively, aligning closely with experimental outcomes. The study underscores that the fire performance of GFRP-reinforced slabs is strongly dependent on both the thermal protection afforded by concrete cover and the anchorage conditions in the cooler zones of the structure.

Abbas et al. (2013) [40] explored the retrofitting of reinforced concrete one-way slabs damaged by high temperatures using CFRP sheets. The study evaluated the effects of various exposure temperatures (300°C, 500°C, and 700°C) and cooling methods (gradual and sudden cooling) on the performance of retrofitted slabs. A total of 21 slabs with compressive strengths of 20 MPa, 30 MPa, and 40 MPa were tested. The slabs were exposed to high temperatures, loaded to failure, retrofitted with CFRP sheets, and then re-tested to measure load capacity, deflection, and failure modes. The results indicated that slabs in the control group, which were retrofitted after loading until failure, regained 93.95% to 97.92% of their original load capacity, while slabs exposed to higher temperatures regained between 42% and 84%. The slabs with gradual cooling exhibited higher residual load capacity and less deflection than those with sudden cooling. Concrete crushing at mid-span was the predominant failure mode, with partial CFRP debonding observed in slabs subjected to higher temperatures. The study concluded that higher compressive strength concrete slabs showed better stiffness and load capacity post-retrofitting, suggesting the need for further research on the long-term performance of CFRP retrofitting and optimization of the bonding process, particularly in compression zones.

Santos (2016) [41] investigated the fire behavior of GFRP RC concrete slabs, comparing them to steel-reinforced concrete slabs. Twelve slab strips, each 1.5 m long, 0.25 m wide, and 0.11 m thick, were tested under the ISO 834 standard [39] fire curve while maintaining a service mechanical load. The study examined the effects of concrete cover (2.5 cm and 3.5 cm) and lap splice lengths (30 cm and 60 cm) on fire resistance. GFRP slabs with continuous reinforcement achieved up to 120 minutes of fire resistance, provided the anchorage zones remained cool. However, slabs with lap splices exposed to fire failed in under 30 minutes, highlighting the critical role of lap splices in fire performance. Increasing concrete cover had minimal effect on fire resistance. Numerical simulations predicted thermal and mechanical responses well, validating experimental results. The study underscores the importance of lap splice design for ensuring adequate fire resistance in GFRP-reinforced structures.

Gooranorimi et al. (2018) [42] investigated the post-fire behavior of GFRP bars and GFRP RC slabs to assess their residual strength after fire exposure. Twelve RC slabs, each 1980 mm long, 355 mm wide, and 152 mm thick, were tested, half exposed to a standard furnace fire for two hours, while the other half remained unexposed as controls. The slabs were reinforced with two types of GFRP bars: GFRP-A, with a fine-sand-coated, helically wrapped fiber surface, and GFRP-C, with a ribbed deformed surface. During the fire exposure, slabs were subjected to sustained service loads, simulating typical in-service conditions. After the fire exposure, the slabs were tested for residual flexural strength using a three-point bending test at ambient temperature. Results showed that fire-exposed slabs maintained structural integrity, with GFRP-A slabs exhibiting a 10% increase in load capacity, while GFRP-C slabs showed a 10% decrease compared to controls. Mechanical testing of extracted GFRP bars indicated slight reductions in transverse shear strength (5% for GFRP-A and 11% for GFRP-C), but horizontal shear strength increased by 15% for GFRP-A and 7% for GFRP-C. Furthermore, Tg of the fire-exposed bars increased, with GFRP-A showing a 47% increase and GFRP-C showing a 25% increase. These findings suggest that GFRP bars, when properly designed with adequate concrete cover, maintain their performance and structural integrity under fire conditions. This study underscores the potential of GFRP as a durable reinforcement material for concrete structures in fire-prone environments.

Abdullah and Al-Khazraji (2019) [43] conducted an experimental investigation on six high-strength laced reinforced concrete one-way slabs exposed to fire flames as shown in Figure 12. The slabs, each with a compressive strength of approximately 60 MPa, were subjected to fire at 500°C for two hours and then cooled suddenly by spraying water. The study aimed to evaluate the effect of laced steel reinforcement ratios (0.0021, 0.0040, and 0.0060) on the slabs' performance after fire exposure. The slabs were tested under a four-point bending test to examine their residual bending strength, deflection, and failure modes. The results revealed that the fire-exposed slabs showed a decrease in residual bending strength. The residual bending strength for slabs with laced ratios of 0.0021, 0.0040, and 0.0060 were 72.56%, 70.54%, and 70.82%, respectively. In contrast, the deflection increased by 11.34%, 14.67%, and 17.22% for the corresponding slabs compared to non-burned specimens. The increase in deflection and reduction in load capacity were attributed to the loss of concrete compressive strength and the weakening of the bond between the concrete and reinforcement. However, the presence of laced reinforcement helped maintain some structural capacity after fire exposure, showing the importance of this reinforcement in fire-prone applications. The study suggests that further research is needed on optimizing laced reinforcement ratios for better fire resistance, as well as exploring alternative materials and retrofitting methods to enhance fire resistance.

Hajiloo et al. (2019) [8] examined the fire resistance of reinforced concrete one way slab with GFRP bars, each measuring 3.9 meters in length, 1.2 meters in width, and 200 mm in thickness, with only 40 mm of concrete cover. The slabs were subjected to sustained loading during a 3-hour fire exposure, following the fire curve of ASTM E119 [44]. The study focused on the structural behavior of the slabs, monitoring temperature variations, deflections, and strain during the test. A total of 23 thermocouples were installed to measure temperature in both exposed and unexposed zones of the slabs, Figure 13 shows the test setup. The slabs endured 3 hours of fire exposure without failure, although one slab experienced bond failure due to the deterioration of the GFRP-to-concrete bond in the exposed zone. The temperature in the exposed zones of the GFRP bars reached 600°C, while the unexposed zones-maintained temperatures below 200°C, allowing the bond strength to remain intact in the unexposed areas. This temperature differential ensured that the slabs could still perform structurally under fire conditions. The study highlighted the importance of unexposed anchor zones in preserving the bond strength of GFRP bars, ensuring the slabs' fire resistance and structural integrity during the test.

These findings challenge the conventional need for thick concrete cover, suggesting that GFRP-reinforced concrete slabs can be designed with thinner cover while still meeting fire safety requirements.

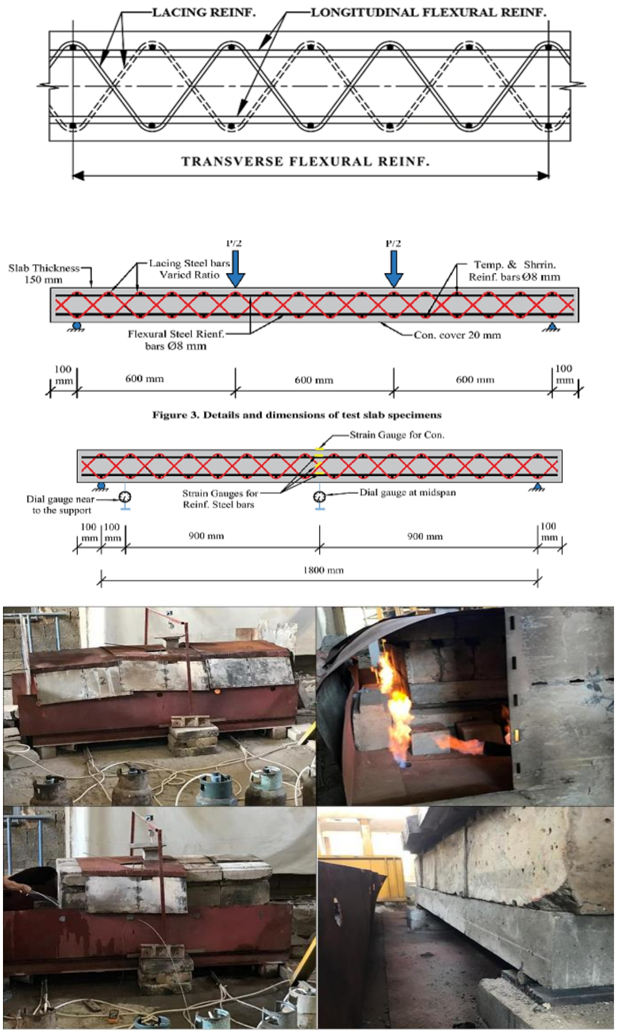

Figure 12. Details of specimens and the fire

process [43]

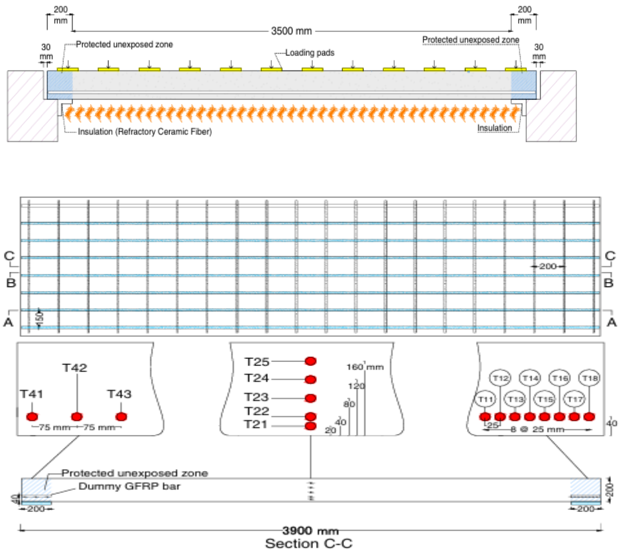

Figure 13. Test setup [8]

Rasheed and Mohammed (2024) [45] studied the structural behavior of concrete one-way slabs reinforced with mixed steel and GFRP bars under fire exposure. The slabs, measuring 1500×540×120 mm, were subjected to fire at 500°C for 1 hour as shown in Figure 14, followed by rapid cooling. GFRP replacement ratios of 0%, 20%, and 40% were tested to assess their impact on the slabs' load capacity, failure modes, deflection behavior, and toughness. The results revealed that slabs with 20% GFRP replacement showed a slight increase in load capacity (2.62%) and toughness (18.30%), while those with 40% GFRP replacement exhibited decreases in both load capacity (3.13%) and toughness (28.16%). The failure mode shifted from flexural failure in the 0% and 20% GFRP slabs to shear failure in the 40% GFRP slab. Cracks formed predominantly in the middle of the slabs, with shear cracks appearing in the 40% replacement slab. The study found that centrally located GFRP reinforcement improved fire resistance compared to reinforcement placed near the ends. The authors suggested further research into optimal GFRP placement and long-term performance under repeated fire exposure to enhance fire-resistant concrete design.

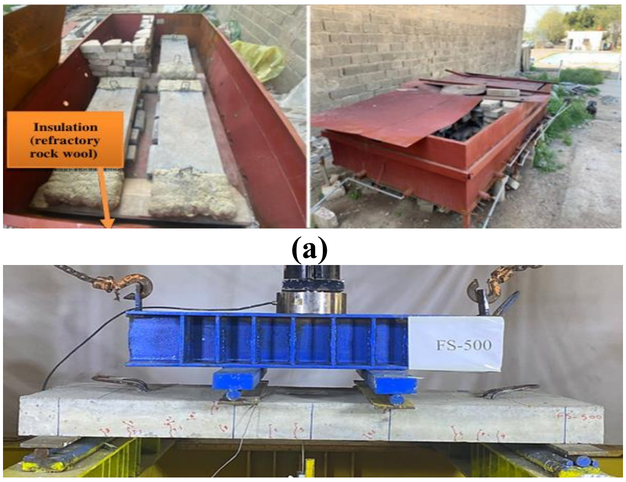

Figure 14. Specimens test (**a**) setup of furnace and specimens, (**b**) test setup [45]

7. RC One-way Slabs with Repeated Load

Sivagamasundari and Kumaran (2008) [46] investigated the flexural behaviour of 21 one-way concrete slabs reinforced with either GFRP (grooved and sand-coated) or conventional steel under monotonic and repeated loading. Slabs measured 2400 mm × 600 mm with 20 mm cover, and variations included reinforcement ratios (0.65%, 0.82%, 1.15%), slab thicknesses (100 mm, 120 mm), and concrete grades (20 and 30 MPa). Monotonic loading tests showed sand-coated GFRP slabs had higher ultimate capacities and better bond than grooved or steel-reinforced slabs. Fatigue tests used constant and variable amplitude loading at 4 Hz; sand-coated GFRP slabs outperformed better. Failures in GFRP slabs occurred via concrete crushing followed by bar rupture, while steel slabs failed through yielding. Analytical results matched experiments well. GFRP slabs, especially with sand-coated bars, demonstrated superior fatigue life and load capacity, supporting their use as an effective alternative to steel in flexural applications.

Klak and Jomaa'h (2024) [47] conducted experimental tests on nine one-way RC slabs (2400×1000×120mm) with 0, 20%, and 40% LECA replacement under fire 25, 400, and 700°C and cyclic loading. While initial elastic stiffness was comparable across all slab types, increasing fire exposure caused significant stiffness reduction (up to 50% for 40% LECA at 700°C). The study revealed three key findings: (1) Structural performance declined with LECA content - 40% replacement showed 35.1% lower load capacity and 37.2% greater deflection at 700°C; (2) Material behavior differed, with LECA slabs developing finer honeycomb cracking versus conventional concrete's wider cracks (up to 2mm); (3) Ductility was unaffected by LECA percentage but decreased with temperature. The 20% LECA mix offered optimal balance, providing 6-10% weight reduction while limiting strength loss to 10-16.6% at 700°C. First cracking consistently occurred at 22-28% of ultimate load. Although LECA's porous structure prevented explosive spalling, high temperatures degraded aggregate-cement bonds. These findings demonstrate that while LECC improves crack distribution, its fire performance requires supplemental protection, particularly for higher replacement ratios. The research provides crucial data for lightweight concrete design, suggesting 20% LECA as a practical threshold when combined with fire mitigation measures.

Cao (2024) [48] experimentally examined the monotonic and cyclic behavior of one-way concrete slabs reinforced with Basalt Fiber Reinforced Polymer (BFRP) bars, GFRP bars, and traditional steel bars. Nine slabs (2000 × 700 × 100 mm) were tested, with three slabs each for BFRP, GFRP, and steel reinforcement. Each slab was subjected to both monotonic and cyclic loading. The cyclic loading was applied using displacement control with two loading schemes: C1 and C2. In C1, the peak deflection (Δ_o) was set at 0.25 Δy (where Δy is the yield deflection of the steel reinforced slab under monotonic loading), with a deflection of 8.0 mm. In C2, the peak deflection was 0.5Δy, corresponding to a deflection of 4.0 mm. These cyclic tests, performed at a frequency of 4 Hz, revealed that BFRP and GFRP slabs exhibited a more uniform curvature, with the failure modes governed by the brittle rupture of the FRP bars. In contrast, steel slabs failed through yielding of the steel bars. The ultimate load-carrying capacities of BFRP and GFRP slabs were significantly higher than those of steel-reinforced slabs, with BFRP slabs demonstrating the highest capacity. Figure 15 shows the load deflection curves for the specimens. The ultimate deflections of BFRP and GFRP slabs were approximately 1.6–2.0 times those of the steel slabs. However, FRP slabs experienced larger stiffness degradations (4.4–7.2% per cycle for BFRP and 4.5–5.1% for GFRP) compared to steel slabs (1.6–3.2%). Despite these higher stiffness degradations, BFRP and GFRP slabs exhibited significantly lower residual deflections, highlighting their self-centering properties. The ductility of BFRP and GFRP slabs (8.5–10.4) was also much higher than that of steel slabs (5.1–6.2), indicating superior deformation capacity. Additionally, the safety factor for BFRP and GFRP slabs was 3.8, compared to 1.0–1.1 for steel slabs, suggesting a much lower probability of failure. The warning index for FRP slabs was also substantially higher, indicating that they offer better warning before failure. These results, along with the theoretical analysis, demonstrate the potential for using FRP reinforcements in concrete slabs, particularly for applications requiring high durability and reduced failure risk, even under cyclic loading.

7. Conclusion

The effect of high temperatures on Glass Fiber Reinforced Polymer (GFRP) bars as reinforcement in reinforced concrete (RC) structures has been extensively studied, revealing both benefits and limitations in fire-prone environments. Key findings include:

- GFRP bars lose significant mechanical properties at temperatures above 100°C, particularly due to resin matrix degradation above 120°C (Tg). Tensile strength and bond strength with concrete decrease at temperatures over 300°C, though some properties partially recover after cooling.
- Fire exposure leads to moisture loss, spalling, and reduced compressive

strength in concrete, especially high-strength concrete, which, along with bond loss between GFRP bars and concrete, weakens structural integrity.

- Factors like concrete cover, anchorage length, and GFRP bar type influence fire resistance. Increased cover and anchorage length improve fire performance, with failure typically occurring around 500°C due to GFRP bar rupture.
- GFRP-reinforced slabs show better ductility and higher safety factors than steel-reinforced slabs under cyclic loads, though they experience greater stiffness degradation, making them ideal for dynamic load applications.

Further studies are needed to understand the long-term effects of repeated fire exposure on GFRP bars. Development of advanced fire-resistant GFRP composites and better modeling are crucial for optimizing GFRP in high-heat environments. In general, GFRP bars offer significant advantages in corrosion-prone environments but require careful consideration for high-temperature applications. Future material design, fire performance, and structural optimization will maximize their potential in fire-resistant concrete construction.

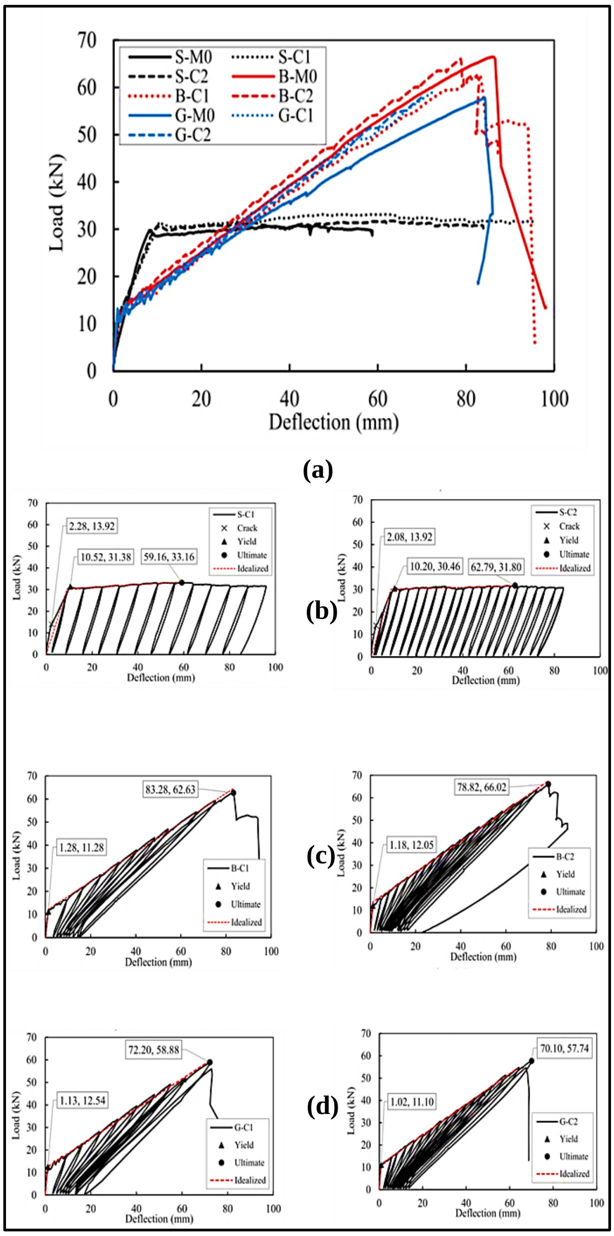

Figure 15. Load vs deflection relationships, (a) load vs deflection got monotonic loading, (b) load vs deflection for cyclic load (c1and c2) of steel reinforcement slabs, (c) load vs deflection for cyclic load (c1and c2) of BFRP reinforcement slabs, (d) load vs deflection for cyclic load (c1and c2) of GFRP reinforcement slabs [48]

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