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Title:

**Global Damage Energy Dissipation in RC Beams
Strengthened with CFRP laminates under Static and Impact
loads.**

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DEDICATION

I dedicate my work to my family and my research supervisor, as they always believed in me, and it has been my greatest asset. I also want to dedicate this research to all my friends & research fellows, for their support throughout this degree, and particularly throughout the process of my research.

CERTIFICATE OF APPROVAL

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Abstract

The research investigates the energy dissipation characteristics of reinforced concrete (RC) beams retrofitted with Carbon Fiber Reinforced Polymer (CFRP) under static and impact loading conditions. The research problem, emphasizes the need for improved retrofitting techniques to enhance structural performance. The study aims to evaluate the effectiveness of CFRP in enhancing the structural performance of RC beams, particularly in terms of load-bearing capacity, energy dissipation, and ductility. Experimental tests were conducted on both pre-retrofitted (un-cracked) and post-retrofitted (cracked) beams, comparing their performance to non-retrofitted control beams. The total of 17 beams, including pre-retrofitted and post-retrofitted glass fiber-reinforced polymer beams (GFRPB), and steel reinforced beams (SRB) specimens were tested by applying compression test, flexure test and tensile test. CFRP, strips and wraps were applied to strengthen the beams, with an emphasis on flexural and shear reinforcement. This research experimentally evaluates the static and impact performance of reinforced concrete beams strengthened with CFRP using both pre-damage and post-damage retrofitting techniques. S The total of 17 beams, including pre-retrofitted and post-retrofitted glass fiber-reinforced polymer beams (GFRPB), and steel reinforced beams (SRB) specimens plain control beam (PCB)—were tested under third-point bending to assess flexural behavior and global energy dissipation compression test, flexure test and tensile test. The testing setup incorporated a Universal Testing Machine (UTM) for static loading, while LVDTs, a calibrated load cell, and an accelerometer were installed to capture load, deflection, and dynamic response during both static and impact events. Impact loading was applied using a 7 kg mass dropped from 4 ft, producing a high-strain-rate impulse recorded by the load cell and LVDTs. In this study for strengthening reinforced concrete members. Sika wrap-230 C and Sika Carbu-dur CFRP was used. The results indicate that CFRP retrofitting significantly improves the energy dissipation and load-bearing capacity of RC beams, with pre-retrofitted beams showing superior performance compared to post-retrofitted beams. The application of CFRP wraps and strips was found to enhance flexural and shear strength, particularly in critical areas such as the mid-sections of the beams. However, debonding between CFRP and concrete was identified as a challenge, especially in post-retrofitted beams with existing cracks. The study also compared the performance of steel-

reinforced and glass fiber-reinforced polymer (GFRP) reinforced beams, with steel-reinforced beams generally exhibiting higher load capacities and energy dissipation. The findings suggest that CFRP retrofitting is a viable and effective solution for strengthening aging or damaged RC structures, particularly in environments prone to loads such as earthquakes or blasts. This research holds significant importance for the field of structural engineering, particularly in the areas of retrofitting and extending the lifespan of aging or damaged concrete structures. It is recommended that structural engineers should prioritize CFRP for retrofitting RC beams, particularly in structures facing dynamic loads or deterioration, and it is advisable to retrofit before any damage appears to maximize energy dissipation and strength. Future work should further investigate how environmental conditions influence long-term CFRP performance, while designers should optimize wrap placement especially at critical mid-sections to enhance shear and flexural behavior. Although CFRP involves higher initial costs, its long-term safety, durability, and reduced repair demands justify the investment and should be carefully weighed in material selection. This research contributes to the development of safer and more resilient infrastructure, particularly in coastal and seismic regions.

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Thank you,

Engr. Muhammad Saeed

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ASTM Standards

ASTM C1314	Standard Test Method for Compressive Strength of Masonry Prisms
ASTM C270	Standard Specification for Mortar for Unit Masonry
ASTM C952	Standard Specification for Bond Strength of Mortar to Masonry Units
ASTM C780	Standard Test Method for Preconstruction and Construction Evaluation of Mortars for Plain and Reinforced Unit Masonry
ASTM C67	Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile (Includes Compressive Strength, Flexural Strength, and Water Absorption)
ASTM C20	Standard Test Methods for Apparent Porosity, Water Absorption, Apparent Specific Gravity, and Bulk Density of Refractory Brick and Shapes
ASTM E23	Standard Test Methods for Notched Bar Impact Testing of Metallic Materials (Charpy Impact Test, adapted for masonry)
ASTM D6110	Standard Test Method for Determining the Charpy Impact Resistance of Notched Specimens of Plastics (For impact weight selection)
ASTM E519	Standard Test Method for Diagonal Tension (Shear) in Masonry Assemblages
ASTM A931	Standard Test Method for Tension Testing of Wire Ropes and Strands (Adapted for bamboo strip tensile testing)
ASTM C469	Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression (For masonry modulus evaluation)
ASTM E2309	Standard Practices for Calibration of Displacement Transducers for Use in Structural Testing (For LVDT and laser displacement sensor calibration)

List of Abbreviations

CFRP: Carbon fiber reinforced polymers.

RC: Reinforced Concrete.

FRP: Fiber reinforced polymer.

EBR: Externally Bonded Retrofit.

NSMR: Near Surface Mounted Retrofit.

GFRP: Glass fiber reinforced polymers.

FE: Finite element.

PCC: Plain Cement Concrete.

SRB: Steel Reinforced Beam.

RGRB: Retrofitted Glass Reinforced Beam.

RSRB: Retrofitted Steel Reinforced Beam.

RGRBV: Retrofitted GFRP reinforced beam without stirrups

RSRBV: Retrofitted Steel reinforced beam without stirrups

PCB: Plain Concrete Beam

SRBV1: Steel reinforced beam without stirrups

GRBV1: GFRP reinforced beam without stirrups

UTM: Universal Testing Machine

Chapter 1 Introduction

1.1 General

Reinforced concrete (RC) structures form the backbone of modern infrastructure, including buildings, bridges, and industrial facilities. Over time, these structural elements experience deterioration due to loading, environmental exposure, material aging, and unexpected events, which reduces their strength and serviceability. To ensure safety and extend structural lifespan, retrofitting techniques have become increasingly important in engineering practice. Among these, fiber-reinforced polymers—particularly carbon fiber-reinforced polymer (CFRP)—have emerged as reliable materials for strengthening and restoring damaged RC components. This study focuses on understanding how CFRP influences the load-bearing behavior and energy dissipation of RC beams under static and impact loading conditions.

A number of novel materials have been employed as structural element retrofitting materials in now a days. Reinforced concrete (RC) beams are made stronger and more ductile by using these materials as jacking. The reaction of retrofitted RC beams under static loads has received a lot of attention [1] In civil engineering, the ability of RC structures to withstand static and impact loading is crucial because it is unknown how RC would behave under various loadings, designing RC beams for buildings to handle loading is a challenging issue. A variety of techniques, such as numerical studies, experimental testing, and analytical models, have been successfully used to comprehend how RC beams behave under static loads [2].

Events, like unintentional collisions, explosions, and natural catastrophes, can seriously harm RC structures, jeopardizing their structural integrity and safety. Improving the load resistance of already-existing structures is crucial for reducing these hazards, extending the life of infrastructure, and guaranteeing community safety. Efficient retrofitting methods can help damaged elements regain their structural capability and become more resilient to impact occurrences in the future [3]. The development and implementation of sophisticated construction materials have gained importance in the search for efficient retrofitting solutions. One of the most popular retrofitting materials is FRP [4]; [5]; [6]; [7]

The joint strengthened by hybrid FRP (carbon-glass) showed enhanced ductility and energy dissipation capacity at a highly competitive cost [8]. An increasingly common retrofit method is the reinforcement of RC structures with CFRP. Since its introduction in the 1980s, the practice of strengthening RC by externally bonded CFRP has drawn interest from researchers worldwide [9]. Adhesive-bonded CFRP retrofitting is becoming widely used worldwide because it is a practical technique that can be used on a variety of concrete structural elements, including walls, slabs, columns, and beams. Researchers investigated that CFRP jackets provided at an inclined orientation for retrofitting the initially stressed beam column joints. Joints that were damaged to three different stress levels were retrofitted with L shape CFRP jackets and tested under static loading condition. It was concluded that retrofitting using CFRP jackets improved ultimate load carrying capacity by 7 to 12% [10]. CFRP was used, for instance, to retrofit a highway RC bridge slab in China [11]. Two main areas exist for CFRP's employment in structural applications. The first is in the construction of new buildings, bridges, and other structures, where CFRP bars are utilized in place of steel reinforcing bars. The second application involves using CFRP externally to enhance structural elements that are structurally weak [12]. Over the past ten years, studying the behavior of retrofitted CFRPC structures has grown in importance as a subject of study. Regarding experimental application, a number of investigations were carried out to examine the behavior of retrofitting beams and the ways in which different parameters affect that behavior. Retrofitting old structures, such as beams, columns, slabs, etc., has become one of the major issues in civil engineering in recent years. Restoring lost load carrying capacity due to corrosion, increasing load carrying capacity for higher permit loads like earthquake load, and providing additional capacity for adding members to the existing structure are the main reasons why existing structures need to be strengthened [13].

In civil engineering applications, structural member upkeep, renovation, and improvement are the most important issues. The application of CFRP that is externally bonded can be categorized as shear strengthening, flexural strengthening, and enhancing the ductility of the compression component. Since CFRP strengthens RC beams, it is known that these beams can have ultimate flexure strengths higher than their initial flexure strengths. However, because of the brittleness of CFRP [14]. Since CFRP has excellent properties such as “high tensile strength, light weight, excellent resistance to corrosion and fatigue,

ease of installation, and durability” it has been utilized extensively for structural rehabilitation, repair, and strengthening [15]; [16]; [17]; [18]; [19]; Research conducted through experiments has demonstrated that retrofitting post-fire CFRC beams can cause flexure failure to change to flexure-shear failure. Retrofitting CFRP results in a 58.2–97.3 % improvement in yield deflection and a 23.1% increase in strength. It does not entirely recover the stiffness that was reduced by 46.4–49.2 % owing to fire, but it does reduce final deflection by 43.0–55.5 % and ductility by 69.7–74.7 % [5]. Additionally, CFRP reinforcement can greatly extend the fatigue life and lower the average stress in the original structure [18].

Nowadays, externally bonded CFRPs are widely used because of their easy production and low labor needs. However, because of the debonding failure between the CFRP and concrete, only 20–30% of the CFRP's tensile strength may be used with this procedure. In addition to offering more benefits like lowering the deflection and crack widths of the strengthened concrete structures, postponing the onset of concrete cracking and the yielding of the internal steel reinforcements, and eliminating premature debonding failure, pre stressed CFRP has demonstrated more effective strengthening results. Determining the application system, the end anchorage, and the pre stress control value, however, is more difficult [20]; [21]. By using suggested static tests to examine the impact of CFRP retrofitting on the overall seismic performance of frames, it was discovered that CFRP-reinforced frame structures display an optimized failure mode across the structure [22]; [23]; [24].

Seismic testing on the reinforced RC frame structure shown that CFRP reinforcement can enhance the overall structure's strength, ductility, and energy dissipation capacity. The aforementioned investigations and finite element simulation studies have confirmed that CFRP retrofitting improves the bearing capacity and ductility of structural components, which is advantageous to the structure's seismic performance. Nevertheless, few studies have examined the effects of CFRP reinforcement on the overall seismic performance of the structure or have used parametric quantitative analysis. The studies mentioned above are restricted to the CFRP reinforcement of individual components, such as RC beams, slabs, and columns [25]; [26]; [27]. Based upon the published literature, it can be concluded that, CFRP is a viable alternative material for repair and strengthening of reinforced concrete structures. The RCC structures, which require retrofitting, are already

stressed to a particular level due to the loads experienced by the structure in its life span, and therefore, it is deemed imperative to study the effect of the initial stress level on the behavior of the structures after retrofitting, specifically of the beam-column joints, for which not much work has been reported.¹ In the present study, the effect of initial stress levels on the various parameters such as ultimate load carrying capacity, stiffness and ductility of reinforced concrete exterior beam-column joints retrofitted with CFRP (carbon fiber reinforced polymer) with two layers, has been presented [10].

1.2 Problem statement

RC beams are critical components of structural systems, yet their performance under static loads can deteriorate significantly over time due to cracking, corrosion, and environmental factors. This deterioration compromises their ability to dissipate energy and sustain loads, posing safety risks and increasing maintenance costs. The traditional approach of replacing damaged RC components is often impractical due to high costs, extended timelines, and the disruption it causes. Many buildings constructed in various regions of the world using outdated design codes are structurally unsafe despite the implementation of newer standards. Structural members, such as beams and columns that are cracked by earthquake loads or other stresses become ineffective. Coastal constructions face additional challenges, as corrosion and deterioration of RC elements in a marine environment can lead to cracking, delamination, and debonding due to rusted steel. In extreme events like earthquakes or blast loads, local failure of such components necessitates retrofitting to sustain partial structural operations. Replacing these damaged elements is costly and time-consuming, making strengthening a viable alternative to increase load-carrying capacity and prolong service life.

Retrofitting using carbon fiber-reinforced polymer (CFRP) has gained attention as a cost-effective and efficient solution to address these challenges. CFRP materials enhance the structural capacity, energy dissipation, and durability of RC beams while mitigating risks of further degradation. RC frame structures built with the design principle of "strong columns and weak beams" are often damaged during earthquakes by the yielding mechanism of the "beam hinge," which relies on energy dissipation for optimal structural performance. However, actual earthquake damage frequently shows yielding at the column ends, leading to undesirable failure modes [28]; [29]; [30]; [31]; [32]. The failure

modes of RC beams and columns can be improved using CFRP, which provides an efficient solution to this real-world issue [23].

Research needs to advance further to establish a complete understanding about how CFRP-retrofitted RC beams dissipate energy under static loading contexts. This investigation examines and evaluates the different energy dissipation mechanics together with load-carrying strength and structural performance between beams with pre-applied and post-applied CFRP retrofitting treatments. Received performance data from CFRP application allows researchers to develop better retrofit strategies for maintaining both structural safety and longevity of aging or damaged structures.

1.3 Scope

The study performed analyzed CFRPC beams only under static testing procedures. Results from tests using compression, flexure and tension provided significant data for developing restorative procedures which enhance multiple construction elements damaged by deterioration or corrosion or aging. Static force testing was used to evaluate the differences in both control beam structures and retrofitted beams.

1.4 Objectives

1. To determine the behavior of CFRP Retrofitted Beams through experimental study.
2. Comparison between control beam and strengthened beams.
3. Comparison between Steel Reinforced and GFRP Reinforced beams.
4. To determine the energy dissipation of Steel reinforced and GFRP reinforced Retrofitted beams.

1.5 Research Gap

Although extensive literature demonstrates the effectiveness of CFRP in enhancing the flexural strength, shear capacity, and overall performance of RC beams, significant gaps remain regarding its contribution to global energy dissipation under static loading, particularly when comparing pre-retrofitted and post-retrofitted beams. Existing studies primarily focus on strengthening techniques, debonding mechanisms, and localized failure behavior, but they do not adequately quantify how CFRP influences total energy

absorption across different reinforcement types such as steel-reinforced and GFRP-reinforced beams. Moreover, limited research investigates how initial damage conditions in RC beams affect CFRP's ability to control crack propagation and enhance ductility. The absence of comparative experimental data on pre-damaged vs. undamaged beams, combined with insufficient attention to global energy dissipation trends in hybrid reinforcement systems, creates a clear need for the present study.

1.6 Research Significance

This study provides practical insights into how CFRP improves the structural capacity and energy dissipation of RC beams, helping engineers select economical and effective retrofitting strategies for deteriorated structures. The findings are especially useful for regions facing aging infrastructure or exposure to static and environmental loading. While the results are valuable for understanding beam-level performance under controlled laboratory conditions, they offer guidance for real-world retrofitting decisions.

1.7 Limitations

This research Program only includes experimental testing which examines CFRP beams before and after retrofitting under load.

This research is limited to specific tests of RC beams with CFRP materials which reduces the general applicability to various other forms of retrofitting and RC structure configurations.

The research analysis does not demonstrate how various environmental conditions affect retrofitted beam performance across different locations.

Chapter 2 Literature Review

2.1 General

"Strengthening" in the context of construction technology refers to the renovation, restoration, and maintenance of building materials. The installation of structural components during retrofitting aims to enhance their overall performance concerning compressive, flexural, and shear strength [33]; [36]; [34]. The initial performance is not as important as this development in structural integrity. The process of making up for and restoring the strength and performance that structures have lost in a variety of circumstances is known as rehabilitation [35]; [36]; [37]; [38]. The structural members' quality is raised during the repair procedure to satisfy the necessary standards. Many experimental and analytical research have been carried out throughout the years to obtain a comprehensive grasp of beam behavior.

The study of energy dissipation in RC beams retrofitted with CFRP under static loads is critical due to the widespread use of RC structures in infrastructure and the frequent challenges they face from environmental degradation and loading conditions. Previous research highlights the advantages of CFRP as a retrofitting material, including its ability to enhance flexural and shear strength, minimize deflection, and improve energy dissipation. Experimental and analytical studies have demonstrated significant improvements in the performance of retrofitted beams, including increased load-bearing capacity and reduced susceptibility to cracking and debonding. However, gaps remain in understanding the comparative behavior of pre and post-retrofitted beams under static loads and the specific energy dissipation characteristics influenced by CFRP application. This literature review examines the advancements in retrofitting techniques, evaluates the effectiveness of CFRP under static loads, and identifies best practices for optimizing structural performance and extending the service life of RC beams.

2.2 Fiber Reinforced Polymer (FRP)

FRP is an anisotropic material with excellent technical qualities along the direction of the reinforcing fiber. As such, it is strongly advised to restrict the construction along the FRP's major fiber direction, although it is weak in the transverse direction [39]; [40]; [41]. FRP configuration is used based on the idea of employing a bonding agent, like epoxy resin, to

attach the FRP to the concrete surface. When designed and built correctly, this link enables the FRP and concrete to work together as a composite structure, improving seismic performance [42]; [43]. First, the concrete surface must be cleaned. Next, a layer of primer and epoxy must be applied. Finally, the FRP sheets must be laid up with epoxy until the desired number of layers is reached. Numerous FRP have been utilized for retrofitting, such as “sprayed FRP, quasi-isotropic laminates, CFRP GFRP, aramid fiber-reinforced polymer, and basalt fiber-reinforced polymer (BFRP)” because of its excellent mechanical qualities, CFRP is the most widely used of these composite materials [44]; [45]; [46]. [47]; [48]; [49]; [50]; [51]; [52]; [53]; [54].

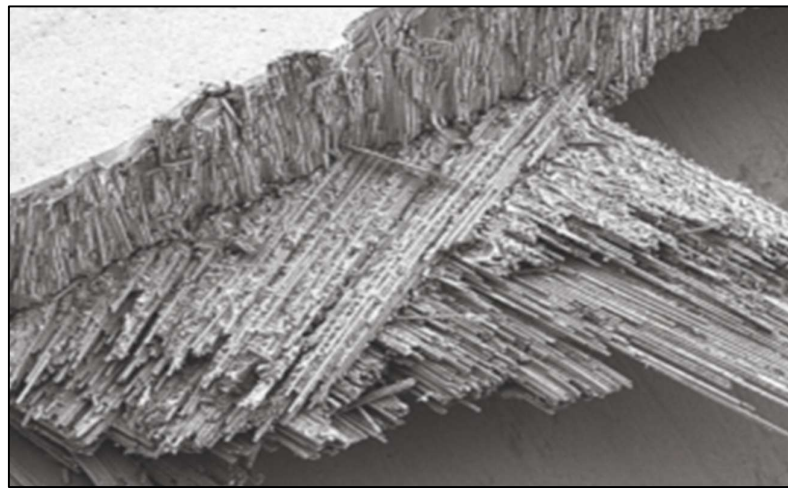


Figure # 2.2-1 Fiber Reinforced Polymer Concrete (FRPC) [55]

2.3 Carbon Fiber Reinforced Polymers (CFRP)

The diameter of CF ranges from 5 to 10 μm . Its characteristics depend on the raw material, the certain production process, and the method used in its creation. For many structural applications, it is the most effective lightweight material to utilize as compare to traditional metals. The superior quality of the graphite crystallites is responsible for the high modulus and specific tensile strength, which are the primary characteristics. These characteristics make carbon fibers the preferred material to replace traditional materials with while also reducing the product's weight. By increasing the size of the crystals and aligning them along the fiber axis, technological advancements produced the improved elastic modulus. Commercial carbon fibers are known for their high “Young's modulus (200–500 GPa) and high “tensile strength (between 3 and 7 GPa)”. Additionally, it was discovered that “carbon fibers tensile strength is only 10%–60% of its axial compressive strength, and its

transverse compressive strength is 12%–20%” of that as well. Their compressive strength is 1-3 GPa, higher as compare to polymeric fibers but still lower than inorganic fibers. Its stiffness is determined by the regularity and aligning of their atomic structures, which allows a variety of elastic moduli to be produced in CF. Different carbon fiber qualities that may be divided into different CF types can be generated based on the production circumstances [56].

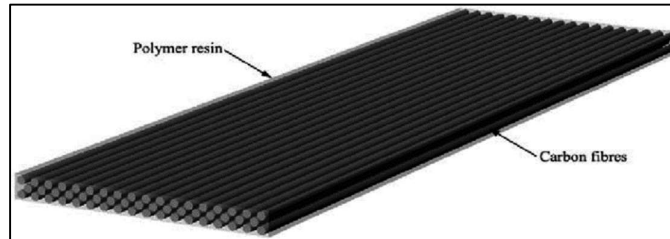


Figure # 2.3-1 Carbon Fiber Reinforced Polymer (CFRP) [57]

A common material used in the strengthening, modernization, and retrofitting of buildings and bridges is carbon fiber reinforced polymer, or CFRP. In place of traditional joint techniques, adhesive bonding techniques have been widely employed in construction, especially when employing Carbon Fiber Reinforced Polymer (CFRP) for retrofitting. The primary goal of CFRP development is to strengthen and modify existing structures rather than replacing or destroying faulty ones. The high strength to weight ratio, high tensile modulus, which results in a ductile structure behavior, and the fact that CFRP is widely available in a variety of shapes, including sheets, lamination, rebar’s, and strips, are the main advantages of employing it to strengthen reinforced concrete structures. However, the primary disadvantage of CFRP is its high cost in comparison to other FRP varieties [58]; [59]. Applying CFRP has established itself as a legitimate technique for reinforcing or renovating already-existing reinforced concrete elements (RCEs). Numerous studies have demonstrated how well CFRP works to improve the flexural performance of RC beams under loads [45]; [48]; [39]. The primary components of the CFRP-concrete bonded system, which is utilized to strengthen RC structures externally, are glue, CFRP dry fiber sheets, and anchors if needed [54]. It is commonly believed that full composite activity takes place between the CFRP materials and the concrete parts, such as beams. However, the adhesive’s shear stiffness and strength—which must be adequate to transfer shear pressures between the CFRP and the concrete substrate—have a significant impact on the

bonding quality. Additionally, the characteristics of the concrete and the surface preparation have a significant impact on the bond quality [44]; [46]; [53].

2.4 Glass Fiber Reinforced Plastic (GFRP)

The component of fiberglass reinforced polymer is glass fiber, also referred to as fiberglass, which is typically added to the composite at a weight percentage of 0.5-2.0%. Glass fiber is primarily used in GFRP, a plastic composite, to increase the plastic's strength and stiffness. The way different chemicals combine provides fibers with great protection. GFRP is readily available and reasonably priced, which is why the civil sector has been using it since the 1930s. The polymer matrix types, fiber content, reinforcing fiber, fiber orientation, and bonding between the fibers and matrix determine the quality of GFRP. GFRP is resistant to heat, salt, chemicals, and the environment. Its strength to weight ratio is strong, with values ranging from 9.67 kg/m² to 19.52 kg/m². Moreover, GFRP is regarded as an excellent insulator and inexpensive reinforcing material.



Figure # 2.4-1 Glass Fiber Reinforced Polymer (GFRP) Rebar [60]

GFRP has a creep strain of between 0.3 and 1%. By adding an anchorage system at both ends of the plate, the thickness of the plates can be raised by more than 6.35 mm, increasing the strength of GFRP by 40% to 100%. If GFRP composite sheets were attached externally, the fatigue life of reinforced concrete beams subjected to cyclic load increased dramatically. The primary application of GFRP is as reinforcing material for non-structural elements like brick walls and secondary structures like bridges, domes, and building frames. The main benefit of GFRP over other FRP varieties is its low cost. However, it's extremely low tensile modulus means that using it as the primary

reinforcement for structural members is not advised [61]; [62]; [63]; [64]; [65]; [66]; [67]; [68]; [69]; [70].

2.5 Performance of SRB, CFRC and GFRPB under Static Loading Conditions

In the field of structural engineering, the ability to withstand impact and blast wave loadings is crucial for the durability of RC infrastructures. Research has explored the effectiveness of using carbon fiber to enhance the mechanical performance of concrete. The study examines how different lengths and proportions of carbon fibers impact the strength of CFRC. By adding 12 mm and 24 mm fibers, both untreated and heat-treated, at a 1% fiber-to-cement ratio, the concrete's compressive, flexural, and impact performance improved. The best results came from an equal mix of 50% 12 mm and 50% 24 mm fibers, particularly in impact resistance and blast strength. Microscopic analysis of the samples provided insights into fiber failure modes, highlighting the valuable information on enhancing the durability of RC structures through retrofitting with carbon fiber, which can improve infrastructure performance under dynamic loads [71]. The fractured toughness of "Plain Cement Concrete (PCC), Steel Fiber Reinforced Concrete (SFRC), and Glass Fiber-Reinforced Concrete (GFRP)" using photographic records (GFRP) were analyzed by the researchers and the findings showed that the cracking process under static loading was not drastically different from that under critical impact loading [72]. A study evaluated the shear capacity of RC beams strengthened with sprayed GFRPs through drop weight testing at impact velocities up to 3.96 m/s. The findings showed that the sprayed GFRPs remained intact without fracturing, and increasing the GFRP thickness, especially in three-sided samples, significantly enhanced the shear capacity compared to two-sided samples [73]. Previous research assessed the performance of RC beams strengthened with CFRP under both static and impact loads. The study involved four beam groups: unstrengthened (B1), those with CFRP longitudinal strips (B2), wrapped in CFRP fabric (B3), and those incorporating both strips and wraps (B4). Findings revealed that group B4 had an 84.88% increase in static load capacity and a 57.89% enhancement in deflection resistance compared to group B1. While B4 experienced minimal damage, B1 suffered a collapse. Additionally, numerical modeling using LS-DYNA demonstrated strong agreement with experimental outcomes, showing discrepancies of up to 12.5% [72]. The use of stiffeners on GFRP composite beams has

been shown by authors, to increase the beams' strength and damping time under impact loads. Simultaneously, it decreased the damping ratio because the increased vibration duration brought about by the concrete's increased compressive strength. They also observed that the profiles collapsed after absorbing over 45% of the load due to secondary crushing and the non-linear behavior of the concrete [21]. A previous study demonstrated that incorporating stiffeners in glass fiber-reinforced polymer (GFRP) composite beams significantly enhances their strength and damping time under impact loads. However, this also leads to a reduction in the damping ratio due to the longer vibration duration resulting from the increased compressive strength of the concrete. Additionally, it was noted that secondary crushing and the non-linear behavior of the concrete contributed to the collapse of the profiles after they had absorbed over 45% of the applied load [74].

Eight test beams with lengths of 1m underwent examination as they received FRP reinforcement through multiple layers applied with CFRP sheets. The beam received its impact load through the process of raising and releasing one beam end onto another support. The research results showed that beams achieved better flexural strength and smaller maximum deflection through CFRP reinforcement. The experimental results from studies that explored high loading rates on RC beams strengthened with CFRP laminates demonstrated a 5% enhancement in strength and stiffness measurements without any modifications to the beam failure pattern as flexural [75]; [76]. Analytical non-linear FE models served to evaluate the impact behavior of composite RC beams that utilized GFRP materials. The analysis used Abaqus to develop these models which evaluated structural members strengthened with GFRP sheets under different dynamic loading types such as quasi-static loading. The developed models showed high accuracy when estimating retrofitted beam response after dynamic load exposure. The research established that installing FRP on RC beams results in substantial improvements of their dynamic characteristics along with damage reduction in repeated impact scenarios. The deflection characteristics along with stress and strain data from experimental studies served Abaqus to carry out its analysis. A hollow solution technique inside Abaqus software enabled solving the set of equations to determine unknown variables; [77]; [78]; [79]; [80]; [81]. All these studies provides critical findings which support the main objectives for this project about static load energy dissipation performance in CFRP retrofitted RC beams.

2.6 Flexural and Shear Enhancement with CFRP and GFRP

A study was conducted on FE Analysis of Reinforced Concrete Beams Strengthened with CFRP in Flexural, eight beams were tested with CFRP in soffit bonding. Finite Element Model show slightly more stiffness than the test data in both linear and non-linear ranges. This was because of Bond Slipping, Micro cracks in actual beams were excluded in finite element model [82]. Another study was done on RC beams using CFRP, six beams were tested having various combinations of CFRP sheets and strips. The presence of shear strips to enhance shear strength has the dual benefit of delaying de bonding of CFRP sheet used for flexural [83]. Another research was done on effect of plates and the adhesive used, a total of eight cases with different configuration of spew fillet and different tappers have been considered. Result showed that the adhesive stress especially normal stresses on the steel and the CFRP interfaces are different due to the load transfer and the influence of singularity at the adhesive corner [84]. A research was done on strengthen RC beam, they tested twelve beams with three different reinforcement ratios. In the strengthened specimen with the large reinforcing bar ratio, close to the maximum code value of maximum reinforcement, failure occurred with adequate ductility [85]. Another research was done on CFRP in UK, 1998, observed that CFRP plates bonded to the beams soffits were effective for reducing concrete tensile strains and encourages the tiny cracks development [86]. The enhancement of RC beams performance with FRP composite retrofitting is the subject of more study. Applying FRP materials as externally bonded reinforcement to RC structures can effectively achieve a greater degree of fiber usage before premature debonding failure [87]. Another research was done on FEM, eight beams were studied under 4-point loading. The results revealed that that behavior of retrofitted beam is directly related to the length [88]. Study was conducted on effect of concrete composition on FRP/Concrete bond capacity, ten different compositions were tested by direct shear method and conclude that the actual concrete composition plays an important role in determining the bond capacity in the FRP to concrete joint [89]. According to a research done on retrofitting T-beams using steel plate, the cracking load, yield load, and ultimate load may all be considerably improved by widening the plate and lowering the area of the anchor bolts. However, the ultimate load and cracking were not correlated with increasing steel plate area [90].

An additional investigation was conducted on the experimental evaluation of fatigue loading on FRP-strengthened RC bridge girders. The bonded epoxy/FRP laminates were found to exhibit superior fatigue loading resistance in comparison to the steel reinforcement [91]. A different experimental investigation on FRP to concrete bonded joints came to the conclusion that thorough specimen preparation is crucial since it might have a big impact on the outcome [92]. Another study was done on "Externally Bonded Retrofit (EBR)" and "Near Surface Mounted Retrofit (NSMR)", concluding that the NSMR members had about 1.5 times greater bond strength than that of EBR [93]. The study was done on strength and ductility of RC beams retrofitted by CFRP results concluded that the effect on ductility arising from strengthen existing RC beams with CFRP laminates cannot be ignored, even if it is not clear at this stage how to apply the concept of ductility [94]. While GFRC beams are utilized sparingly in the literature, many researchers used FRC to evaluate the shear behavior of beams. The purpose of this study is to determine how well the shear behavior of R.C. beams is affected by the use of discrete glass fibers in the concrete mix. Additionally, talk about how GFRC beams with the same fiber volume ratio that are reinforced with longitudinal steel or GFRP bars behave under shear.

The shear behavior of the specimens demonstrated the impact of utilizing GFRP bars for reinforcement. The longitudinal GFRP reinforcement resulted in a marginal increase in the shear capacity of GFRC beams without stirrups. Because of their low modulus of elasticity, the beams reinforced with GFRP bars do not yield and exhibit a linear-elastic behavior until brittle tensile failure, bigger deflections, and broader fractures form prior to failure. A balance between strength and serviceability should be taken into account while using GFRP bars [86].

Research indicates that increasing the percentage of fibers enhances both the shear cracking load and the ultimate load of concrete, as fibers improve tensile strength. For instance, incorporating 0.2% and 0.6% steel fibers resulted in increases of 12.5% and 31.25% in the first shear cracking load, respectively, and 11.43% and 28.57% for the ultimate load. Similarly, 0.2% and 0.6% glass fibers contributed to increases of 5.88% and 18.75% in the first shear cracking load, and 2.86% and 22.86% in ultimate load, respectively. The addition of fibers not only boosted the ultimate load capacity but also improved stiffness, leading to reduced deflection under the same load. This effect is

particularly notable in beams reinforced with both fibers and stirrups. However, maximum deflection tends to increase with higher fiber percentages, as the concrete becomes more ductile and fails after significant deformation. Stirrup presence in the shear zone helps mitigate sudden and brittle shear failures. Additionally, the combination of fibers and stirrups enhances ductility by increasing concrete's tensile strength. The impact of steel fibers on shear strength, stiffness, and ductility is greater than that of glass fibers, due to the superior modulus of elasticity and tensile strength of steel [95]; [96].

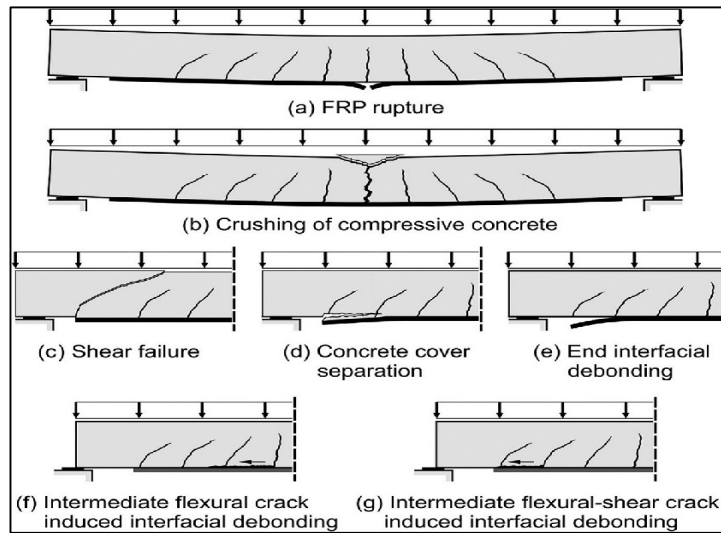


Figure # 2.6-1 Induced Interfacial Debonding by Flexural Cracks and Flexural Shear Cracks [97]

2.7 Properties of FRPC

The mechanical properties of glass fiber-reinforced composites (GFRCs) are largely determined by the bond strength between the resin and glass phases. GFRCs exhibit impressive mechanical characteristics, including a relatively high elastic modulus and strong adhesion to the resin. Additionally, they offer appealing aesthetics and resistance to fatigue, acids, and solvents.

Table 2.7-1 Mechanical Properties of FRPC [59]				
Trade Name	Tensile Strength (MPa)	Elasticity Modulus (GPa)	Ultimate Tensile Strain	Yield Strength (MPa)
Steel	350–450	200	0.5–0.30	500
CFRP	1200–2250	100–147	0.012–0.017	1755–3600

GFRP	600–710	30–46.4	0.015–0.020	600–1400
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2.8 Debonding of CFRC and GFRC

Debonding is the term used to describe the separation of concrete and steel plates caused by improper pouring and curing, steel corrosion, concrete creep and shrinkage, external forces, and temperature changes during the service life [74]. Because of the numerous nonlinear processes that occur in the structure, including adhesive bridging phenomena and concrete cracking, the prediction of the debonding failure modes is extremely difficult. The primary numerical models that are accessible in the technical literature are based on strength and fracture techniques and are offered to forecast the debonding mechanisms in FRP-strengthened reinforced concrete structural elements [98]; [99]; [100]; [101]; [102]; [103]. To reduce the debonding dangers of FRP-to-concrete bonded joints, a great deal of research has been done. U-wrapped strips, anchor bolts, transverse wrapping, longitudinal chasing, bolted angles, and plate anchors are among the methods that have been suggested thus far to increase the bonding strength. These procedures, while effective, were predicated on the idea that the strengthened beams remained intact. Actually, there's a good chance that the beams that need to be strengthened have been there for a while and have developed cracks. There is proof that the current flat slab bridge typically operates with cracks. The debonding failure may result from the original cracks causing stress concentration after strengthening [104]; [105]; [106]; [107]; [108]; [109].

However, the impact of the initial damage on the FRP debonding resistance was typically overlooked by the bonding strength improvement techniques that were already in use. Consequently, it's critical to examine the debonding resistance of a strengthened beam with initial in order to confirm the efficacy of the strengthening technique. A second study is conducted on debonding behavior. The observed debonding issues in beams evaluated under two-point load pose a significant obstacle to the widespread implementation of FRP composite in structural strengthening and repair applications [110].

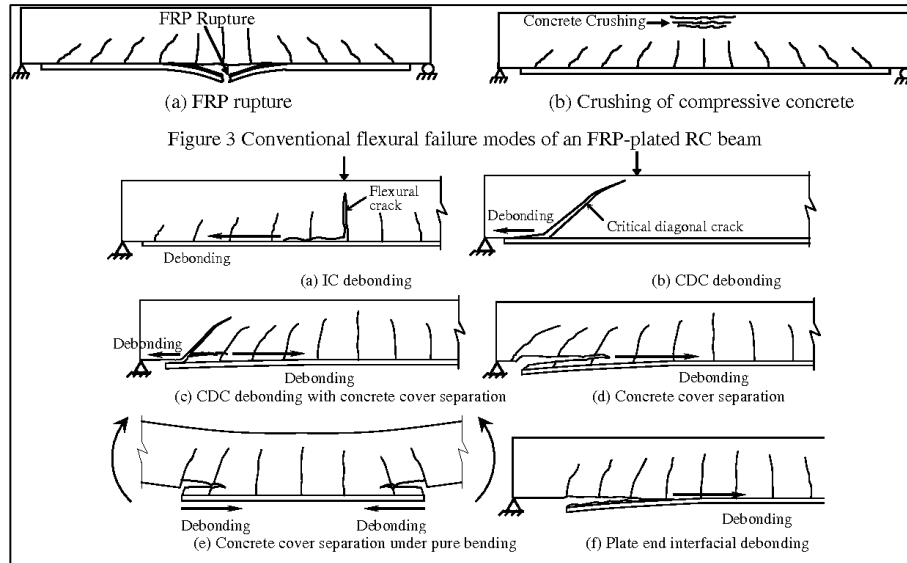


Figure # 2.8-1 Debonding Failure modes of FRPC Beams: [111]

Flexural strength is enhanced with by retrofitting with CFRP but the failure behavior of the system can become more brittle due suddenly debonding [112]. Another study was done on debonding of CFRP, concluded that in soffit plate, plate end debonding by either separation of concrete over or by interfacial debonding in concrete adjacent to the adhesive to concrete interface was the most common debonding phenomenon [113]. Another study on debonding phenomenon, concluded that the debonding failure mode of NSM CFRP strips in bond tests was interfacial debonding at the FRP epoxy interface [114]. Another research is done on debonding. They concluded that FRP strain distributions is non-uniform and needs to be considered in predicting the shear resistance contributed by the FRP through the use of a strain distribution factors [115]. Another study was done on debonding failure, their results showed that most of the beam failed by debonding in the form of the separation of the concrete cover from the steel tension reinforcement and for both types of plate ends [110].

2.9 Compressive Strength

Compressive strength is the capacity of a material or structure to bear the loads placed upon its surface without any fracture or deformation. It is a crucial factor in determining the structural integrity of concrete. The contributing elements to the compressive strength of concrete include the water-cement ratio, aggregate type, and curing conditions. Adherence to the correct protocol when conducting a concrete cube test allows for an accurate assessment of the concrete's compressive strength and quality assurance [8].

2.10 Summary

The literature reviewed in Chapter 2 shows that CFRP is a widely adopted strengthening material because of its high tensile strength, corrosion resistance, lightweight nature, and ease of installation. These properties make CFRP particularly effective in improving the flexural strength, shear capacity, crack behaviour, and overall energy dissipation of RC beams. Numerous experimental and analytical studies confirm that CFRP-retrofitted beams exhibit enhanced load capacity, stiffness, and durability, especially under static loading conditions. Research comparing steel-reinforced (RSRB) and GFRP-reinforced (RGRB) beams further highlights distinct trends, showing that CFRP typically produces higher stiffness and improved crack control in RSRB due to the higher modulus of steel, while RGRB strengthened with CFRP tends to display increased energy absorption and controlled deformation because of GFRP's lower stiffness and higher flexibility. A variety of laboratory testing methods—such as flexural loading, strain measurement, load–deflection monitoring, and failure mode observation—are commonly used to assess strengthened beams. Additionally literature highlights that RSRB + CFRP: Better crack control, slower stiffness degradation, and highest energy absorption at increasing loading rates. RGRB + CFRP: Controlled but wider cracking, faster stiffness loss, and lower energy absorption, especially under rapid loading. Moreover, previous studies examining both static and impact loading demonstrate how loading rate affects cracking patterns, stiffness degradation, and energy absorption characteristics. Collectively, the reviewed works provide a comprehensive understanding of CFRP-based retrofitting practices and the importance of experimental testing in evaluating the performance of RC beams under different loading conditions.

Chapter 3 Methodology

The experimental research procedure is presented in detail in this section. The research defines energy dissipation behavior of reinforced concrete beams strengthened with carbon fiber-reinforced polymers which undergo static loading conditions. Selection of materials and preparation of specimens along with equipment testing systems represents the methodology steps. The data collection process receives detailed description alongside analysis methods that validate both reliability and accuracy of recorded results. This research design gives engineers a step-by-step approach to recreate experiments and execute findings in actual engineering projects.

3.1 Research Approach

The research used a combination of qualitative and quantitative methods where literature study provided background knowledge and experimental tests measured retrofitted RC beam performance under laboratory control conditions. The investigation provides direct real-time observations regarding beam structural performance after different FRP types (Carbon, Glass and Steel fibers) have been implemented for static testing. Real-life conditions simulate the experimental data collection process in laboratory settings. The research studies pre- and post-retrofitted beams to show how efficient reinforcement becomes during structural aging cycles thus improving knowledge about structural maintenance planning and techniques.

3.2 Methodology Flow Chart

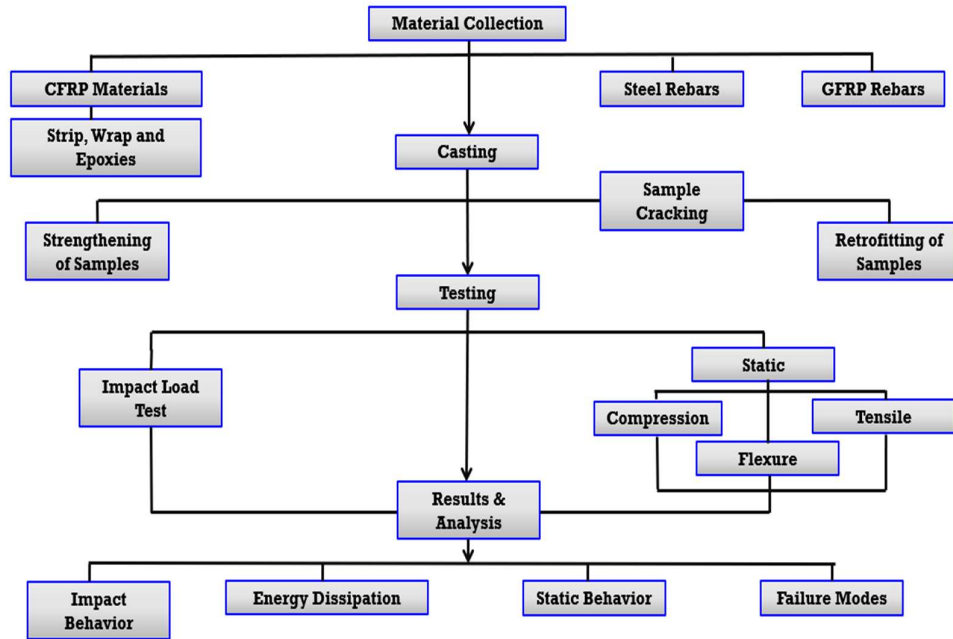


Figure # 3.2-1 Research Design Flowchart

Static load testing of specimens took place through a primary data collection method for each beam using Universal Testing Machine (UTM). Throughout the failure test the machines applied growing amounts of force to the beams while recording fundamental measurement data including deflection, load-bearing capacity, and energy dissipation at each step.

3.3 Experimental Program

The research adopted a controlled experimental protocol through testing 17 RC beam specimens including 1 control beams next to 16 retrofitted beams. CFRP strips and wraps were used to enhance the load capacity while dissipated energy in the beams. The study made use of specialized equipment to test specimens through static loading which duplicated authentic real-world scenarios. This design allows for a detailed comparison between the un-strengthened (control) and retrofitted beams, evaluating the impact of the retrofitting techniques on structural behavior. Each beam was carefully prepared and reinforced based on a specific retrofitting strategy. The experiment includes clear distinctions between beams retrofitted before they experience any damage (pre-retrofitting) and those retrofitted after damage has occurred (post-retrofitting). By

adopting this design, the study can provide valuable data on how retrofitting affects beams at different stages of deterioration.

The specimens tested in the experimental part of the study were composed of concrete, steel and high strength CFRP strips and wrap. The mechanical properties of some of these materials were determined by conducting appropriate test as per ASTM standards. Four test cubes having size (6inx6inx6in) were casted to determine the actual compressive strength of concrete for each specimen. All the cubes were cured for 28 days and tested as per ASTM C39. Sample of cube testing is shown below”

3.3.1 Mix Design

ACI Committee 211 method was used for the mix design, Sand fineness modulus was calculated as 2.6, and water cement ratio as 0.48

Table # 3.3-1 Concrete Mix Design

S. No	Description of Item	Design Quantity
1	Cement (ordinary Portland)	306 kg/m ³
2	Sand (Lawrensour)	660kg/m ³
3	Corse Aggregate (3/8”)	1054kg/m ³
4	Water Content	180kg/m ³
5	Total Weight	2200kg/m ³

3.3.2 Steel Reinforcement

Grade-60 reinforcing was used in this study, #4 rebar were used as main bars at tension and Compression zone and #3 rebar were used for transverse reinforcement in the specimen. The tensile tests performed on steel bars of #3 as per ASTM A370 standard as shown below;

3.3.3 Carbon fiber reinforced Polymers (CFRP) Strip and CFRP Wrap

For strengthening reinforced concrete members, the Sika Dur commercially sold by Sika Pakistan (Islamabad) under the name ‘Type S 812, having design value of tensile strength 4.06×10^5 psi (2800 MPa), modulus of elasticity 23.2×10^6 psi (160,000 MPa), design strain 0.85%, thickness 0.047 in. (1.2 mm) and tensile strength 60.4×10^3 lbs. (269 kN) was used for experiment.

And CFRP Wrap (Sika wrap-230 C), commercially sold by Sika Pakistan (Islamabad), is a “unidirectional woven carbon fiber fabric with mid-range strength, designed for installation using the dry or wet application process”. The fabric is stable due to the use of heat-set weft strands in its manufacturing process. It is a multifunctional fabric that may be used for many strengthening purposes. Adaptable and adaptive to various surface planes and geometries (such as walls, soffits, columns, chimneys, piles, beams, and silos) [116]

In this study for strengthening reinforced concrete members. Sika wrap-230 C with thickness of 1.0 mm, ultimate load is 350KN/m width per layer and tensile modulus of 28 KN /mm² was used.

CFRP strips were bonded to the RCC beam using Sikadur 30, a two-component, 100% solids, moisture-insensitive, high-modulus, high-strength structural epoxy paste adhesive. Sikadur 30 has to cure at room temperature for seven days. It is advised that concrete be at least 21–28 days old before plying epoxy, and that the minimum temperature for application be 40F (4.45° C) [116].



1



2



3



4



5



6

Figure # 3.3-1 Components of Mix Design (1: Sika Carbon Dur [117]; 2: Sika Wrap 230 [117]; 3: Epoxy (Sikadur 30) [120]; 4: Concrete Cube casting; 5: Steel and GFRP Bars; 6: Sikadur 30 epoxy mixture

Table 3.3-2 Material Properties

S.no	Description of Item	Properties	
		Property	Value
1	Steel Reinforcement	Yield Strength	420 MPa (60000) <i>psi</i>
2	GFRP Reinforcement	Yield Strength	420 MPa (60000) <i>psi</i>
3	Concrete	Compression Strength	20 MPa (2900) <i>psi</i>
4	Concrete	Flexure strength	4.75 MPa (690) <i>psi</i>
5	CFRP Strip	Ultimate strength	2800 MPa (406000) <i>psi</i>
6	Sika Wrap	Ultimate Load	350 KN/m (23) <i>Kips/ft</i>

3.4 Test Specimens

All 17 specimens were 24 in. long and 6 in. x 6 in. in cross section. The cross sectional detail and longitudinal detail are shown below.

Table # 3.4-1 Number of specimens Casted

S.#	Description	Remarks	Description	Remarks
1	PCB	Plain Concrete beam		
2	SRB1	Steel Reinforced beam	GRB1	GFRP Reinforced beam
3	SRB2	Steel Reinforced beam	GRB2	GFRP Reinforced beam
4	SRB3	Steel Reinforced beam	GRB3	GFRP Reinforced beam
5	SRB4	Steel Reinforced beam	GRB4	GFRP Reinforced beam
6	SRB5	Steel Reinforced beam	GRB5	GFRP Reinforced beam
7	SRB6	Steel Reinforced beam	GRB6	GFRP Reinforced beam
8	SRBV1	Steel reinforced beam without stirrups	GRBV1	GFRP reinforced beam without stirrups
9	SRBV2	Steel reinforced beam without stirrups	GRBV2	GFRP reinforced beam without stirrups

3.4.1 Specimen Preparation

Concrete specimens were casted in the molds. Slump and ratio of concrete was according to mix design. Companion test cubes were casted for each batch of concrete. The multiple steel bars were tied together with wire to form a three-dimensional grid, for casting concrete beams, a series of wooden formwork frames were arranged linearly and steel reinforcement bars were placed in them, as shown below. This setup define the shape of the concrete and the reinforcement bars, provide structural strength and durability.

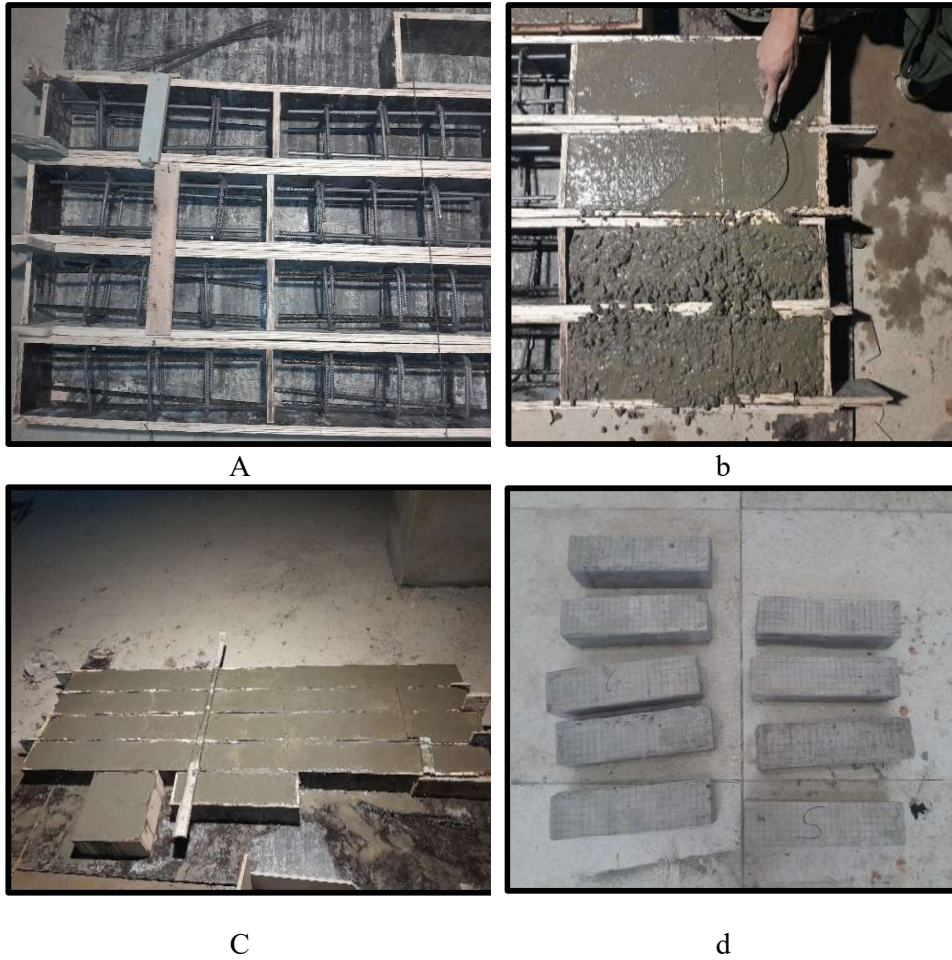


Figure # 3.4-1 various stages of beam casting

3.4.2 Pre-damage and Post-damage Strengthening of Beams

Out of 17 beams few beams were strengthen by CFRP Strip at bottom, few beams were strengthen by CFRP Wrap at bottom, and few beams were strengthen by CFRP strip at bottom supported by CFRP wrap.

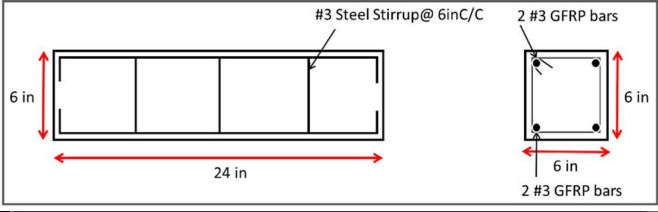
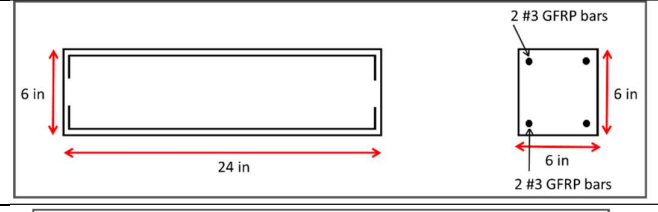
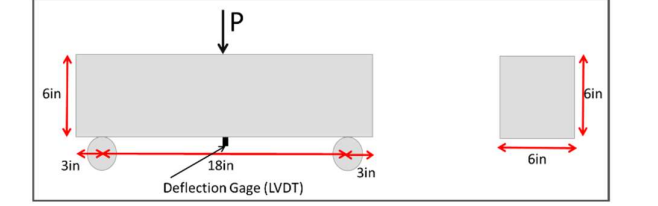
A total of 17 no of specimens were constructed comprising of multiple sub sets. Set-1 is comprised of 8 steel reinforced beams, Set-2 is comprised of 8 GFRP reinforced beams. A plain concrete beam was also constructed for comparison purpose. Beam was non-reinforced, f_c' was 3000 Psi and f_y was 60,000 Psi, as shown below in table # 3.4-4

Table # 3.4-2 Retrofitting Scheme

Post Retrofitting of Beams (cracked Specimens)		Pre Retrofitting of Beams (Un cracked Specimens)	
RSRB1 (Steel Reinforced Beam 1)		RSRB 4 (Steel Reinforced Beam 4)	
RSRB2 (Steel Reinforced Beam 2)		RSRB 5 (Steel Reinforced Beam 5)	
RSRB3 (Steel Reinforced Beam 3)		RSRB 6 (Steel Reinforced Beam 6)	
RGRB 1 (GFRP Reinforced Beam 1)		RGRB 4 (GFRP Reinforced Beam 4)	
RGRB 2 (GFRP Reinforced Beam 2)		RGRB 5 (GFRP Reinforced Beam 5)	
RGRB 3 (GFRP Reinforced Beam 2)		RGRB 6 (GFRP Reinforced Beam 6)	
RSRBV1 (Steel Reinforced Beam 1, Only designed for flexure)		RSRBV2 (Steel Reinforced Beam 2, Only designed for flexure)	
RGRBV1 (GFRP Reinforced Beam 1, Only designed for flexure)		RGRBV2 (GFRP Reinforced Beam 2, Only designed for flexure)	

Six Specimens were GFRP reinforced were design for flexure and shear. GFRP rebar was used for flexure and steel rebar was used for shear reinforcement. And also Six Specimens were GFRP Reinforced beams design for flexure and shear. Two Specimens were steel reinforced, designed only for flexure and two Specimens were GFRP bars reinforced only design for flexure as shown in below table # 3.4-3;

Table # 3.4-3 Beams Diagrams		
Beams Description	Beam Diagrams	Remarks
Plain Concrete Beam		Beam Without Reinforcement
SRB1- SRB6		Steel Reinforced beams
SRBV1 & SRBV2		Steel Reinforced beams (Only Flexure Design)

GRB1-GRB6		GFRP Reinforced Beams
GRBV1 & GRBV2		GFRP Reinforced Beams (Only Flexure Design)
Fluxure testing Of Beams		Beam Testing Under 3 rd Point Loading

Four specimens were pre retrofitted and 4 specimens were post retrofitted by CFRP Strips in both sets (GFRP and Steel).

The diagram shown below in figure depicts a reinforced concrete beam with a CFRP wrap adhered to its underside and strip at its bottom as shown in figure # 3.4-4 below. 2 specimens from each set were retrofitted by CFRP strip (1 was post retrofitted and 1 was pre retrofitted). The dimensions of the beam and the CFRP strip and wrap were specified, including the total length, width, and exact placement of the CFRP strip and wrap.

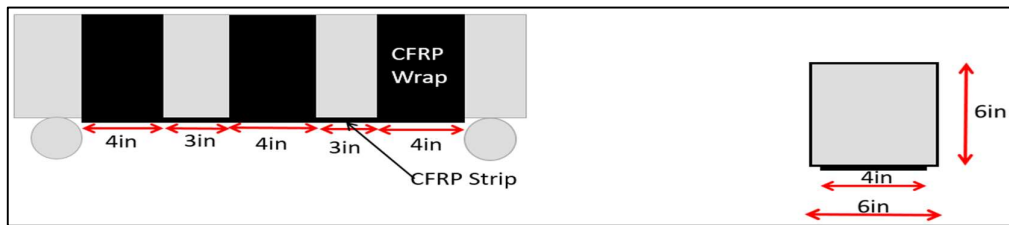


Figure # 3.4-2 Side View of beams strengthened by CFRP Strip

The diagram shown below in figure # 3.4-5 depicts a reinforced concrete beam with a CFRP wrap adhered to its underside and strip at its bottom, specimens from each set were retrofitted by CFRP wrap.

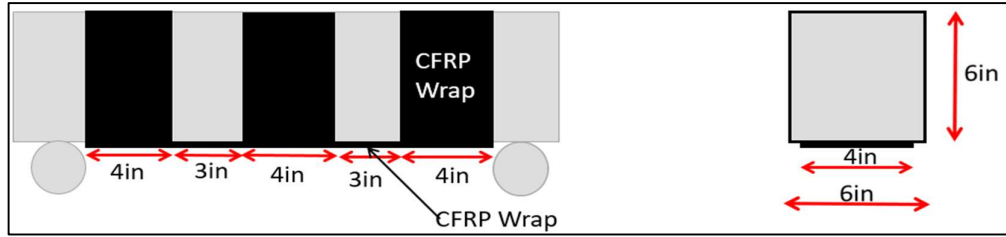


Figure # 3.4-3 Side View of beams strengthened by CFRP wrap

A reinforced concrete beam with a CFRP wrap adhered to its underside and strip applied to its bottom surface and the overall length, width, and specific placement of the wrap and strip and beam is shown below in figure # 3.4-6

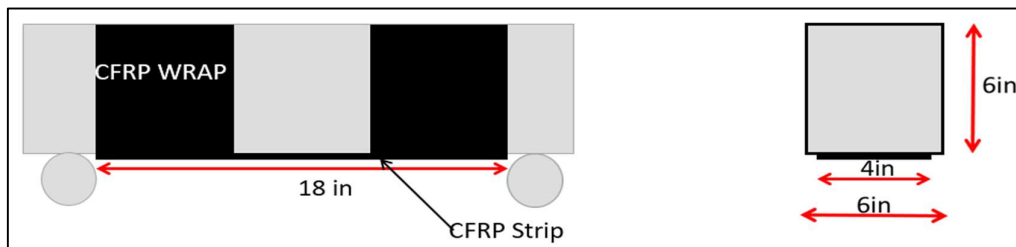


Figure # 3.4-4 Side View of beams strengthened by CFRP strip

The diagram of a RC beam with a CFRP wrap adhered to its underside as well as applied to its bottom surface is shown below in figure # 3.4-7

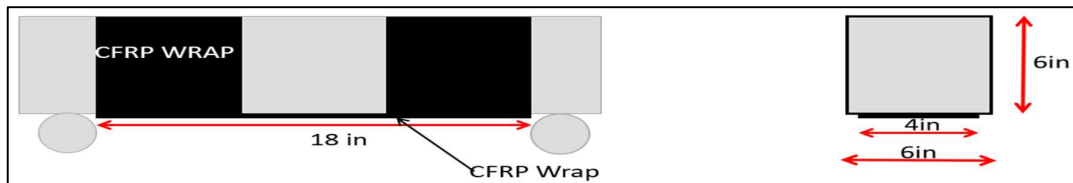


Figure # 3.4-5 Bottom view of beams strengthened by CFRP wrap

A RCB with a CFRP strip applied to its bottom surface and wrap adhered to its underside including the overall length, width, and the specific placement of the strip and wrap is illustrated below in figure # 3.4-8

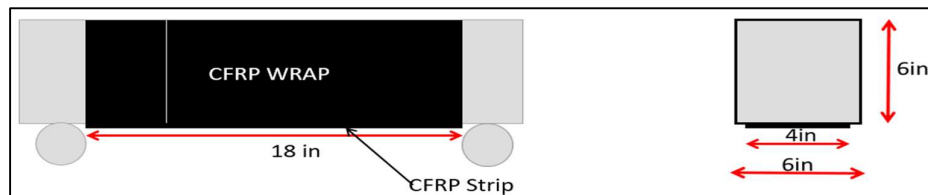


Figure # 3.4-6 Bottom view of beam strengthened by CFRP wrap and strip

3.4.3 Testing Setup

UTM (also known as “universal tester, universal tensile machine, materials testing machine, materials test frame”) is used to find out the “tensile strength (pulling), “compressive strength (pushing), flexural strength, bending, shear, hardness, and torsion”. The purpose of this device is to provide essential information for the design and quality guarantee of materials [116]. UTM consist of Loading unit, Supporting frame .Base and Supports. The rate of application of load was controlled from loading unit. Load was applied by load cell.

sp



Split Tensile Test Of Cube



Steel Bar Tensile Test.



Flexure Test of beam



Compression test of Concrete Cube

Figure # 3.4-7 Testing Setup

Chapter 4 Results and Discussion

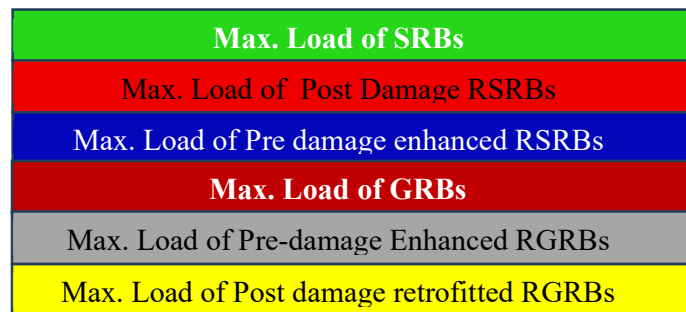
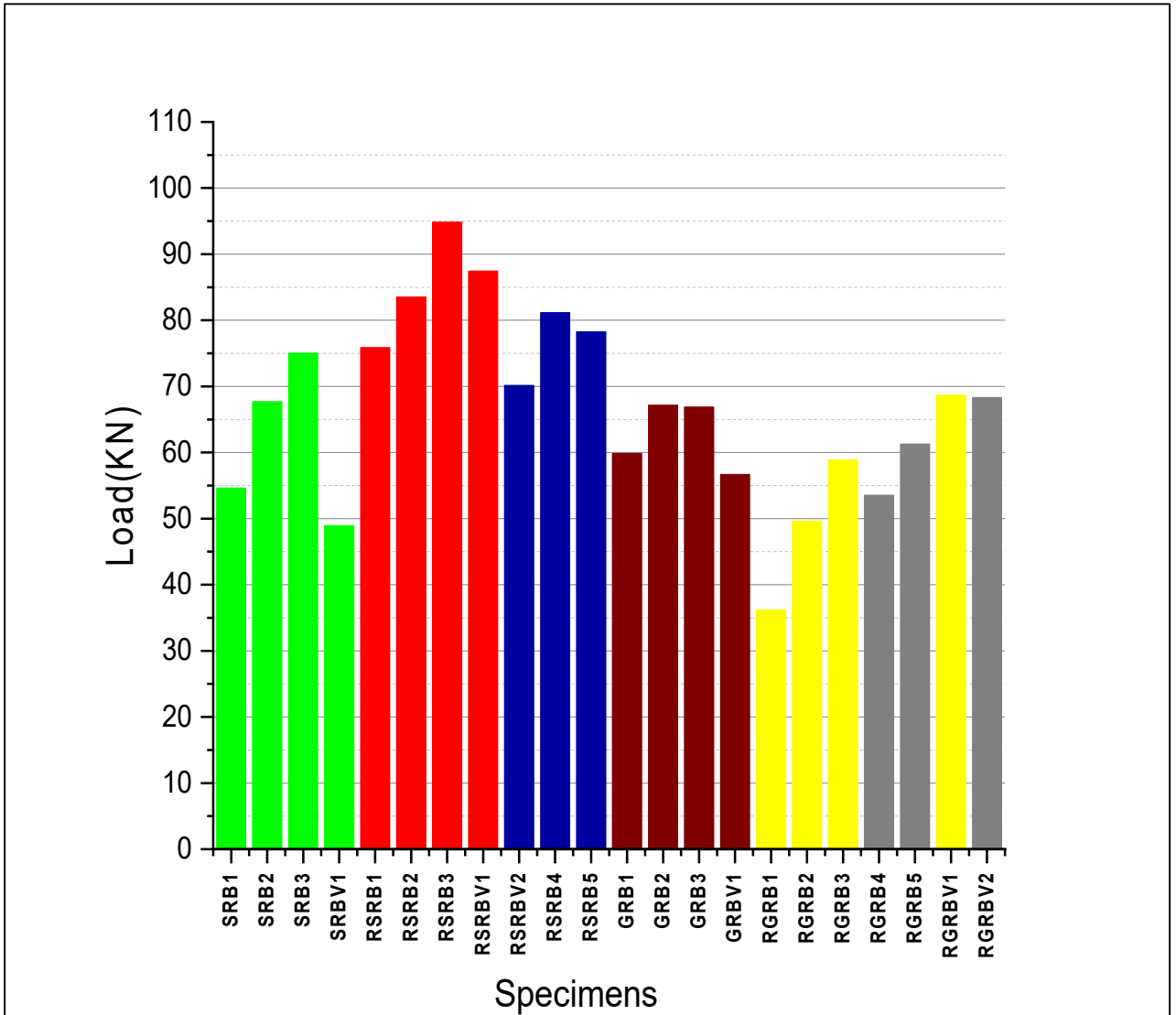
4.1 General

This chapter outlines the findings from the experimental tests performed on both retrofitted and non-retrofitted RC beams. The results are analyzed to demonstrate the impact of retrofitting on the beams' structural strength, particularly in terms of load-bearing capacity and energy dissipation. Furthermore, a detailed comparison between pre-retrofitted, post-retrofitted, and control beams is provided to evaluate the overall effectiveness of the applied reinforcement techniques.

The analysis of the collected data was conducted using specialized software, which allowed for the generation of detailed graphs and calculations. The primary focus of the analysis was on comparing the performance of control beams to retrofitted beams under static load. The load-deflection graphs provided a clear representation of each beam's behavior under stress, highlighting key differences in performance. Energy dissipation, which is a critical factor in determining how well a structure can absorb and distribute forces, was analyzed for each beam. The area under the load-deflection curve was used to calculate the total amount of energy dissipated by each beam, with retrofitted beams generally showing higher energy dissipation compared to control beams. This indicates that retrofitting can significantly improve the structural resilience of RC beams.

Further analysis was done to compare pre-retrofitted beams with post-retrofitted ones. This comparison highlighted the benefits of retrofitting early in the lifespan of a structure, as pre-retrofitted beams showed superior performance in terms of load-bearing capacity and energy dissipation compared to beams retrofitted after damage had occurred. This analysis is crucial for informing future engineering practices related to the timing and application of retrofitting techniques.

4.2 Static Load Performance of Pre and Post Retrofitted Beams



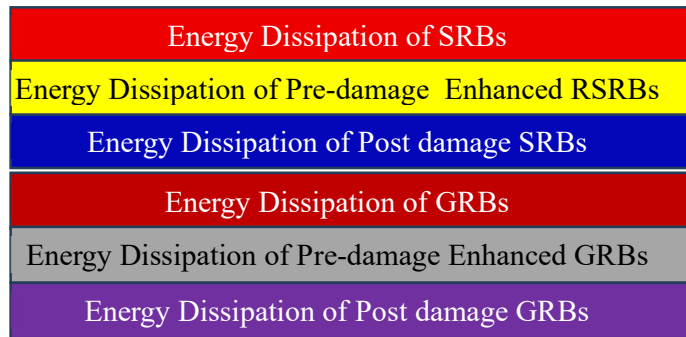
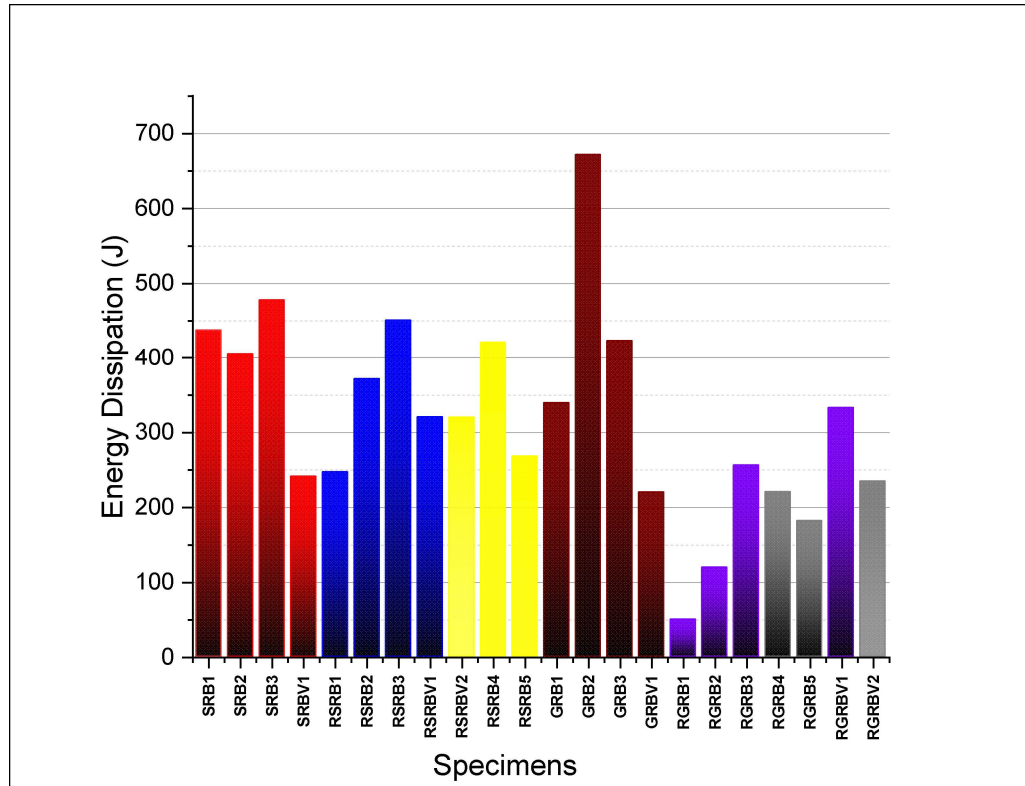


Figure # 4.2-1 Testing Setup

4.3 Impact Load Tests

Two reinforced concrete beams, designated as SRB6 and GRB6, were tested under impact loading conditions both before and after retrofitting with CFRP strips and CFRP wrapping. The objective of these tests was to evaluate the structural response, enhancement in performance, and changes in failure behavior resulting from the CFRP retrofit. A load cell was mounted on the impact device to accurately record the time-dependent impact force applied to each beam. Linear Variable Differential Transformers (LVDTs) were installed at predetermined locations along the beam span to measure the corresponding deflections during the impact event. Additionally, an

accelerometer was fixed to the side face of each beam to capture its acceleration response, providing further insight into the dynamic behavior under impact loading.

The combined measurements of impact force, deflection, and acceleration enabled a comprehensive assessment of the beams and overall dynamic performance before and after CFRP strengthening.

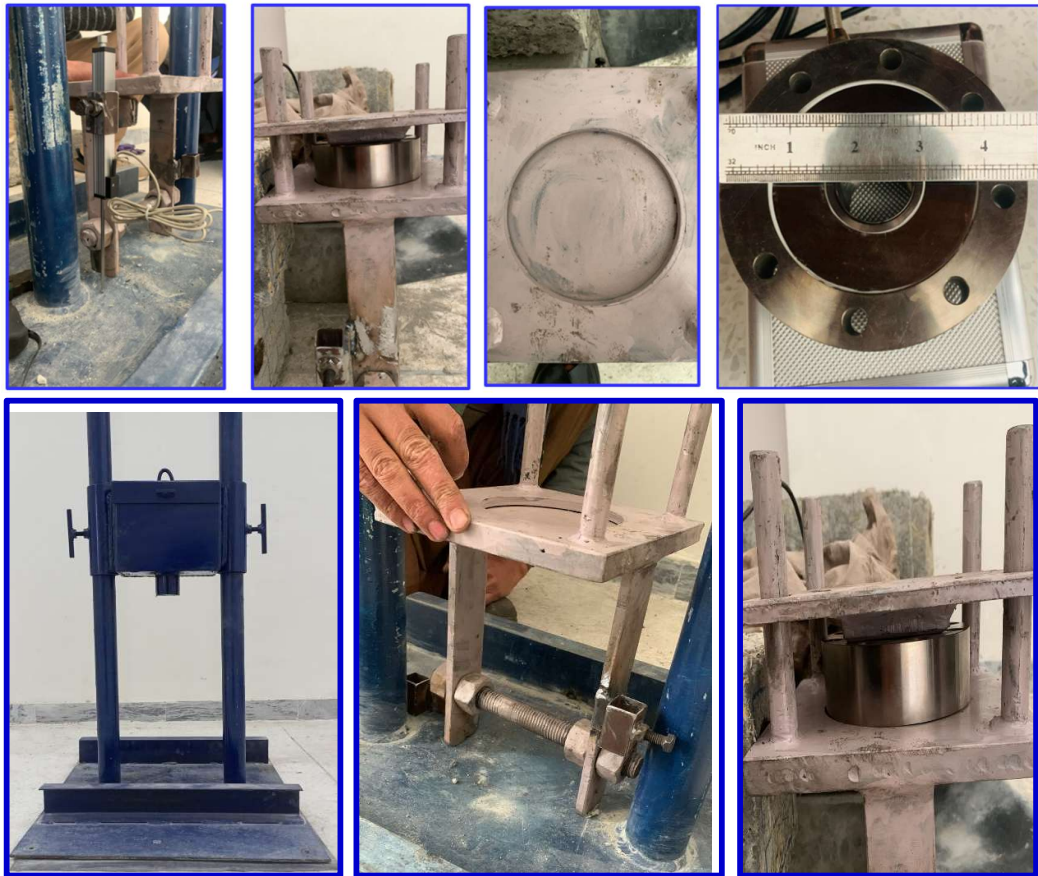


Figure # 4.3-1 Impact load Setup with load cell protection assembly and load cell
This setup was developed for Load cell unit protection during impact.

4.4 Comparative Study of All Specimens

Load Time curve for Steel Reinforced Beam (SRB)

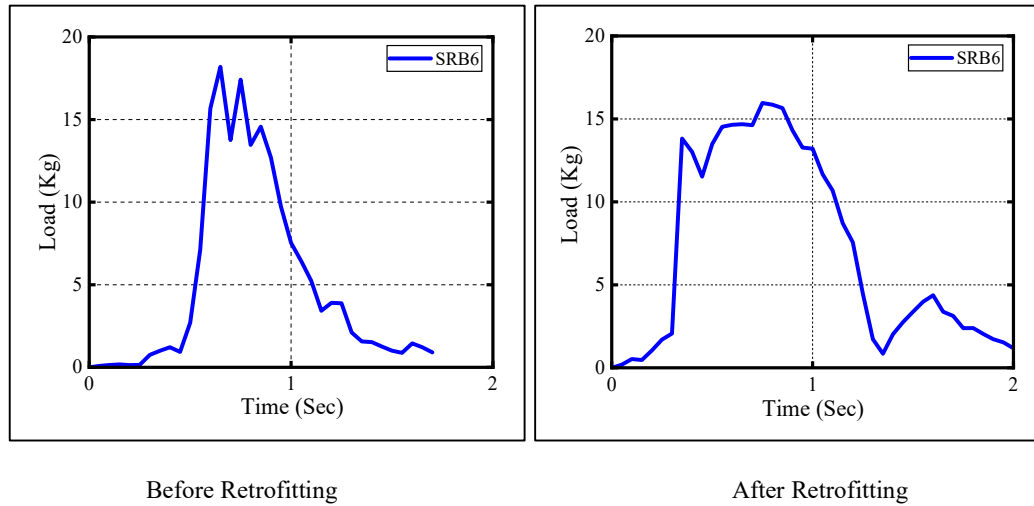


Figure # 4.4-1 Load vs Time Curve of SRB6

Load Time curve for Glass Reinforced Beam (GRB)

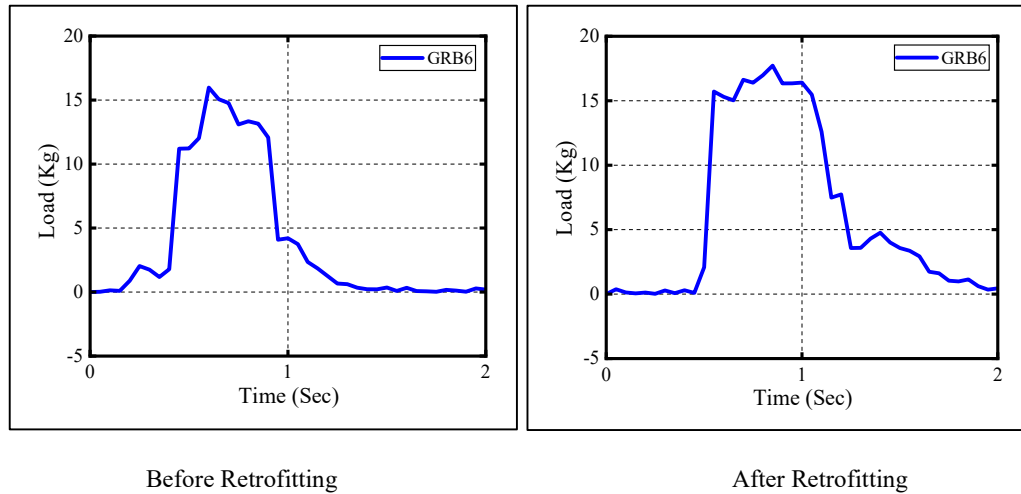
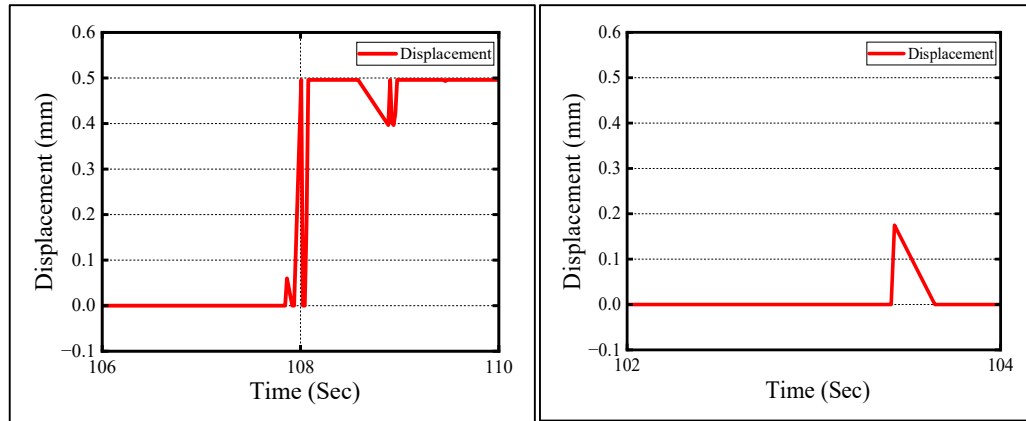


Figure # 4.4-2 Load vs Time Curve of GRB6

Displacement Time curve for Glass Reinforced Beam (GRB)

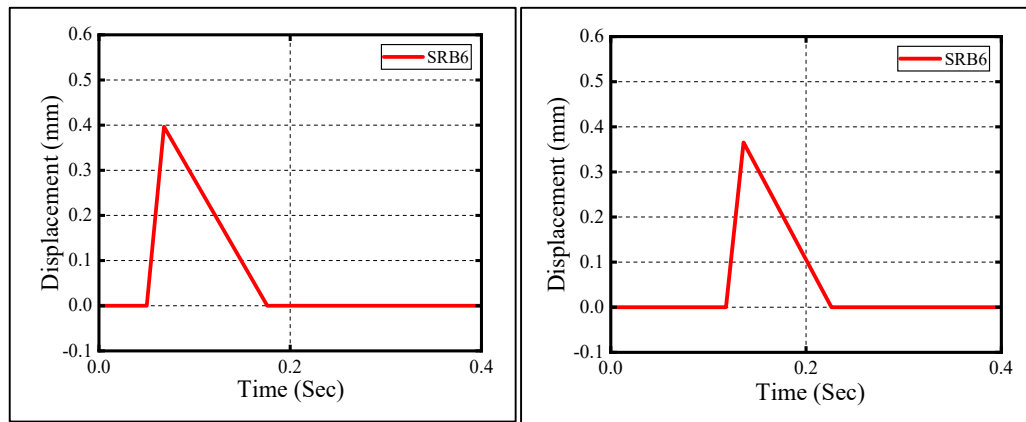


Before Retrofitting

After Retrofitting

Figure # 4.4-3 Displacement vs Time Curve of GRB6

Displacement Time curve for Steel Reinforced Beam (SRB)



Before Retrofitting

After Retrofitting

Figure # 4.4-4 Displacement vs Time Curve of SRB6

Time Acceleration curve for Steel Reinforced Beam (SRB)

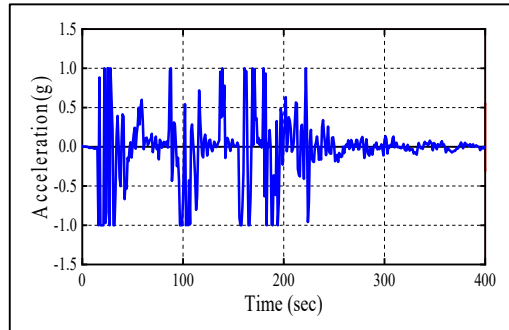


Figure # 4.4-5 Acceleration vs Time Curve of SRB6 before Retrofitting

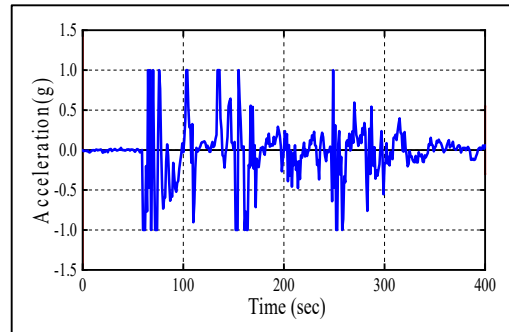


Figure # 4.4-6 Acceleration vs Time Curve of SRB6 after Retrofitting

Time Acceleration curve for Glass Reinforced Beam (GRB)

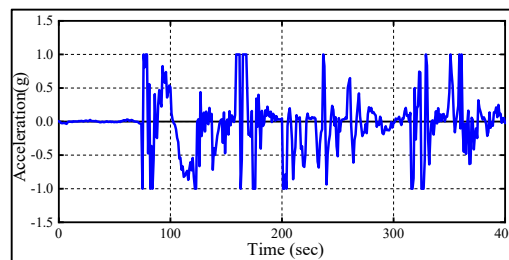


Figure # 4.4-7 Acceleration vs Time Curve of GRB6 before Retrofitting

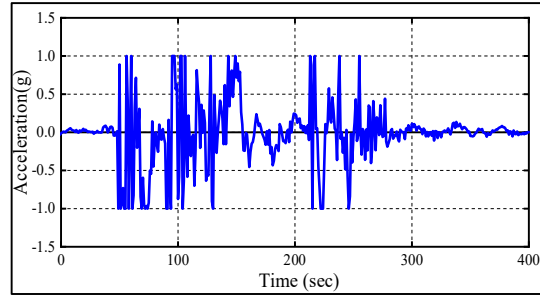


Figure # 4.4-8 Acceleration vs Time Curve of GRB6 after Retrofitting

Table # 4.4-1 Comparison between Steel Reinforced and GFRP Reinforced (Both Non Retrofitted) Beams

Steel Reinforced Beams				GFRP Reinforced beams			
Beam Name	Max. Load (kN)	Max Deflection (mm)	Energy Dissipated (J)	Beam Name	Max. Load (kN)	Max Deflection (mm)	Energy Dissipated (J)
SRB1	54.6	9	437.19	GRB1	59.813	10.2	338.85
SRB2	67.65	11	405.5	GRB2	67.13	17.19	672.04
SRB3	75	8.43	477.5	GRB3	66.86	13.16	423.25
SRBV1	48.91	8.01	241	GRBV1	56.65	10.66	219.83

Table # 4.4-2 Comparison between Steel Reinforced and GFRP Reinforced (Post damage Retrofitted) Beams

Steel Reinforced Post Retrofitted beams				GFRP Reinforced Post Retrofitted beams			
Beam Name	Max. Load (kN)	Max Deflection (mm)	Energy Dissipated (J)	Beam Name	Max. Load (kN)	Max Deflection (mm)	Energy Dissipated (J)
RSRB1	75.85	6.14	246.7	RGRB1	36.14	3.14	49.57
RSRB2	83.5	7.6	370.96	RGRB2	49.6	4.95	119.16
RSRB3	94.82	9.94	590.85	RGRB3	58.85	9.15	255.7
RSRBV1	87.4	6.38	320	RGRBV1	68.67	6	332.5

Table # 4.4-3 Comparison between Steel Reinforced and GFRP Reinforced (Pre Retrofitted) Beams

Steel Reinforced Pre-Retrofitted beams				GFRP Reinforced Pre-Retrofitted beams			
Beam Name	Max. Load (kN)	Max Deflection (mm)	Energy Dissipated (J)	Beam Name	Max. Load (kN)	Max Deflection (mm)	Energy Dissipated (J)
RSRB4	81.14	6.5	420.79	RGRB4	53.5	5.41	219.96
RSRB5	78.23	5.01	267.78	RGRB5	61.25	4.41	181.25
RSRBV2	70.13	6.07	319.7	RGRBV2	68.27	5.17	234.16

Table # 4.4-4 Comparison between Post Retrofitted beams and Pre Retrofitted beams

Post Retrofitted beams				Pre Retrofitted beams			
Beam Name	Max. Load (kN)	Max Deflection (mm)	Energy Dissipated (J)	Beam Name	Max. Load (kN)	Max Deflection (mm)	Energy Dissipated (J)
RSRB1	75.85	6.14	246.7	RSRB4	81.14	6.5	420.79
RSRB2	83.5	7.6	370.96	RSRB5	78.23	5.01	267.78
RSRB3	94.82	9.94	450.5	RSRB6			
RSRBV1	87.4	6.38	320	RRRBV2	70.13	6.07	319.7
RGRB1	36.14	3.14	49.57	RGRB4	53.5	5.41	219.96
RGRB2	49.6	4.95	119.16	RGRB5	61.25	4.41	181.25
RGRB3	58.85	9.15	255.7	RGRB6			
RGRBV1	68.67	6	332.5	RGRBV2	68.27	5.17	234.16

Table # 4.4-5 Comparison between Non Retrofitted beams, Post Retrofitted beams and Pre Retrofitted beams

Non Retrofitted beams					Post-Retrofitted beams					Pre-Retrofitted beams			
Beam Name	Max. Load (kN)	Max Defl (mm)	Energy Dissipated (J)	K Value	Beam Name	Max. Load (kN)	Max Defl (mm)	Energy Dissipated (J)	K Value	Beam Name	Max. Load (kN)	Max Defl (mm)	Energy Dissipated (J)
SRB1	54.6	9	437.19		RSRB1	75.85	6.14	246.7		RSRB4	81.14	6.5	420.79
SRB2	67.65	11	405.5		RSRB2	83.5	7.6	370.96		RSRB5	78.23	5.01	267.78
SRB3	75	8.43	477.5		RSRB3	94.82	9.94	450.5		RSRB6			
SRBV1	48.91	8.01	241		RSRBV1	87.4	6.38	320		RRRBV2	70.13	6.07	319.7
GRB1	59.81	10.2	338.85		RGRB1	36.14	3.14	49.57		RGRB4	53.5	5.41	219.96

GRB2	67.13	17.19	672.04		RGRB2	49.6	4.95	119.16		RGRB5	61.25	4.41	181.25
GRB3	66.86	13.16	423.25		RGRB3	58.85	9.15	255.7		RGRB6			
GRBV1	56.65	10.66	219.83		RGRBV1	68.67	6	332.5		RGRBV2	68.27	5.17	234.16

4.5 Global Energy Dissipation of Glass Fiber Reinforced Beams (GRB) in Flexure

The maximum load taken by the glass reinforced beams (GRB1, GRB2, GRB3) with the corresponding deflection values, area under the curves showing the amount of energy dissipated by the tested beams, are shown and discussed below along other mechanical properties of all the beams including strengths.

1. GRB 1

The global energy dissipation of GRB1 was low, as shown by the small shaded area under its curve. The beam absorbed limited strain energy and showed poor toughness. Paver energy was concentrated in the early stage, dropping sharply after peak load. Cracks appeared early at the tension face and spread quickly. They remained localized and did not distribute across the span. Stiffness degraded rapidly, and the beam failed in a brittle manner. Overall, the response of GRB1 highlights the inherent weakness of non-retrofitted GFRP beams, which lack both controlled crack progression and sufficient global energy dissipation, making them vulnerable under static loading.



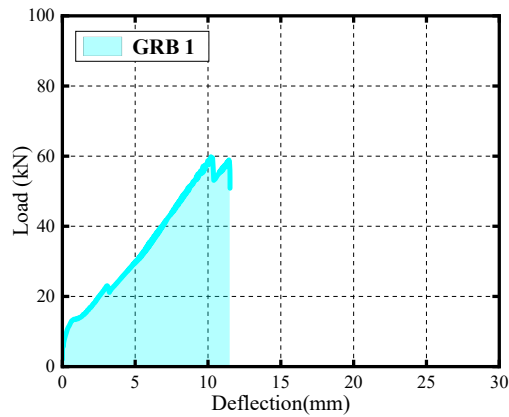


Figure # 4.5-1 Energy Dissipation Curve for GRB1

2. GRB2

GRB2 showed marginally better performance than GRB1, but its global energy dissipation remained poor. Paver energy was released quickly without sustained absorption. Cracks developed as localized brittle fractures with minimal flexural contribution, highlighting the inherent weakness of un-strengthened GFRP beams.

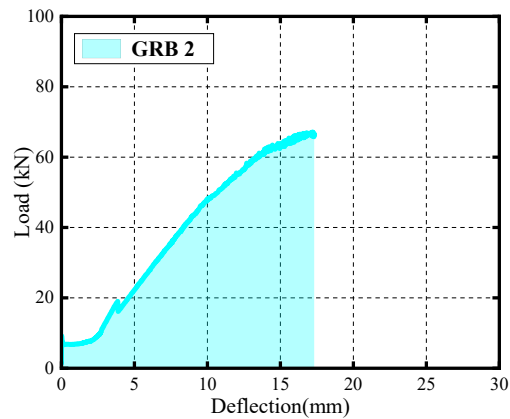
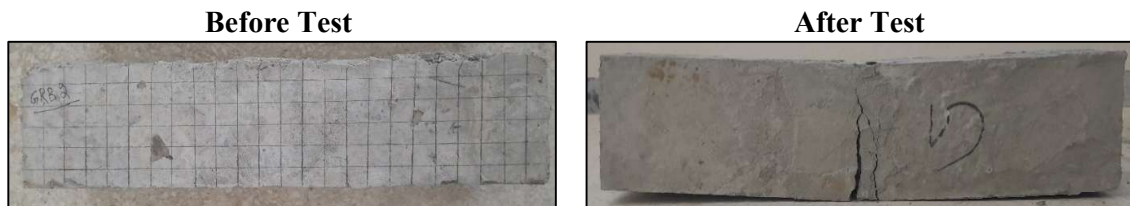


Figure # 4.5-2 Energy Dissipation Curve for GRB2

3. GRB 3

The global energy dissipation of GRB3 was very limited. The shaded area under the curve is small, showing weak toughness and low energy absorption. Paver energy increased quickly at early loading but dropped soon after peak load. Cracks formed early and propagated rapidly. They remained concentrated in a narrow zone without proper distribution. The beam lost stiffness sharply and failed in a brittle manner. GRB3 confirmed the poor ductility and low energy dissipation of non-retrofitted GFRP beams.

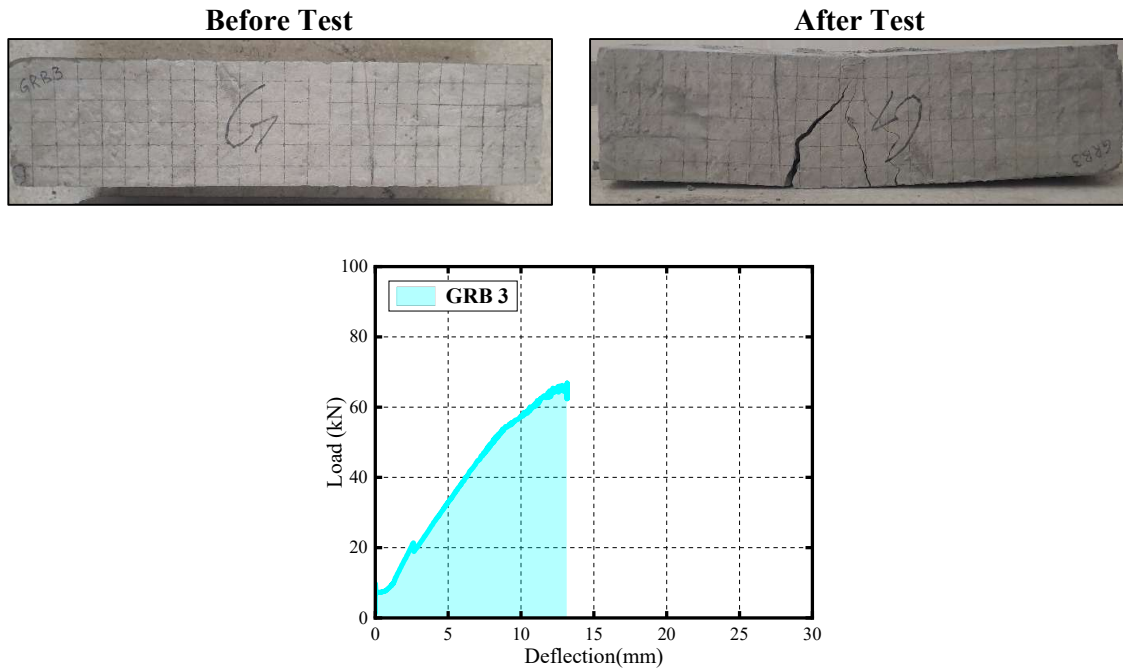


Figure # 4.5-3 Energy Dissipation Curve for GRB3

4. GRBV 1

The global energy dissipation of GRBV1 was low, as shown by the small shaded area under the curve. The beam absorbed only a limited amount of strain energy, reflecting weak toughness and ductility. Paver energy was concentrated in the early loading phase and dropped rapidly after peak load, indicating poor capacity to sustain energy release. Crack behaviour was brittle, with early initiation of flexural cracks that propagated quickly without wide distribution. The cracks localized near the mid-span and caused sudden stiffness degradation. The beam failed abruptly, confirming the inherently brittle nature of non-retrofitted GFRP reinforcement with very limited energy dissipation.

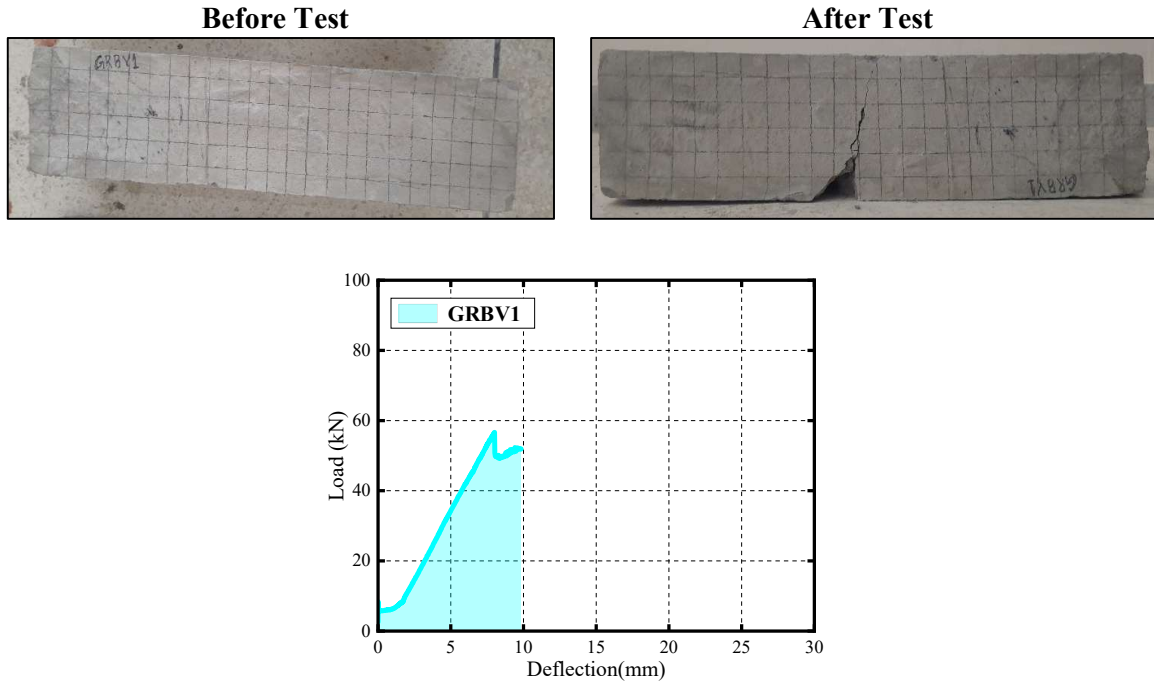


Figure # 4.5-4 Energy Dissipation Curve for GRBV 1

4.6 Global Energy Dissipation of Steel Reinforced Beams (SBR)

The maximum load taken by the all steel reinforced beams (SRB 1, SRB 2, SRB 3) with the corresponding deflection values, area under the curves showing the amount of energy dissipated by the tested beams, are shown and discussed below along other mechanical properties of all the beams including strength.

1. SRB 1

The global energy dissipation of SRB1 was limited, with a narrow shaded area under the curve. Paver energy was concentrated in a short deformation range, reflecting poor toughness. Cracks developed rapidly as localized flexural lines, widening quickly into dominant cracks without distribution. The brittle failure mode reduced overall ductility.



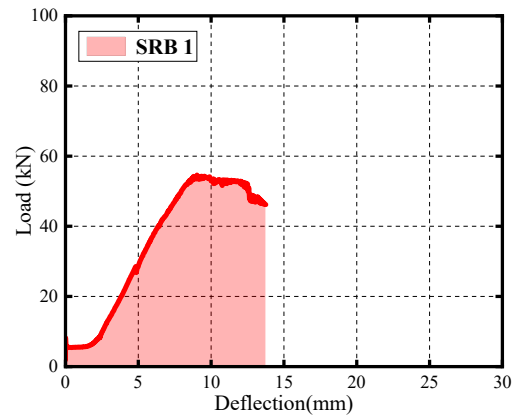


Figure # 4.6-1 Energy Dissipation Curve for SRB 1

2. SRB 2

SRB2 displayed slightly higher global energy dissipation than SRB1, but still lacked sustained deformation capacity. Paver energy increased sharply in the early stages, followed by abrupt collapse. Crack behavior was dominated by localized flexural cracks, which merged rapidly, leading to brittle rupture and poor energy release.

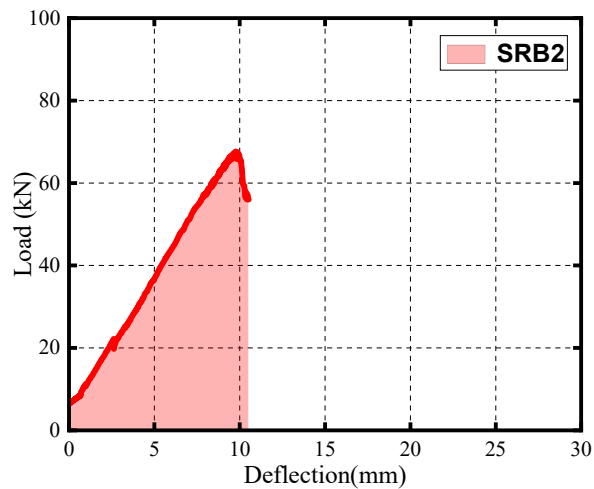
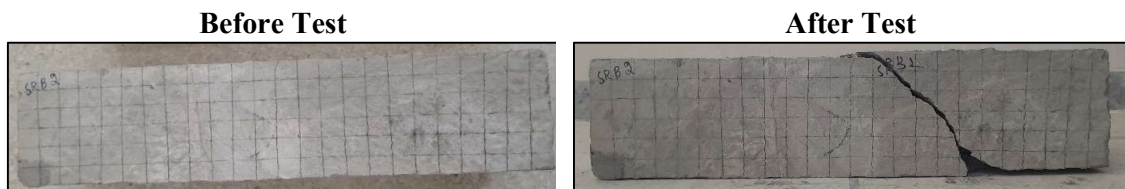


Figure # 4.6-2 Energy Dissipation Curve for SRB 2

3. SRB 3

The global energy dissipation of SRB3 remained minimal, with paver energy concentrated in early deformation. Crack propagation was sudden, with limited distribution across the beam. The specimen failed in a brittle manner with inadequate ductility, confirming the vulnerability of un-strengthened steel beams.

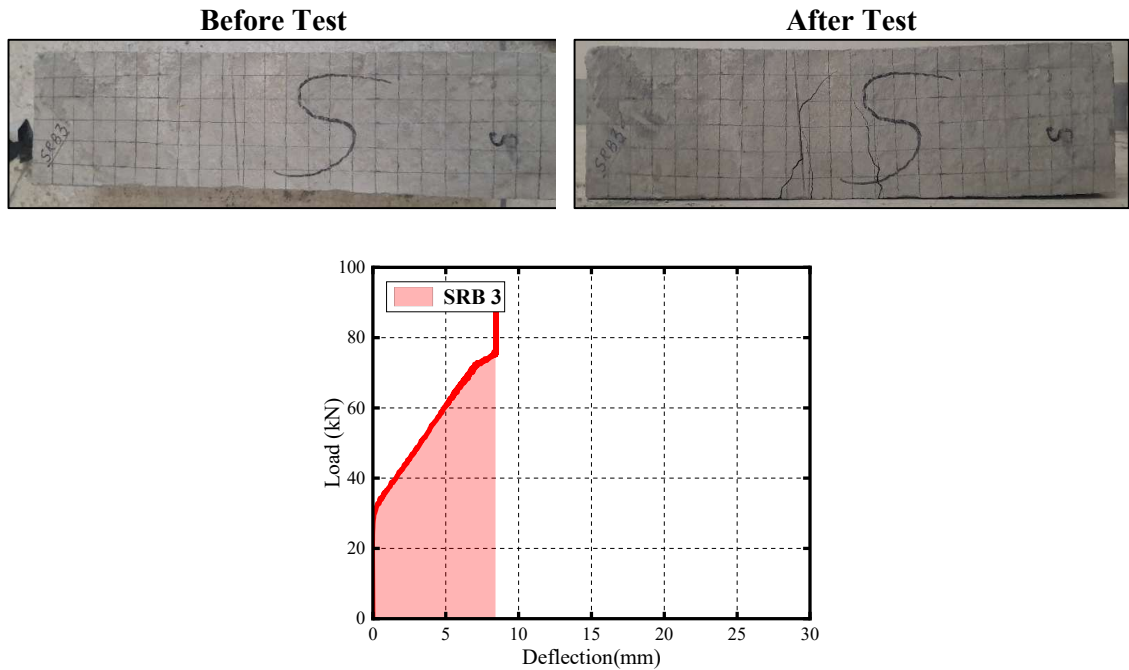


Figure # 4.6-3 Energy Dissipation Curve for SRB 3

4. SRBV 1

The global energy dissipation of SRBV1 was moderate, as shown by the limited shaded area under the load–deflection curve. The beam absorbed strain energy within a short deformation range, indicating restricted toughness and ductility. Paver energy rose steadily during initial loading but reduced quickly after peak load, reflecting poor ability to sustain energy release. Crack behavior was characterized by early initiation of flexural cracks, which widened rapidly at mid-span. The cracks remained localized, leading to stiffness degradation and a brittle mode of failure. The overall response confirmed that non-retrofitted steel beams, while stronger than GFRP beams, still lacked sufficient energy dissipation capacity without external strengthening.

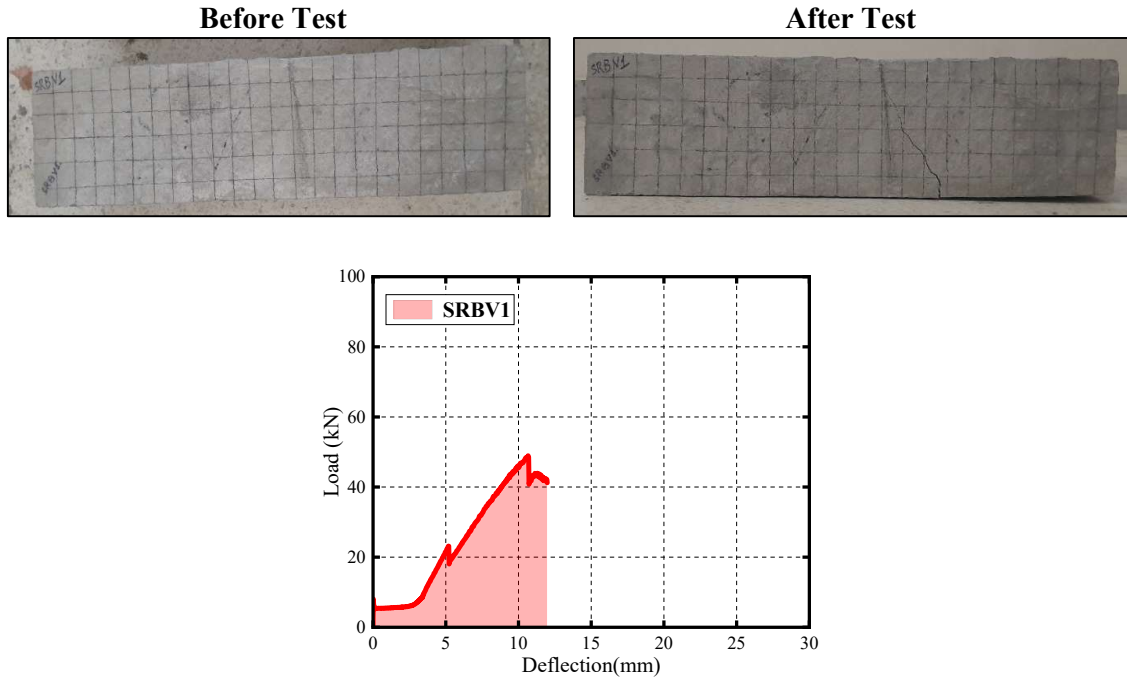


Figure # 4.6-4 Energy Dissipation Curve for SRBV 1

4.7 Test Results for Energy Dissipation in Specimens after Retrofitting

4.7.1 RGRB: Retrofitted Glass Reinforced Beams

The maximum load taken by the retrofitted glass beams (RGRB1, RGRB2, RGRB3, RGRB4 and RGRB 5) with the corresponding deflection values, area under the curves showing the amount of energy dissipated by the tested beams, is shown and discussed below along other mechanical properties of all the beams including strength and stiffness values.

1. RGRB 1

The global energy dissipation capacity of RGRB1 improved significantly over GRB1. Paver energy showed a gradual rise as CFRP confinement enhanced ductility and delayed brittle failure. Crack behavior shifted from early brittle rupture to progressive flexural cracking, with CFRP wraps providing effective control. Although ultimate absorption remained lower than steel beams, the enhancement confirmed CFRP's positive influence on GFRP systems.

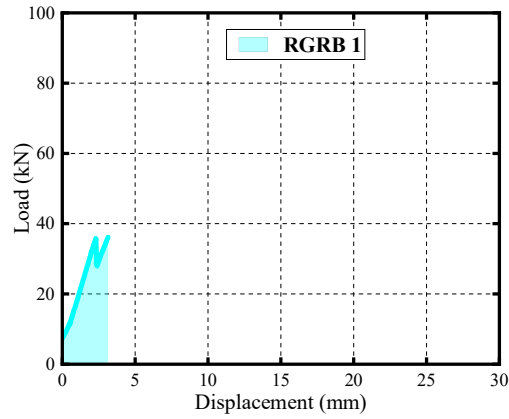
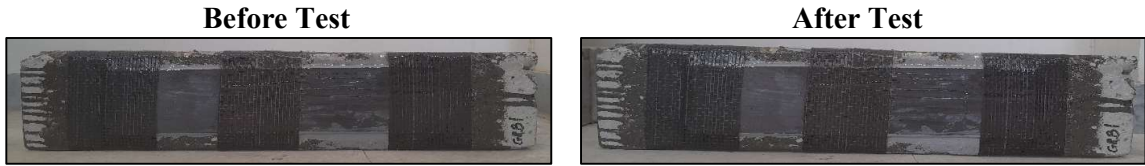


Figure # 4.7-1 Energy Dissipation Curve for RGRB 1

2. RGRB 2

RGRB2 exhibited stable energy dissipation with smoother load–deflection transitions compared to GRB2. Paver energy contribution was distributed across a wider deformation range, reflecting controlled crack development. CFRP prevented sudden stiffness loss, and cracks propagated as flexural lines with limited widening. The beam’s toughness and resilience improved markedly under CFRP strengthening.



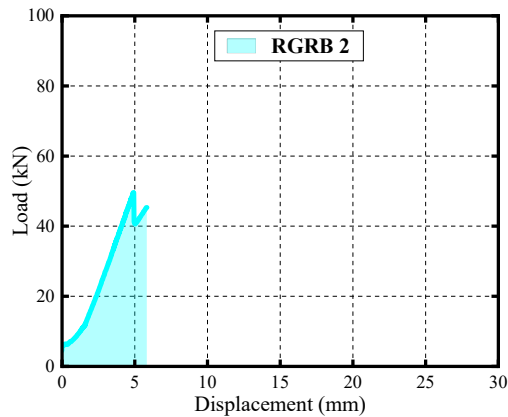


Figure # 4.7-2 Energy Dissipation Curve for RGRB 2

3. RGRB 3

The global energy dissipation curve for RGRB3 indicates increased absorbed energy and extended ductility compared to the non-retrofitted GFRP beam. Paver energy showed consistent growth throughout deformation, reflecting gradual energy release. Crack behavior transitioned from early brittle shear cracks to a controlled flexural pattern due to CFRP strengthening. This ensured more stable performance under loading.

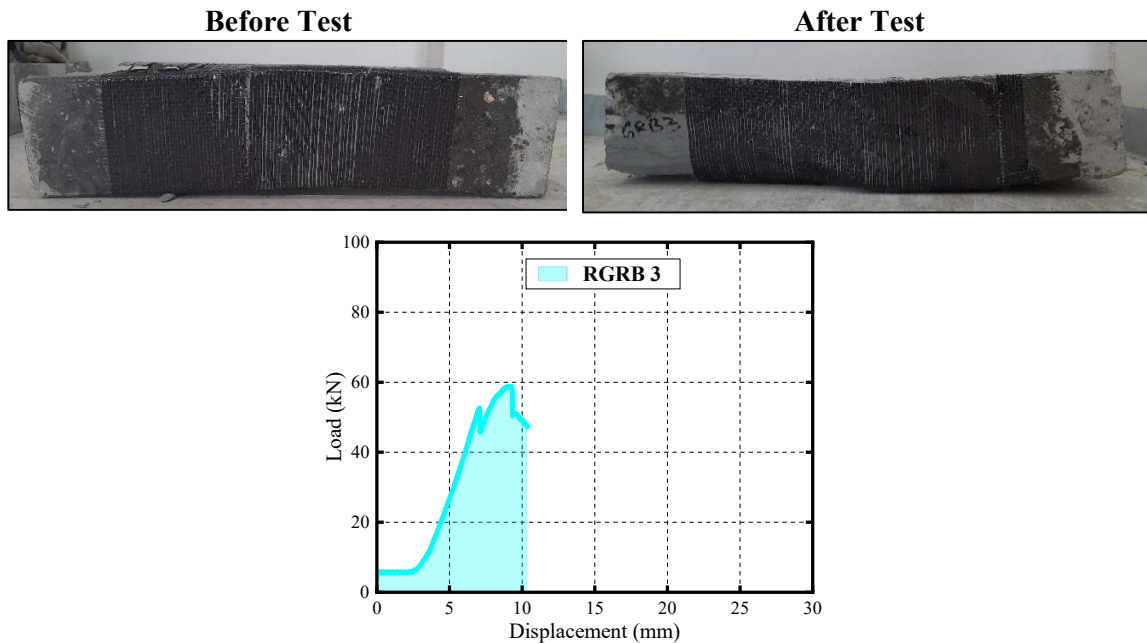


Figure # 4.7-3 Energy Dissipation Curves for RGRB3

4. RGRB 4

RGRB4 demonstrated balanced global energy dissipation with sustained deformation capacity. Paver energy accumulation was gradual, reflecting stable crack propagation. Cracks initiated as fine flexural cracks at the bottom fiber and remained distributed across the span, with CFRP restricting sudden widening. The specimen showed ductile performance compared to its brittle non-retrofitted counterpart.

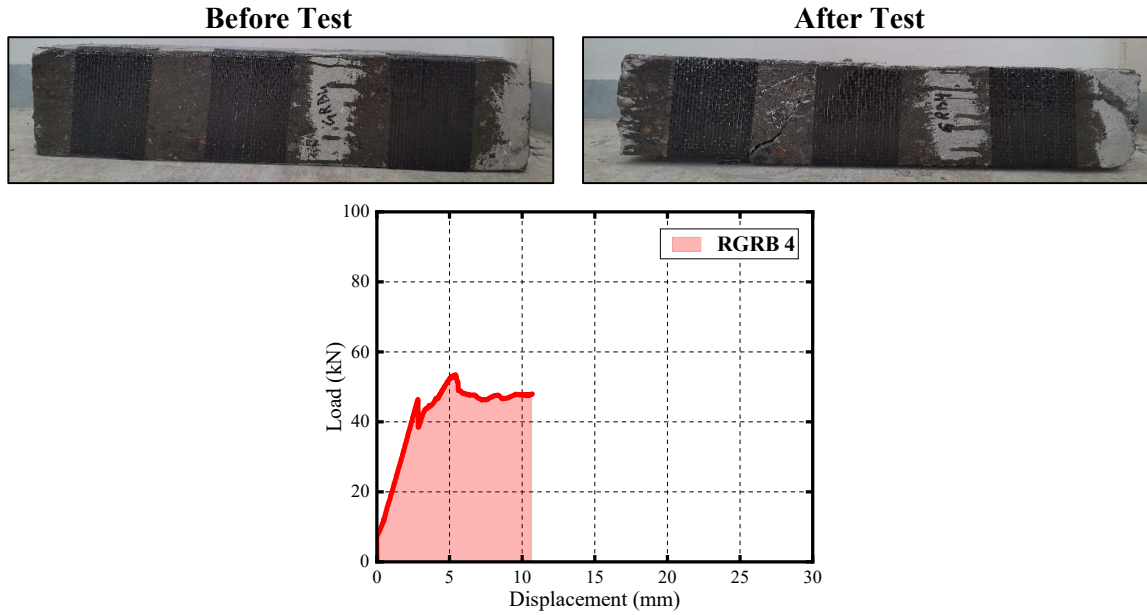


Figure # 4.7-4 Energy Dissipation Curve for RGRB 4

5. RGRB 5

RGRB5 achieved the highest global energy dissipation among GFRP retrofitted beams. The paver energy curve indicated steady and prolonged absorption, while crack behaviors showed progressive widening of flexural cracks without premature shear failure. CFRP effectively enhanced ductility and energy absorption, transforming an otherwise brittle beam into a tougher, more resilient system.



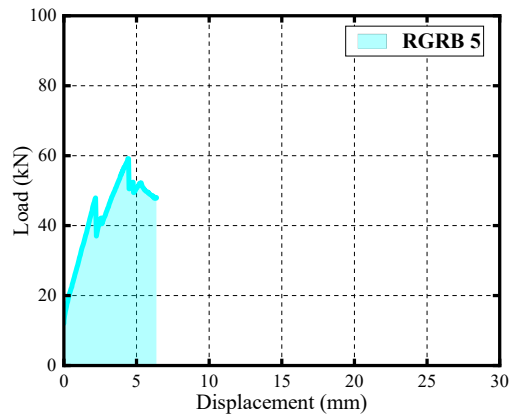


Figure # 4.7-5 Energy Dissipation Curve for RGRB 5

4.7.2 RSRB: Retrofitted Steel Reinforced Beams

The maximum load taken by the retrofitted steel beams (RSRB1, RSRB2, RSRB3, RSRB4 and RSRB 5) with the corresponding deflection values, area under the curves showing the amount of energy dissipated by the tested beams, is shown and discussed below along other mechanical properties of all the beams including strength, stiffness values.

1. RSRB 1

The global energy dissipation of RSRB1 is evident from the broad shaded area under the load–deflection curve, highlighting a significant ability to absorb strain energy throughout deformation. The paver energy contribution increased steadily, reflecting progressive crack development rather than sudden failure. Micro-cracks initiated early at the mid-span and propagated in a controlled manner, with CFRP confinement preventing abrupt widening. Flexural cracks dominated the failure mode, indicating ductile performance and confirming CFRP’s effectiveness in enhancing toughness.



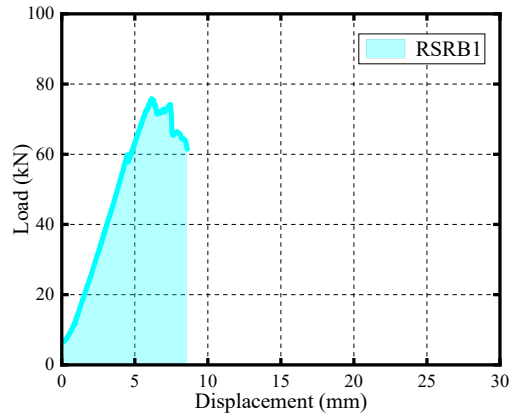


Figure # 4.7-6 Energy Dissipation Curves for RSRB 1

2. RSRB 2

RSRB2 exhibited stable global energy dissipation, with an extended deformation range before ultimate collapse. Paver energy rose gradually, showing effective energy release as cracks multiplied across the span. Crack behavior remained controlled, with CFRP delaying the onset of shear cracks and ensuring flexural behavior dominated. Compared to SRB2, this specimen demonstrated improved ductility and resilience under cyclic loading.

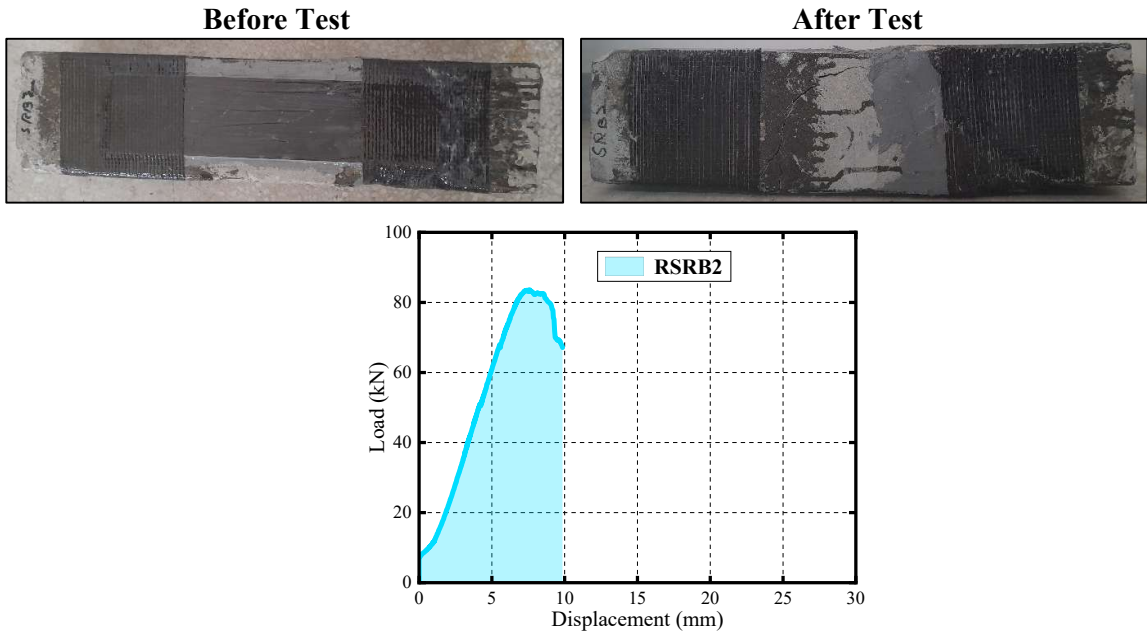


Figure # 4.7-7 Energy Dissipation Curves for RSRB 2

3. RSRB 3

The dissipation curve for RSRB3 illustrates higher global energy absorption compared to its unstrengthen counterpart. Paver energy distribution was uniform, showing a steady rise across the load history. Cracks initiated as fine flexural lines at the tension face, later merging into wider cracks, but the CFRP reinforcement prevented premature debonding and localized shear cracking. This behaviour highlights the role of CFRP in prolonging deformation capacity while reducing brittleness.

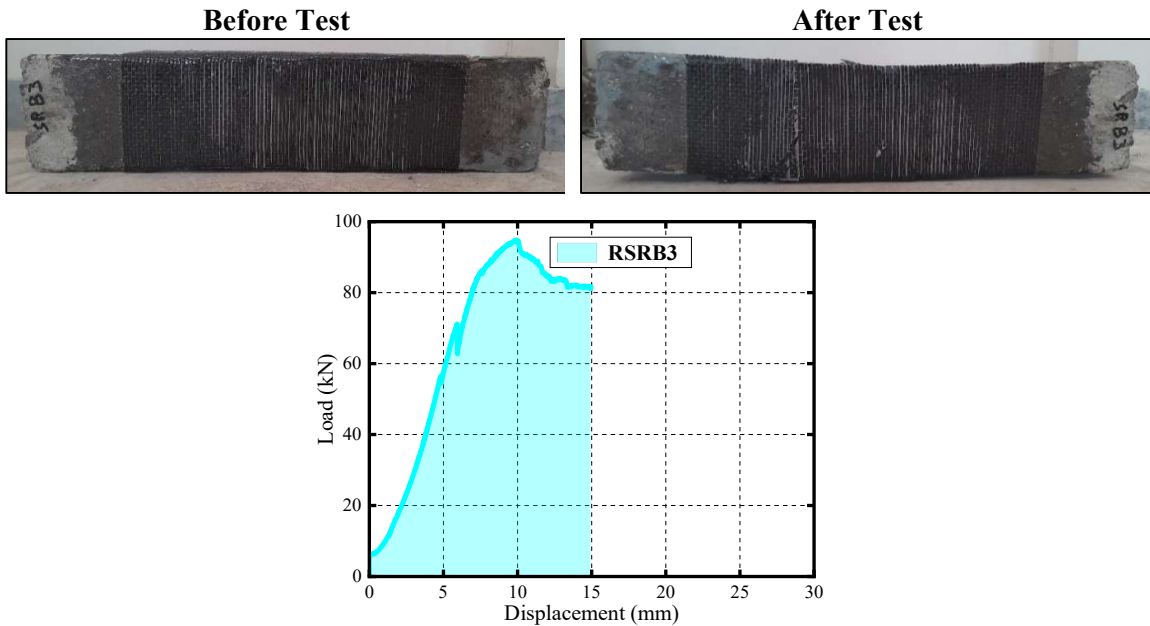


Figure # 4.7-8 Energy Dissipation Curves for RSRB 3

4. RSRB 4

RSRB4 sustained a large deflection capacity with significant global energy dissipation. Paver energy accumulation remained consistent, as CFRP strips bridged cracks and transferred stresses evenly. Crack propagation occurred gradually, with flexural cracks dominating while shear cracks remained limited. This balanced behaviour indicates improved ductility and toughness, reflecting CFRP's role in redistributing stresses and preventing sudden rupture.



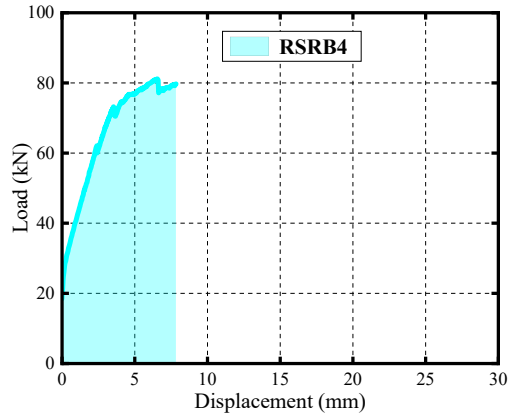


Figure # 4.7-9 Energy Dissipation Curves for RSRB 4

5. RSRB 5

RSRB5 displayed the highest toughness among the retrofitted steel beams. The global energy dissipation curve had the largest area, indicating sustained energy absorption throughout deformation. Paver energy contribution was gradual, with no abrupt release, reflecting stable crack progression. Cracks initiated as hairline flexural cracks, later widening moderately under load, while shear cracks were effectively suppressed. This progressive damage mechanism demonstrates CFRP’s ability to transform brittle failure into ductile behavior.

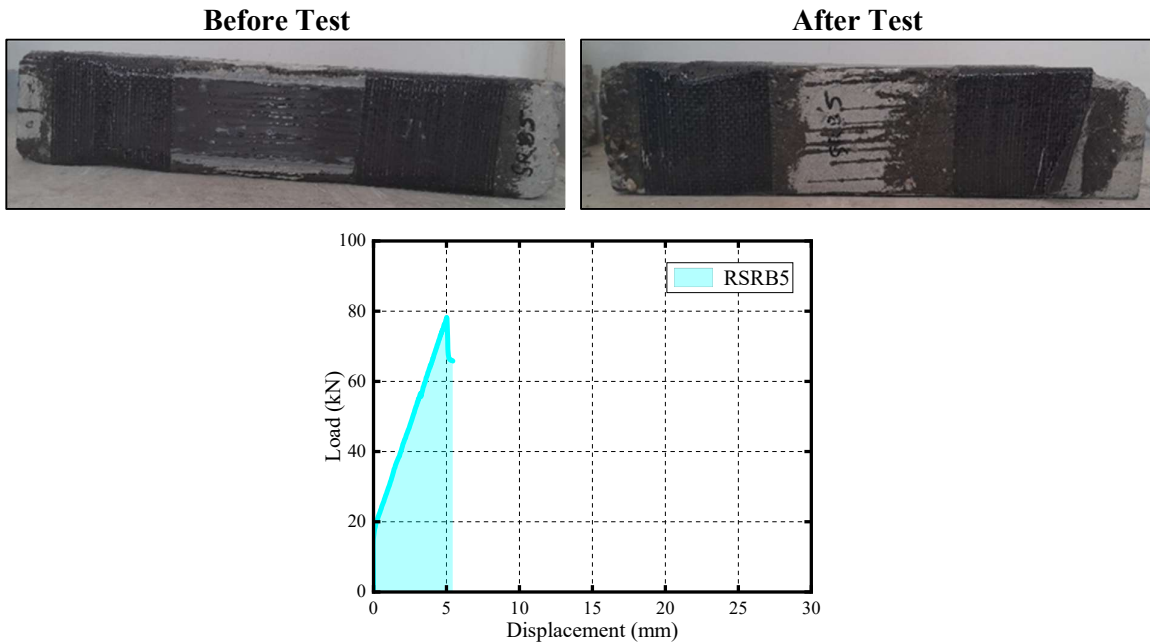


Figure # 4.7-10 Energy Dissipation Curves for RSRB 5

6. RGRBV

The maximum load taken by the RGRBV 1 and RGRBV 2 with the corresponding deflection values, area under the curves shows the amount of energy dissipated by the tested beams, as shown and discussed below along other mechanical properties of all the beams including strength, stiffness values.

7. RGRBV 1

The global energy dissipation of RGRBV1 was moderate, as shown by the shaded area under the load–deflection curve. The beam absorbed a fair amount of strain energy but remained less efficient compared to steel retrofitted beams. Paver energy contribution increased gradually during the early loading phase but declined rapidly after reaching peak load, reflecting limited energy sustainability. Crack behavior indicated a brittle tendency. Flexural cracks formed early in the tension zone and propagated quickly with restricted distribution across the span. Although CFRP retrofitting delayed stiffness loss to some extent, the cracks widened abruptly after peak load. The overall response of RGRBV1 demonstrates that while CFRP improved ductility and toughness compared to non-retrofitted GFRP beams, its performance remained below that of retrofitted steel beams.

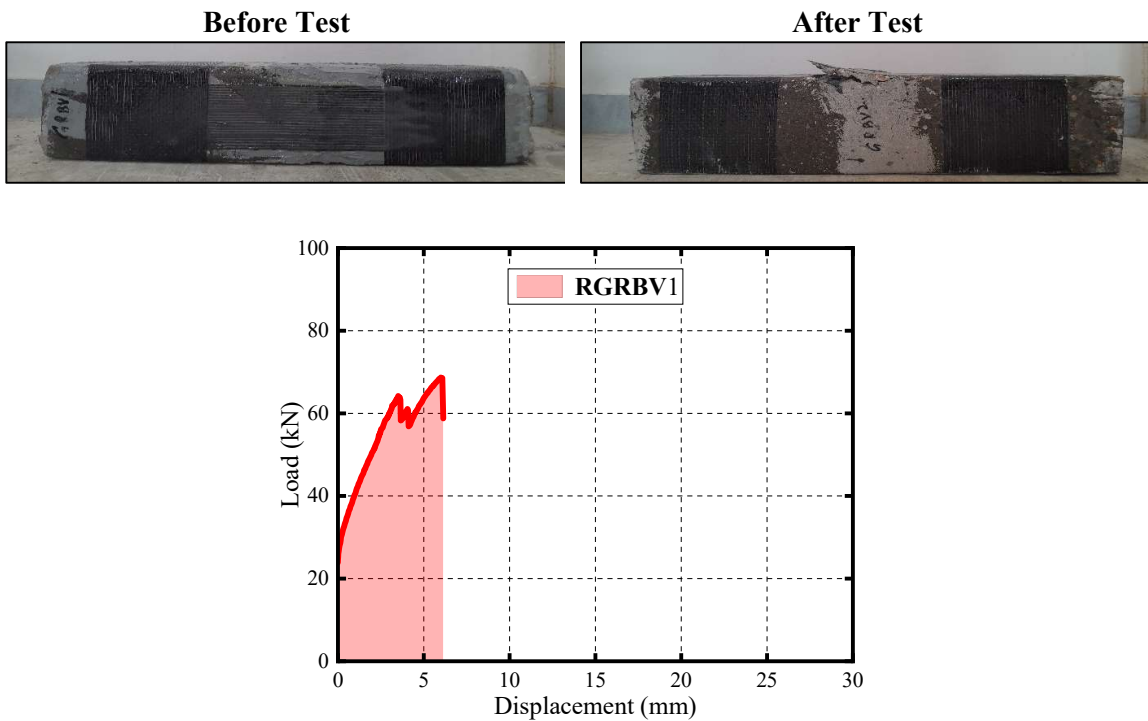


Figure # 4.7-11 Energy Dissipation Curves for RGRBV 1

8. RGRBV2

The global energy dissipation of RGRBV2 was limited, as indicated by the small shaded area under the load–displacement curve. The beam absorbed only a modest amount of strain energy, showing low toughness and ductility compared to steel retrofitted beams. Paver energy contribution was concentrated in the early loading stage and dropped quickly after peak load, reflecting weak ability to sustain energy release. Crack behavior was brittle. Flexural cracks initiated early and propagated rapidly without spreading across the span. Although CFRP retrofitting delayed failure to some extent, the cracks widened suddenly and led to stiffness degradation. The overall response of RGRBV2 confirms that while CFRP improved performance compared to non-retrofitted GFRP beams, the improvement remained modest, with the beam retaining brittle characteristics.

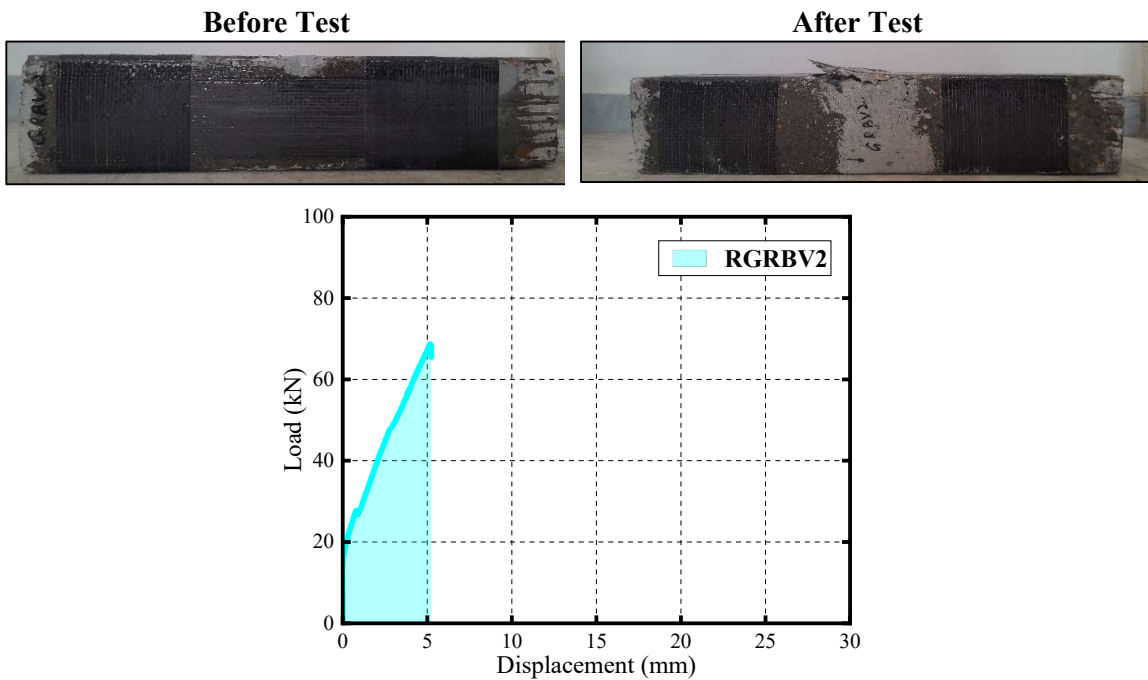


Figure # 4.7-12 Energy Dissipation Curves for RGRBV 2

9. RSRBV

The maximum load taken by the RSRBV beams with the corresponding deflection values, area under the curves showing the amount of energy dissipated by the tested beams, as shown and discussed below along other mechanical properties of all the beams including strength and stiffness values.

10. RSRBV 1

The global energy dissipation of RSRBV1 was considerable, as reflected by the broad shaded area under its load–displacement curve. The beam absorbed a large amount of strain energy across its deformation range, showing improved toughness and ductility. Paver energy increased gradually with loading and was sustained until peak displacement, reflecting stable and efficient energy release. Crack behavior was ductile, with fine flexural cracks forming first at the tension zone. These widened progressively under load, while CFRP confinement restrained shear cracks and prevented sudden brittle rupture. The overall response of RSRBV1 highlights the effectiveness of CFRP in enhancing toughness, extending deformation capacity, and ensuring controlled crack progression in retrofitted steel beams.

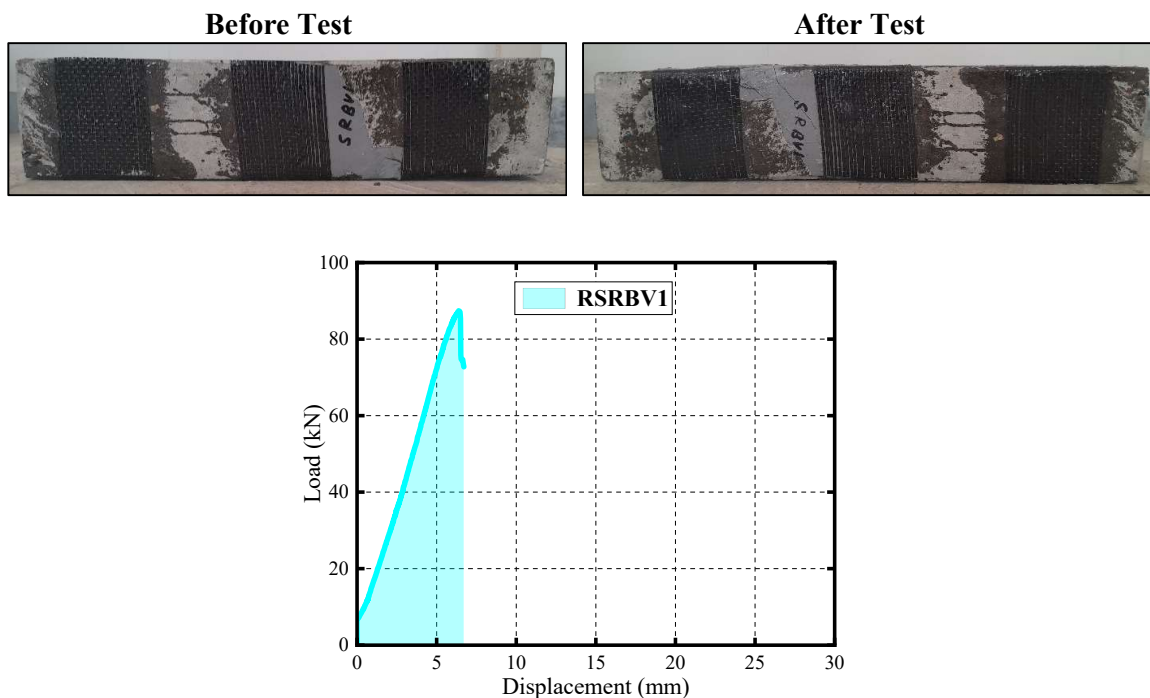


Figure # 4.7-13 Energy Dissipation Curves for RSRBV 1

11. RSRBV 2

The global energy dissipation of RSRBV2 was considerable, as indicated by the shaded area under its load–displacement curve. The beam absorbed a high amount of strain energy within a moderate deformation range, reflecting improved toughness and ductility compared to non-retrofitted steel beams. Paver energy contribution increased steadily with loading, showing controlled energy absorption and delayed stiffness loss.

Crack behaviour was ductile, with initial flexural cracks forming gradually at the tension zone and widening under load. CFRP confinement effectively restrained rapid propagation of shear cracks and prevented brittle rupture. The overall response of RSRBV2 highlights the enhanced stability, toughness, and controlled crack progression achieved through CFRP retrofitting.

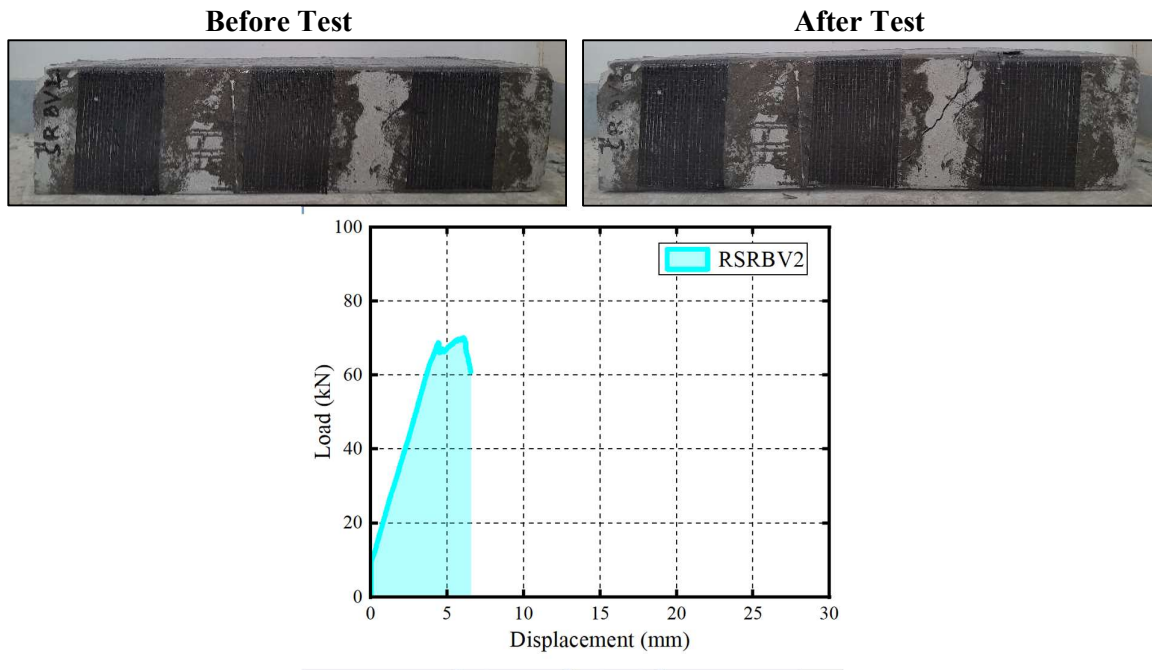


Figure # 4.7-14 Energy Dissipation Curves for RSRBV 2

4.8 Comparison between Retrofitted and Non-Retrofitted Steel Reinforced Beams (RSRB vs SRB)

The non-retrofitted beams (SRB 1, SRB 2, and SRB 3) were compared with retrofitted beams (RSRB 1, RSRB 2, RSRB 3) as shown below;

- i. RSRB 1 vs SRB 1

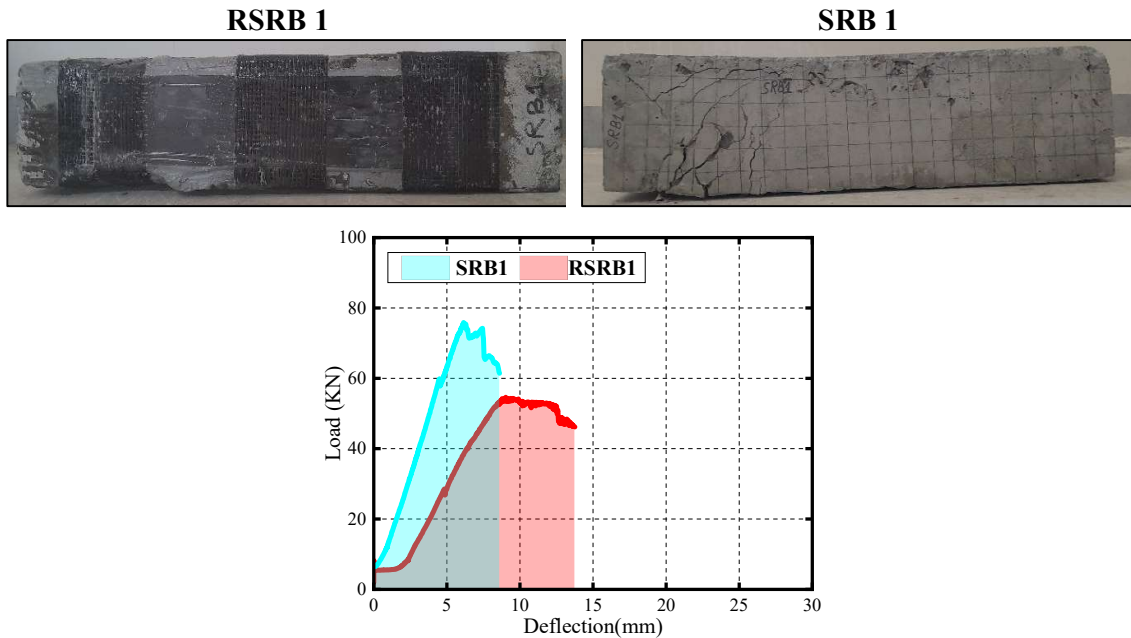


Figure # 4.8-1 Comparison between Retrofitted Steel Reinforced Beam and Steel Reinforced Beam (RSRB 1 vs SRB 1)

Characteristics and Key findings of RSRB1 and SRB1 are given below;

- **Initial Stiffness:** Both beams exhibit similar stiffness in the linear-elastic region; retrofitting did not significantly impact initial stiffness but influenced performance at higher loads.
- **Load-Carrying Capacity:** RSRB 1 reaches ~75kN at 6 mm deflection, a 25% increase over SRB 1 (~60kN at 10 mm), and demonstrating enhanced load capacity.
- **Ductility:** SRB 1 shows greater deflection, making it more effective in absorbing and distributing energy under load. RSRB 1 exhibits a steeper rise but plateaus earlier.
- **Energy Dissipation:** RSRB 1 dissipated just 56% energy compared to SRB 1, as indicated by the larger area under the curve for SRB 1, making it better suited for different] loading. RSRB 1 retains some energy dissipation benefits post-retrofitting.
- **Failure Characteristics:** SRB 1 steadily gains load until failure, while RSRB 1 reaches peak load quickly and plateaus, altering failure behavior.

ii. RSRB 2 vs SRB 2

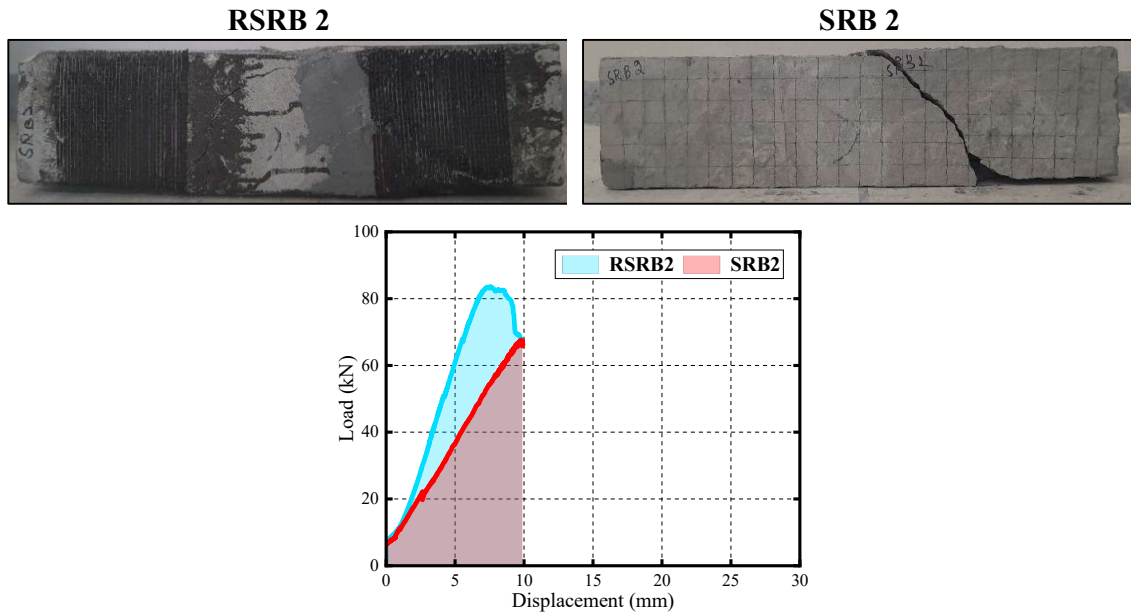


Figure # 4.8-2 Comparison between Retrofitted Steel Reinforced Beam and Steel Reinforced Beam (RSRB 2 vs SRB 2)

Characteristics and Key findings of RSRB2 and SRB2 are given below

- **Initial Stiffness:** Both beams exhibit similar stiffness in the linear-elastic region; retrofitting did not significantly impact initial stiffness but influenced performance at higher loads.
- **Load-Carrying Capacity:** RSRB 2 reaches ~83kN at 7 mm deflection, a 20.29% increase over SRB 2 (~69kN at 16 mm), and demonstrating enhanced load capacity.
- **Ductility:** SRB 2 shows greater deflection, making it more effective in absorbing and distributing energy under load. RSRB 2 exhibits a steeper rise but plateaus earlier.
- **Energy Dissipation:** RSRB 2 dissipates just 35% energy compared to SRB 2 after retrofitting, as indicated by the larger area under the curve for SRB 2. RSRB 2 retains some energy dissipation benefits post-retrofitting.
- **Failure Characteristics:** SRB 2 steadily gains load until failure, while RSRB 2 reaches peak load quickly and plateaus, altering failure behavior.

iii. **RSRB 3 vs SRB 3**

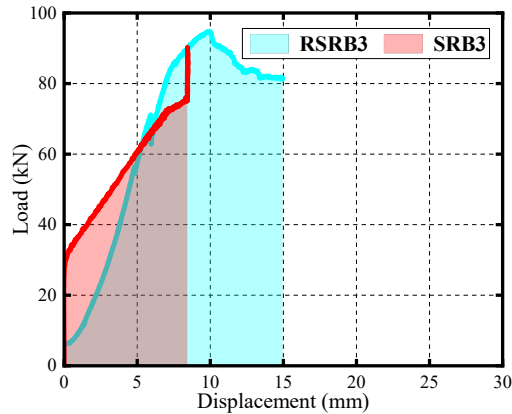


Figure # 4.8-3 Comparison between Retrofitted Steel Reinforced Beam and Steel Reinforced Beam (RSRB 3 vs SRB 3)

Characteristics and Key findings of RSRB3 and SRB3 are given below

- **Initial Stiffness:** RSRB 3 has a higher initial slope than SRB 3, indicating greater stiffness and better resistance to small-load deflection.
- **Load-Carrying Capacity:** RSRB 3 reaches ~80kN, a 166.67% increase over SRB 3 (~30kN), making it more suitable for heavy load-bearing applications.
- **Ductility:** RSRB 3 shows greater deflection before failure, enhancing its ability to absorb deformation without sudden failure.
- **Energy Dissipation:** RSRB 3 dissipates 5.57 joules more energy than SRB 3, making it ideal for more loading conditions.
- **Failure Characteristics:** RSRB 3 fails gradually, while SRB 3 experiences a sharper drop-off in load capacity, giving RSRB 3 better failure predictability and safer performance under extreme conditions.

iv. **RSRBV 1 Vs SRBV 1**

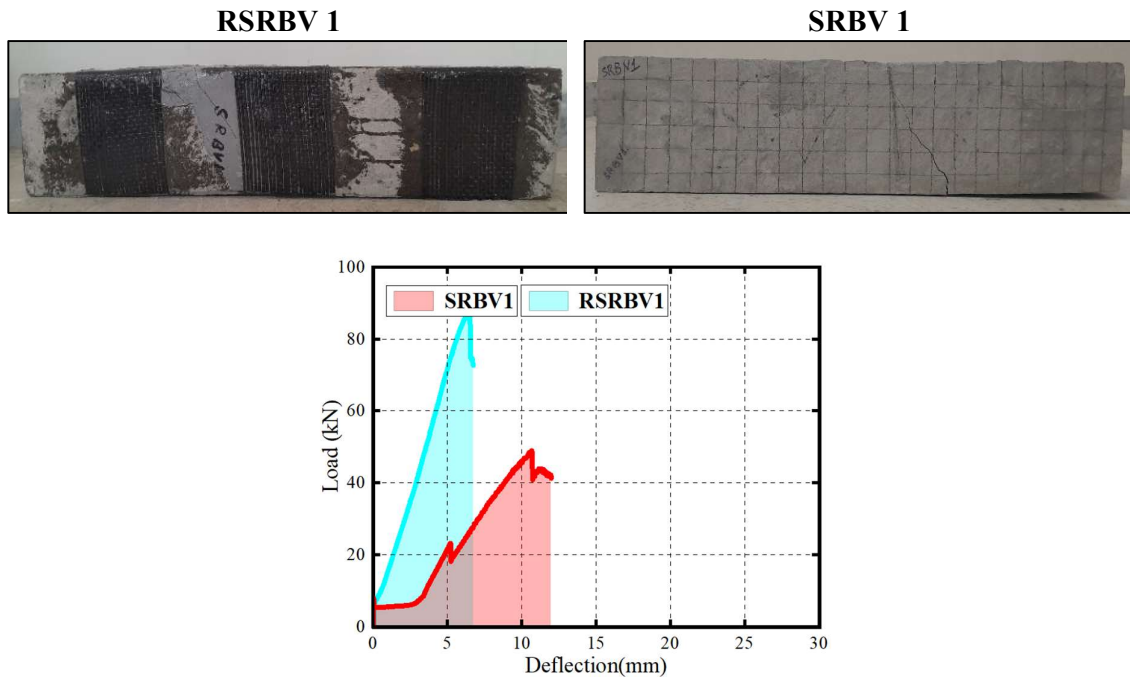


Figure # 4.8-4 Comparison between Retrofitted Steel Reinforced Beam and Steel Reinforced Beam (RSRBV 1 vs SRBV 1)

Characteristics and Key findings of RSRBV1 and SRBV1 are given below

- **Initial Stiffness:** Both beams have similar stiffness in the elastic range; retrofitted beam (RSRBV1) did not alter initial stiffness but improved high-load performance.
- **Load-Carrying Capacity:** RSRBV1 reached ~89 kN, nearly 40% higher than SRBV1 (~59 kN), demonstrating enhanced load-bearing capacity due to retrofitting.
- **Ductility:** RSRBV1 exhibited greater deflection at failure (~8 mm vs. ~6 mm for SRBV1), improving its ability to absorb and distribute energy.
- **Energy Dissipation:** RSRBV1 showed a 46% increase in energy dissipation, making it more resilient to dynamic loading conditions like earthquakes.
- **Failure Characteristics:** SRBV1 experienced brittle failure with a sharp drop in load, while RSRBV1 showed a gradual decline, indicating improved ductile behavior and controlled load redistribution.

4.9 Comparison between Retrofitted Glass Reinforced Beams with Non-retrofitted Glass Reinforced Beams (RGRB vs GRB)

The data shown in the tables given below compares the percentage of energy dissipated and provide the detailed characteristics analysis between retrofitted glass-reinforced beams (RGRB 1, RGRB 2, and RGRB 3) and their corresponding control glass-reinforced beams (GRB 1, GRB 2 and GRB 3). The analysis demonstrates the significant impact of retrofitting on the performance of beams. The retrofitting improves load-carrying capacity, energy dissipation and ductility. These enhancements ensure better structural resilience under static loading conditions.

i. RGRB 1 vs GRB 1

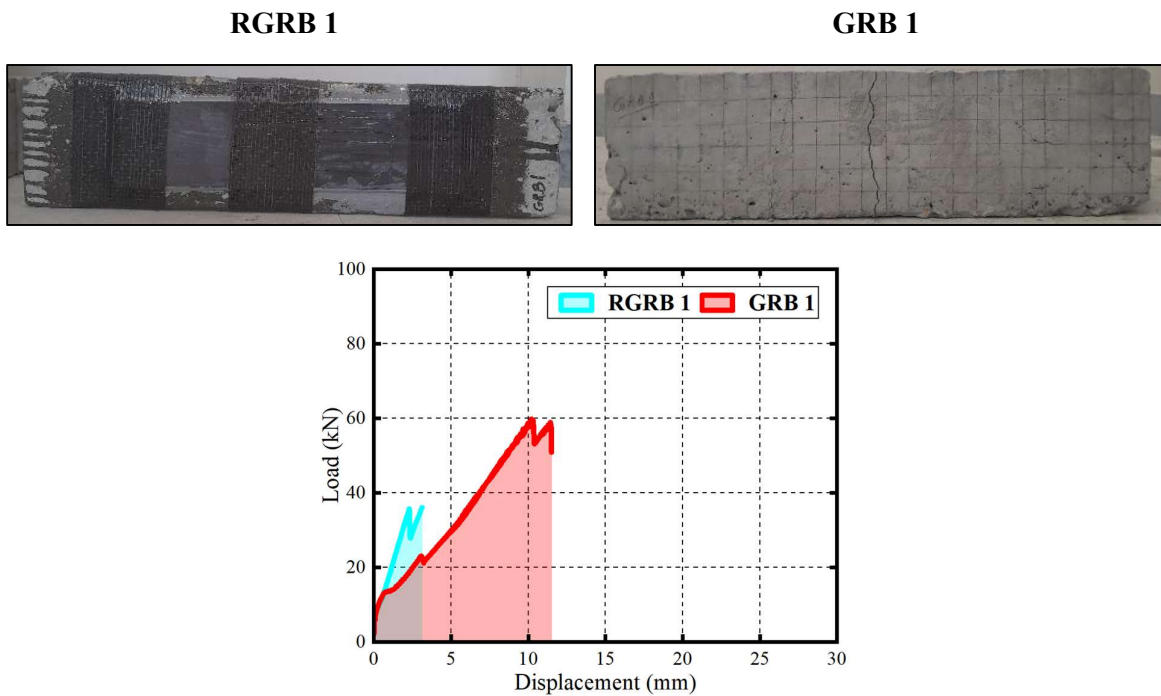


Figure # 4.9-1 Comparison between Glass Non-Retrofitted Beam and Glass Retrofitted Beam (RGRB 1 vs GRB 1)

Characteristics and Key findings of RGRB1 and GRB1 are given below

- **Initial Stiffness:** Both beams exhibit similar stiffness in the elastic range; RGRB1 did not significantly alter initial stiffness but impacted performance at higher loads.

- **Load-Carrying Capacity:** GRB1 reached ~60 kN at ~11 mm deflection, while RGRB1 reached ~38 kN at ~2.5 mm, showing a 36.67% decrease in load capacity after retrofitting.
- **Ductility:** GRB1 displayed a longer deflection range, while RGRB1 plateaued earlier, indicating GRB1 is more ductile and better at absorbing energy under load.
- **Energy Dissipation:** RGRB1 dissipated only 15% of the energy compared to GRB1, making GRB1 more suitable for applications requiring high energy absorption (e.g., seismic conditions).
- **Failure Characteristics:** GRB1 showed a steady increase in load until failure, whereas RGRB1 failed more quickly, suggesting that retrofitting affected the failure mechanism.

ii. **RGRB 2 vs GRB 2**

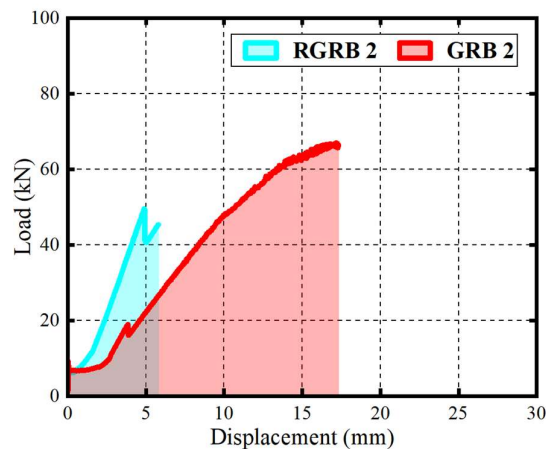


Figure # 4.9-2 Comparison between Glass Non-Retrofitted Beam and Glass Retrofitted Beam (RGRB 2 vs GRB 2)

Characteristics and Key findings of RGRB2 and GRB2 are given below

- **Initial Stiffness:** Both beams exhibit similar stiffness in the elastic range; retrofitting (RGRB2) did not significantly alter initial stiffness but impacted performance at higher loads.
- **Load-Carrying Capacity:** GRB2 reached ~70 kN at ~17 mm deflection, while RGRB2 reached ~50 kN at ~7 mm, showing a 28.57% decrease in load capacity after retrofitting.
- **Ductility:** GRB2 displayed a longer deflection range, while RGRB2 plateaued earlier, indicating GRB2 is more ductile and better at absorbing energy under load.
- **Energy Dissipation:** RGRB2 dissipated only 18% of the energy compared to GRB2, making GRB2 more suitable for applications requiring high energy absorption (e.g., seismic conditions).
- **Failure Characteristics:** GRB2 showed a steady increase in load until failure, whereas RGRB2 failed more quickly, suggesting retrofitting altered the failure mechanism.

iii. **RGRB 3 vs GRB 3**

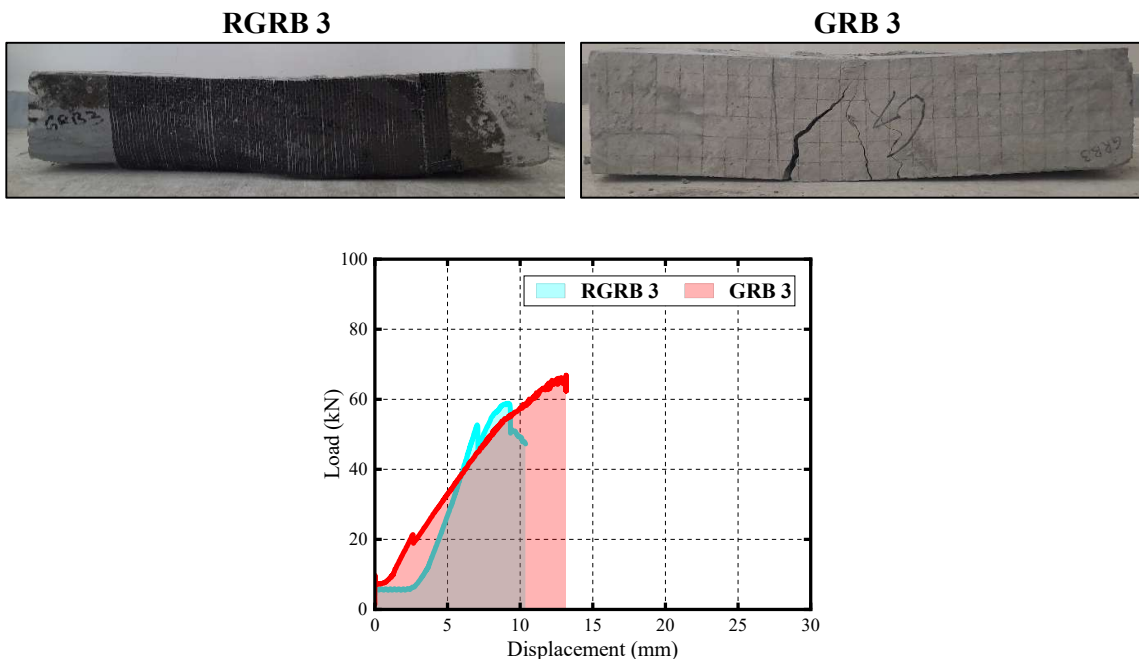


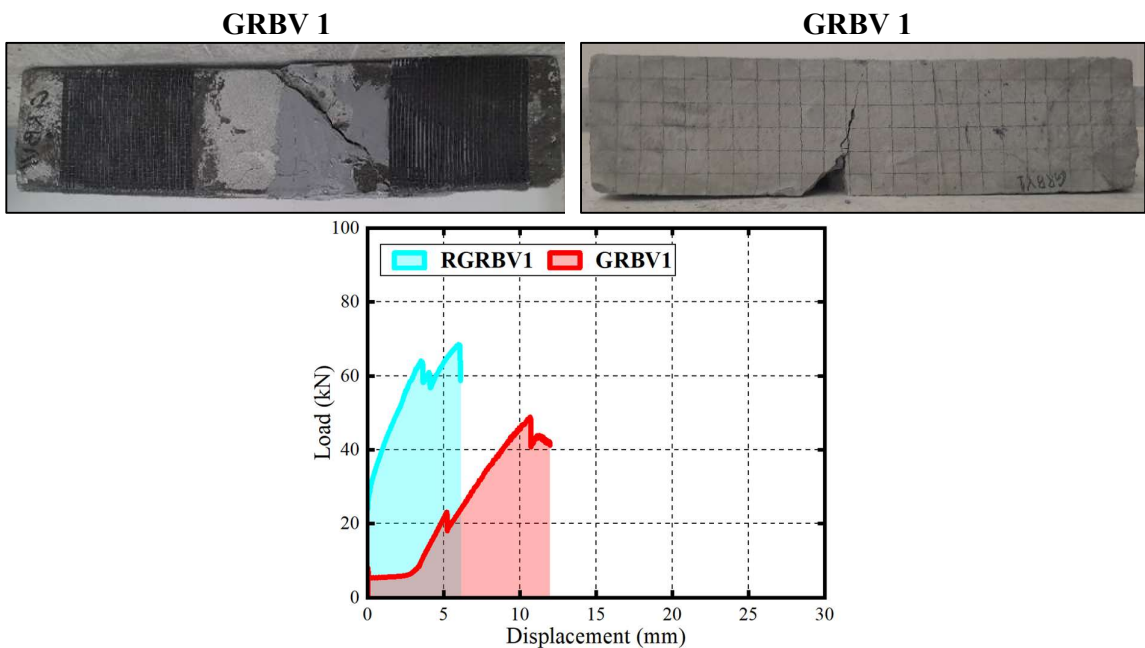
Figure # 4.9-3 Energy Dissipation Curves for RSRB 4 Comparison between Glass Non-Retrofitted Beam and Glass Retrofitted Beam (RGRB 3 vs GRB 3)

Characteristics and Key findings of RGRB 3 and GRB 3 are given below

- **Initial Stiffness:** Both beams exhibit similar stiffness in the elastic range; RGRB3 did not significantly alter initial stiffness but impacted performance at higher loads.
- **Load-Carrying Capacity:** GRB3 reached ~70 kN at ~13 mm deflection, while RGRB3 reached ~55 kN at ~7 mm, showing a 21.43% decrease in load capacity after retrofitting.
- **Ductility:** GRB3 displayed a longer deflection range, while RGRB3 plateaued earlier, indicating GRB3 is more ductile and better at absorbing energy under load.
- **Energy Dissipation:** GRB3 dissipated 253% more energy compared to RGRB3, making GRB3 more suitable for applications requiring high energy absorption (e.g., seismic conditions).
- **Failure Characteristics:** GRB3 showed a steady increase in load until failure, whereas RGRB3 failed more quickly, suggesting retrofitting altered the failure mechanism.

iv. **RGRBV 1 vs GRBV 1**

The non-retrofitted beams (GRBV1) was compared with retrofitted beams (RGRBV 1) as shown below;



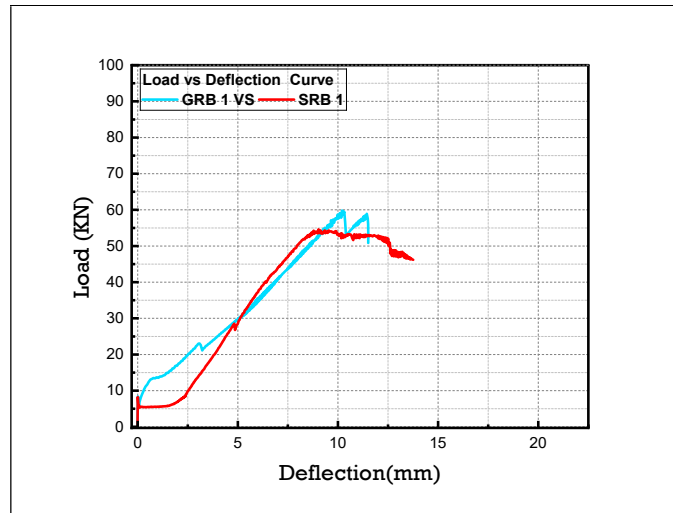
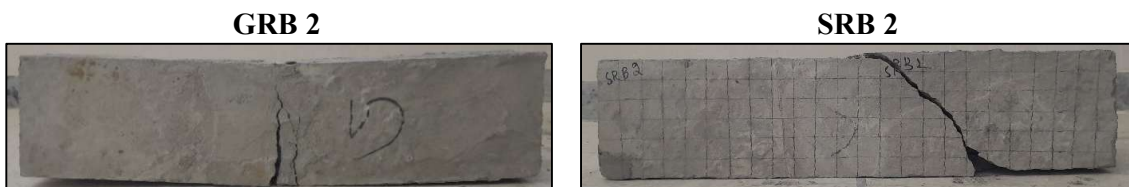


Figure # 4.10-1 Comparison between Non-Retrofitted Beam and Retrofitted Beam (GRB 1 vs SRB 1)

Characteristics and Key findings of SRB1 and GRB1 are given below

- **Initial Stiffness:** Both beams show similar initial stiffness, with retrofitting in SRB 1 not significantly affecting the stiffness under small loads but impacting its performance at higher loads.
- **Load-Carrying Capacity:** GRB 1 reaches 59 kN at 11 mm deflection, outperforming SRB 1 (55 kN at 10 mm), showing a 6.78% higher load capacity for SRB 1.
- **Ductility:** GRB 1 shows greater ductility, enabling better energy absorption and distribution before failure, while SRB 1 shows a quicker initial rise in load with deflection but maintains the load without further significant increase until failure.
- **Energy Dissipation:** GRB 1 dissipates just 32% energy compared to SRB 1, as shown by the larger area under the curve for GRB 1.
- **Failure Characteristics:** GRB 1 fails progressively, while SRB 1 reaches its peak load early and fails sooner, indicating a different failure mechanism

vi. **GRB 2 vs SRB 2**



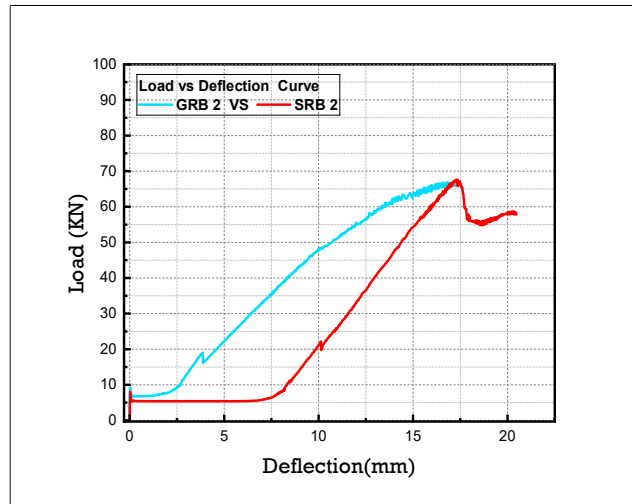
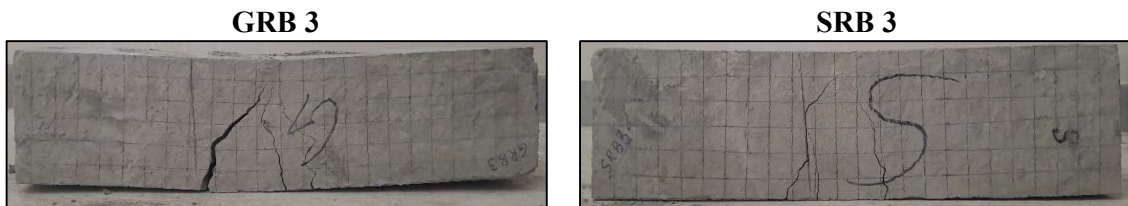


Figure # 4.10-2 Comparison between Non-Retrofitted Beam and Retrofitted Beam (GRB 2 vs SRB 2)

Characteristics and Key findings of SRB2 and GRB2 are given below

- **Initial Stiffness:** Both beams show similar stiffness, with retrofitting in SRB 2 not significantly affecting its initial stiffness.
- **Load-Carrying Capacity:** GRB 2 and SRB 2 both reach a peak load of 68 kN at 17 mm deflection, but GRB 2 achieves this at a lower deflection, indicating stronger performance.
- **Ductility:** GRB 2 demonstrates better ductility with larger deflection, whereas SRB 2 stabilizes at a lower deflection and shows more brittle behavior.
- **Energy Dissipation:** GRB 2 dissipated just 63% energy as compared to SRB 2, as evidenced by the areas under the curves, showing SRB 2 more suitable for structures subjected to forces like earthquakes.
- **Failure Characteristics:** GRB 2 gradually increases its load until failure, while SRB 2 quickly reaches its peak load, failing sooner.

vii. **GRB 3 vs SRB 3**



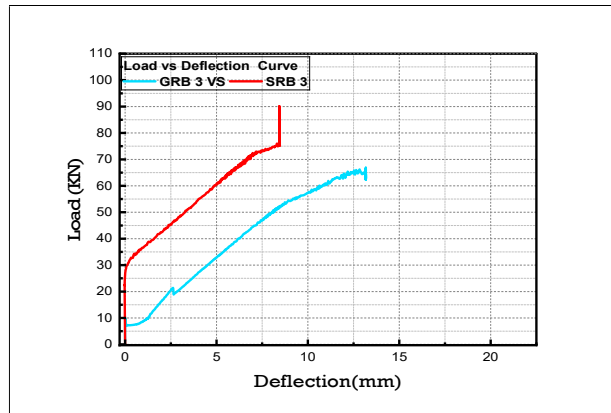


Figure # 4.10-3 Comparison between Non-Retrofitted Beam and Retrofitted Beam (GRB 3 vs SRB 3)
 Characteristics and Key findings of SRB3 and GRB3 are given below

- **Initial Stiffness:** Both beams exhibit similar stiffness in the initial region, with retrofitting in SRB 3 not significantly altering its stiffness but affecting performance at higher loads.
- **Load-Carrying Capacity:** SRB 3 reaches a higher load (75 kN) at around 8 mm deflection compared to GRB 3 (66 kN at 13 mm). SRB 3 has a Load Capacity Percentage of approximately 113.64% and a Percentage Increase of approximately 13.64%. However, SRB 3's post-peak behavior differs with a sharp drop.
- **Ductility:** GRB 3 demonstrates better ductility with a larger deflection range, while SRB 3 stabilizes after a quick load increase, indicating a more brittle behavior.
- **Energy Dissipation:** GRB 3 dissipated just 87% energy compared to SRB 3, indicating GRB 3's lower ability to absorb energy, as observed from the area under the curves.
- **Failure Characteristics:** GRB 3 shows a steady increase in load until failure, whereas SRB 3 reaches its peak load earlier and maintains it until failure, indicating quicker failure post-peak for SRB 3.

4.11 Comparison between Retrofitted Steel reinforced beams and GFRP reinforced Beams

The steel retrofitted beams (RSRBV 1 and RSRBV 2) were compared with GFRP retrofitted beams (RGRBV 1 and RGRBV 2) as shown below;

i. RSRBV 1 Vs RGRBV 1

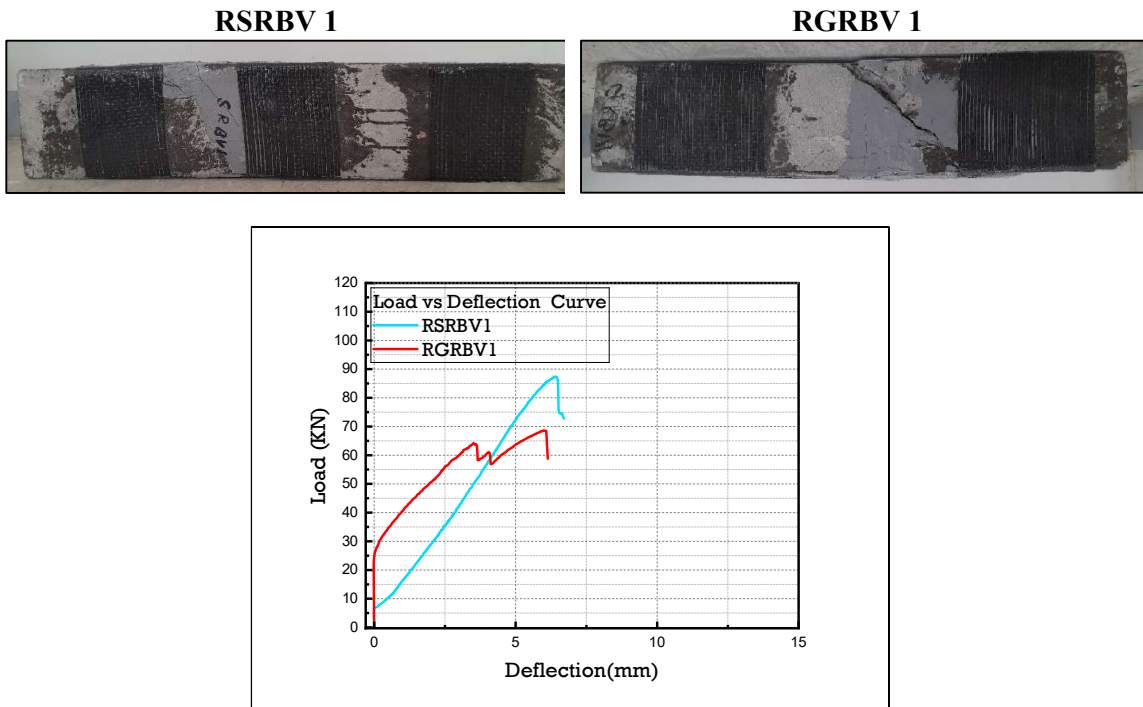


Figure # 4.11-1 Comparison between Steel reinforced beams and GFRP reinforced Beams (RGRBV 1 vs RSRBV 1)

Characteristics and Key findings of RSRBV1 and RGRBV1 are given below

- **Initial Stiffness:** Both beams exhibited similar initial slopes in the linear-elastic region, indicating comparable stiffness under smaller loads. The retrofitting did not significantly affect the initial stiffness but influenced performance under higher loads for both beams.
- **Load-Carrying Capacity:** RGRBV 1 reached a peak load of approximately 70 kN at 6 mm deflection, while RSRBV 1 achieved a higher peak load of 88 kN at 6.5 mm deflection. RSRBV 1 demonstrated a 28.6% increase in load capacity; its Load Capacity Percentage was approximately 125.71%, reflecting a 27.54% improvement in load resistance due to retrofitting.
- **Ductility:** RGRBV 1 exhibited a larger range of deflection, whereas RSRBV 1 showed a quicker rise in load but maintained that load until failure, indicating a more brittle failure compared to RGRBV 1.

- **Energy Dissipation:** RSRBV 1 dissipated 4% more energy compared to RGRBV 1, indicating that RSRBV 1 absorbed and dissipated more energy, making it more effective for dynamic load conditions, as indicated by the smaller area under the curve for RGRBV 1.
- **Failure Characteristics:** RGRBV 1 steadily increased in load until failure, while RSRBV 1 reached its maximum load earlier and maintained it until failure, showing a quicker failure due to retrofitting.

ii. **RSRBV 2 Vs RGRBV 2**

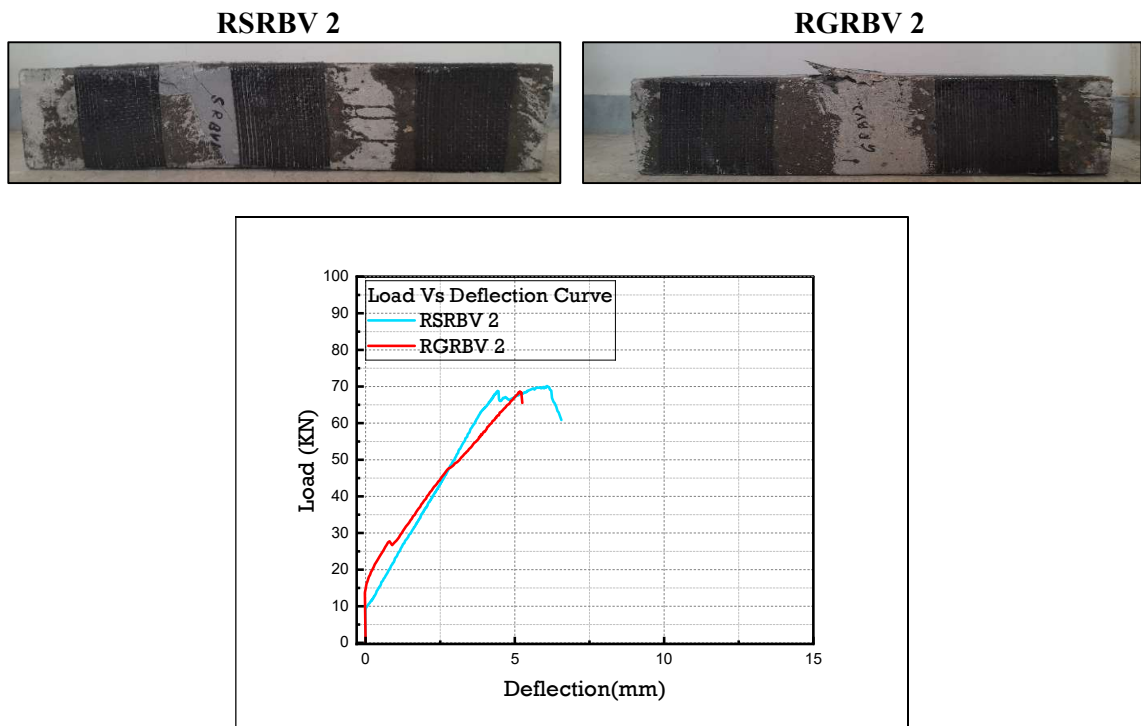


Figure # 4.11-2 Comparison between Steel reinforced beams and GFRP reinforced Beams (RGRBV 2 vs RSRBV 2)

Characteristics and Key findings of RSRBV2 and RGRBV2 are given below

- **Initial Stiffness:** Both beams showed similar initial slopes in the linear-elastic region, indicating comparable stiffness under smaller loads. The retrofitting in both beams did not significantly affect the initial stiffness but influenced performance under higher loads.
- **Load-Carrying Capacity:** RGRBV 2 reached a peak load of approximately 66 kN at 5 mm deflection, whereas RSRBV 2 reached a slightly higher load of

70 kN at 6 mm deflection. RSRBV 2's load capacity is approximately 6.06% higher than RGRBV 2, demonstrating the effectiveness of retrofitting in enhancing load capacity.

- **Ductility:** RGRBV 2 exhibited a larger deflection range, while RSRBV 2 showed a quicker initial rise in load and maintained that load until failure, indicating more brittle behavior compared to RGRBV 2.
- **Energy Dissipation:** RGRBV 2 dissipated 27% less energy compared to RSRBV 2, indicating that RGRBV 2 absorbed and dissipated less energy, making it less effective for structures exposed to dynamic loads.
- **Failure Characteristics:** RGRBV 2 steadily increased in load until failure, while RSRBV 2 quickly reached its peak load early in the deflection process and maintained it until failure, showing a different failure mechanism due to retrofitting

4.12 Comparison between Retrofitted GFRP Reinforced Beams with Retrofitted Steel Reinforced Beams (RGRB vs RSRB)

The retrofitted glass retrofitted beams (RGRB 1, RGRB 2, RGRB 3, RGRB 4 and RGRB 5) were compared with retrofitted steel retrofitted beams (RSRB 1, RSRB 2, RSRB 3, RSRB 4 and RSRB 5) as shown below;

i. RGRB 1 vs RSRB 1



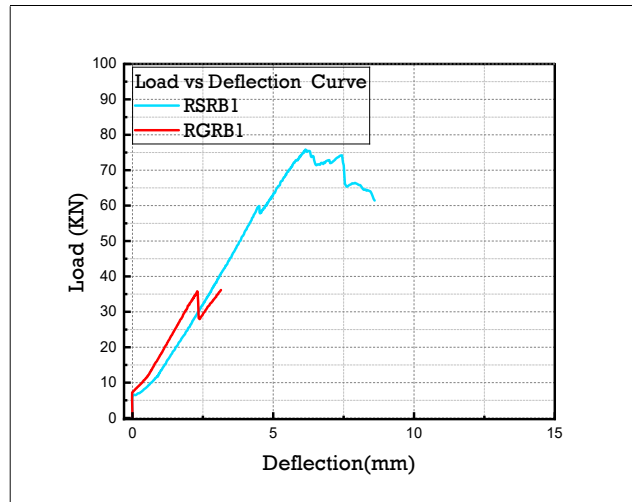


Figure # 4.12-1 Comparison between Steel reinforced beams and GFRP reinforced Beams (RGRB 1 vs RSRB 1)

Characteristics and Key findings of RSRB1 and RGRB1 are given below

- **Initial Stiffness:** Both beams exhibited comparable stiffness in the elastic range; retrofitting did not significantly affect initial stiffness but altered high-load performance.
- **Load-Carrying Capacity:** RGRB1 reached ~36 kN at ~2.5 mm deflection, while RSRB1 achieved ~78 kN at ~6 mm, showing a 116.7% increase in load capacity due to retrofitting.
- **Ductility:** RGRB1 had a larger deflection range, while RSRB1 reached peak load quickly and maintained it until failure. RGRB1 exhibited greater ductility, making it better at energy absorption.
- **Energy Dissipation:** RGRB1 dissipated 80% less energy than RSRB1, indicating lower energy absorption, making it less effective for seismic applications.
- **Failure Characteristics:** RGRB1 showed a steady load increase until failure, while RSRB1 quickly reached peak load and maintained it. RSRB1's retrofitting led to a different failure mechanism, with a rapid load rise and sustained plateau.

ii. RGRB 2 vs RSRB 2

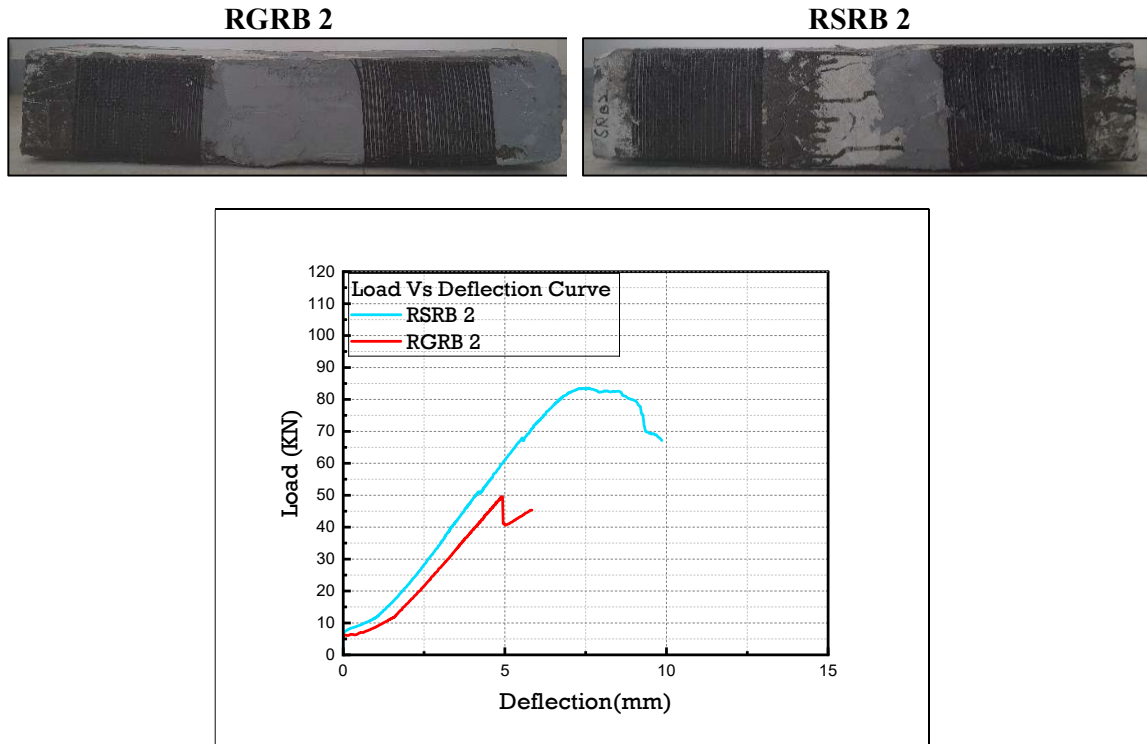


Figure # 4.12-2 Comparison between Steel reinforced beams and GFRP reinforced Beams (RGRB 2 vs RSRB 2)

Characteristics and Key findings of RSRB2 and RGRB2 are given below

- **Initial Stiffness:** Both beams exhibited comparable stiffness in the elastic range; retrofitting did not significantly impact initial stiffness but influenced performance at higher loads.
- **Load-Carrying Capacity:** RGRB2 attained ~50 kN at ~5 mm deflection, while RSRB2 achieved ~85 kN at ~7 mm, showing a 70% increase in load capacity due to retrofitting compared to RGRB2.
- **Ductility:** RGRB2 had a broader deflection range, while RSRB2 reached peak load quickly and maintained it until failure. RGRB2 exhibited greater ductility, enhancing its ability to absorb energy without sudden failure.
- **Energy Dissipation:** RGRB2 dissipated 68% less energy than RSRB2, indicating lower energy absorption, making it less effective for different loading applications.

- **Failure Characteristics:** RGRB2 showed a gradual load increase until failure, while RSRB2 rapidly reached peak load and maintained it before failing. RSRB2's retrofitting resulted in a different failure mechanism, with a quick load rise and a more controlled failure pattern.

iii. **RGRB 3 vs RSRB 3**

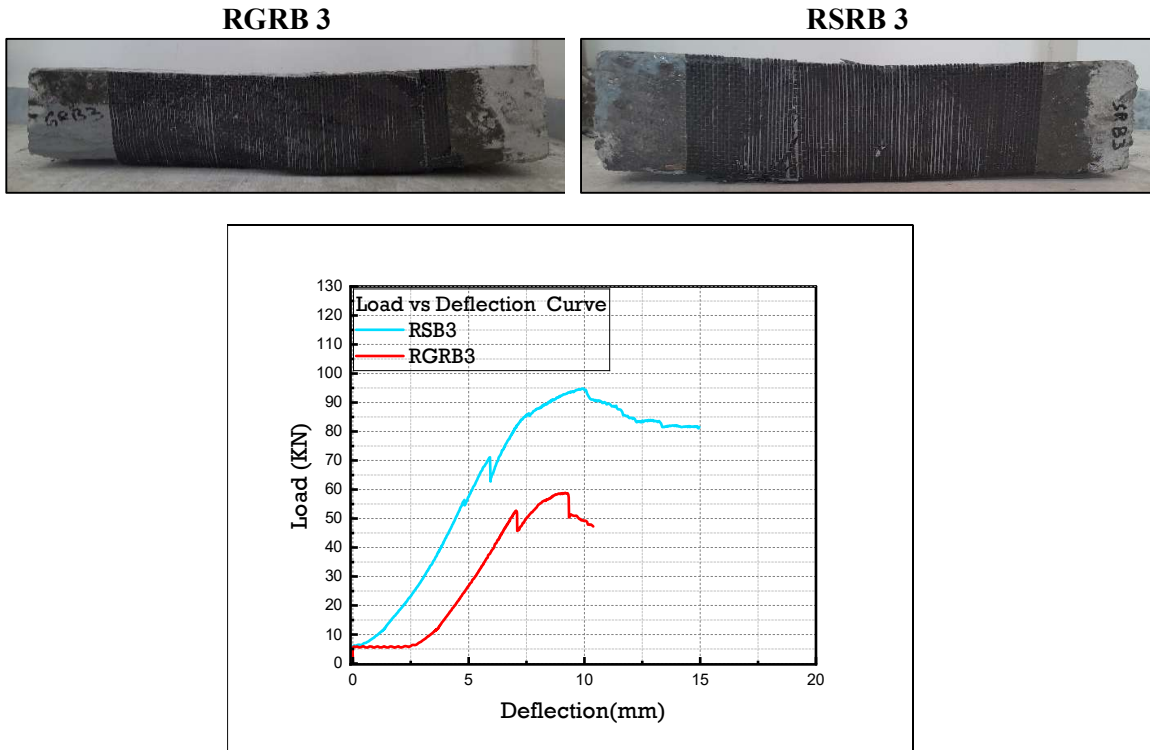


Figure # 4.12-3 Comparison between Steel reinforced beams and GFRP reinforced Beams (RGRB 3 vs RSRB 3)

Characteristics and Key findings of RSRB3 and RGRB3 are given below

- **Initial Stiffness:** Both beams had comparable stiffness in the elastic range. Retrofitting did not significantly alter initial stiffness but influenced higher load performance.
- **Load-Carrying Capacity:** RGRB3 attained ~55 kN at ~7 mm deflection, while RSRB3 reached ~75 kN at ~9 mm, showing a 36.4% increase in load capacity due to retrofitting.
- **Ductility:** RGRB3 had a wider deflection range, while RSRB3 quickly reached peak load and maintained it until failure. RGRB3 exhibited greater ductility, enhancing its ability to absorb energy without sudden failure.

- **Energy Dissipation:** RGRB3 dissipated only 43% energy compared to RSRB3, indicating lower energy absorption, making it less effective for seismic or cyclic loading applications.
- **Failure Characteristics:** RGRB3 showed a gradual load increase to failure, while RSRB3 rapidly reached and maintained peak load before failing, indicating a quicker rise and more controlled failure due to retrofitting,

iv. RGRB 4 vs RSRB 4

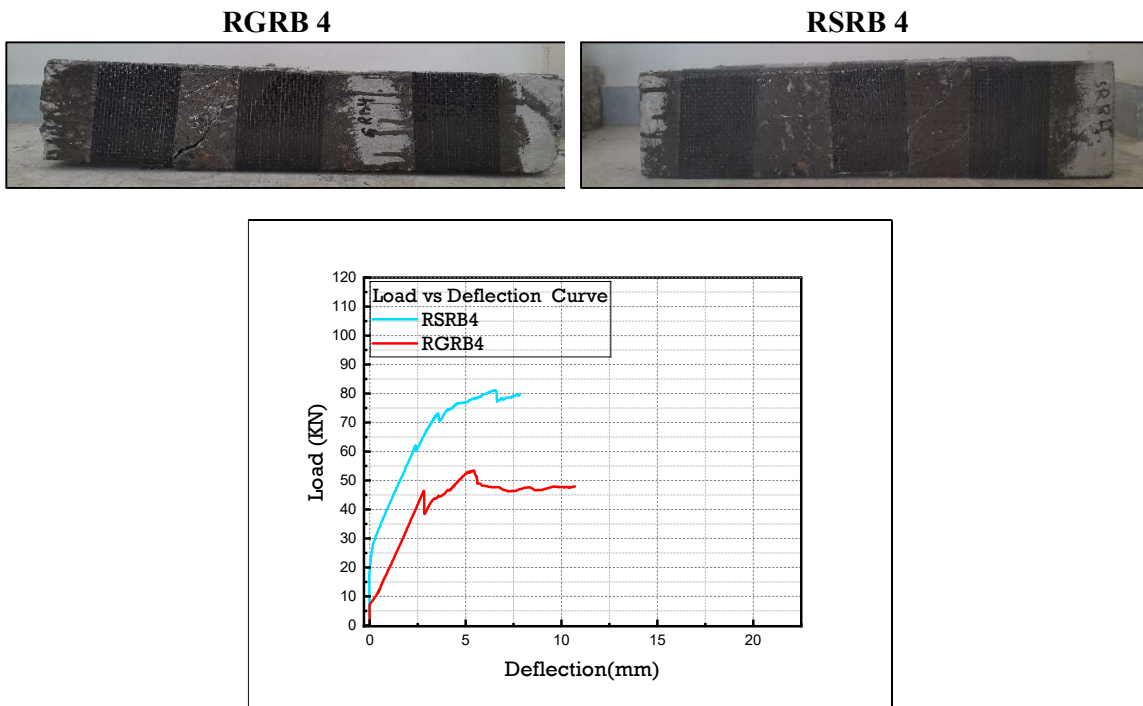


Figure # 4.12-4 Comparison between Steel reinforced beams and GFRP reinforced Beams (RGRB 4 vs RSRB 4)

Characteristics and Key findings of RSRB4 and RGRB4 are given below

- **Initial Stiffness:** Retrofitting didn't significantly change the initial stiffness, but affected performance at higher loads.
- **Load-Carrying Capacity:** RGRB 4 reached a peak load of ~60 kN at around 6 mm deflection. RSRB 4 achieved a higher peak load of ~80 kN at roughly 8 mm deflection, showing a 33.3% higher load capacity than RGRB 4.

- **Ductility:** RGRB 4 had higher ductility, absorbing and distributing energy more effectively without failure.
- **Energy Dissipation:** RGRB 4 dissipated 52% energy compared to RSRB 4.
- **Failure Characteristics:** RSRB 4 had a quicker rise to peak load, leading to a more controlled failure mechanism.

v. **RGRB 5 vs RSRB 5**

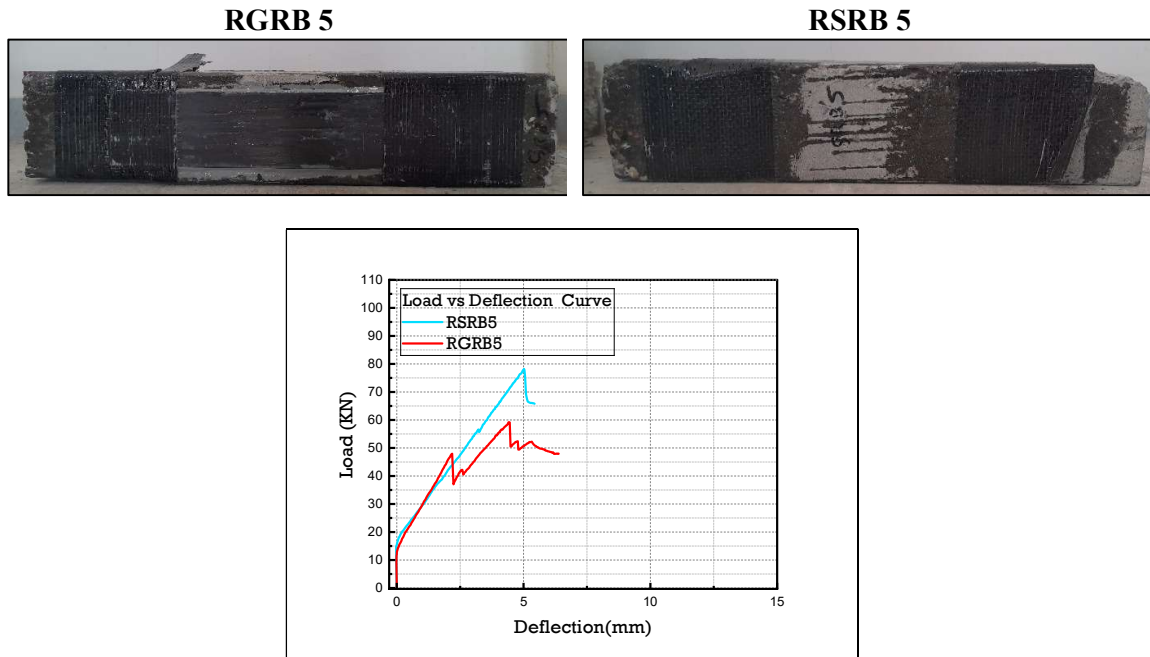


Figure # 4.12-5 Comparison between Steel reinforced beams and GFRP reinforced Beams (RGRB 5 vs RSRB 5)

Characteristics and Key findings of RSRB5 and RGRB5 are given below

- **Initial Stiffness:** Both beams exhibited similar stiffness under smaller loads. Retrofitting didn't significantly alter initial stiffness but impacted higher load performance.
- **Load-Carrying Capacity:** RGRB 5 reached 48 kN at 2.1 mm deflection. RSRB 5 reached 80 kN at 5 mm deflection, showing about 14.3% higher load capacity, demonstrating retrofitting effectiveness.
- **Ductility:** RGRB 5 showed a wider deflection range. RSRB 5 had a steeper initial rise in load with deflection but stabilized at higher load. RGRB 5 exhibited higher ductility.

- **Energy Dissipation:** RGRB 5 dissipated 68% less energy compared to RSRB 5, absorbing and dissipating less energy, making it less effective for structures subjected to varied loads, such as seismic activities.
- **Failure Characteristics:** RGRB 5 showed a steady load increase until failure. RSRB 5 reached peak load quickly and maintained it, resulting in a faster rise to maximum load and a different failure mechanism.

That completes all fifteen sets with consistent formatting and scientific clarity. If you'd like, can now help you compile a comparative matrix, generate a discussion section, or prepare these for submission to Engineering Structures. Just let me know your preferred next step. The load-deflection analysis highlights the significant advantages of retrofitting, with retrofitted beams exhibiting superior load capacity, ductility, and energy dissipation. These improvements make these beams more suitable for high-demand applications requiring enhanced resilience under extreme loads.

4.13 Performance of Beams under Flexure Test

In this section the retrofitting process applied to both post-retrofitted beams (cracked specimens) and pre-retrofitted beams (un-cracked specimens), focusing on their reinforcement using CFRP (Carbon Fiber Reinforced Polymer) wraps and strips, along with their dimensions is discussed in detail. This comparison highlights the effectiveness of retrofitting in improving structural performance. The varying sizes of wraps in all beams aim to restore the beam's flexural strength where cracking had occurred, as shown below.

4.13.1 Pre-Retrofitted Beams (Un-cracked Specimens)

The Following beams were retrofitted before its flexure test.

i. SRB4 (Steel Reinforced Beam 4):

This beam was retrofitted with alternating CFRP wraps of 4 inches, at a distance of 3-inch, followed by 18-inch CFRP strip at the bottom in the middle section, much like SRB1, but applied pre-emptively to prevent future cracking. This method focuses on flexural reinforcement.

ii. SRB5 (Steel Reinforced Beam 5):

An alternate 6-inch CFRP wrap was applied to the central portion of this beam at a distance of 6-inch, with additional 18-inch CFRP strip at the bottom in the middle section, similar

to SRB2. The preemptive application of this reinforcement was designed to enhance bending and shear strength.

iii. SRB6 (Steel Reinforced Beam 6):

Retrofitted with a large 18-inch CFRP wrap in the middle, accompanied by 18-inch CFRP strip at the bottom, SRB6 mirrors the retrofitting pattern of SRB3. The larger wrap provides substantial shear reinforcement.

iv. GRB4 (GFRP Reinforced Beam 4):

Similar to GRB1, GRB4 was retrofitted with alternating 4-inch CFRP wraps at a distance of 3-inch, accompanied by 18-inch CFRP strip at the bottom. This method improves the flexural strength of the GFRP-reinforced beam.

v. GRB5 (GFRP Reinforced Beam 5):

An alternate 6-inch CFRP wraps were applied at a distance of 6-inch, accompanied with 18-inch CFRP strip at the bottom in the middle section, similarly to GRB2. The retrofit was applied to enhance flexural and shear strength in areas likely to undergo stress.

vi. GRB6 (GFRP Reinforced Beam 6):

Retrofitted with an 18-inch CFRP wrap, accompanied with 18-inch CFRP strip at the bottom in the central section, GRB6's design mirrors that of GRB3, with the intention of preventing shear failure in GFRP beams.

vii. SRBV2 (Steel Reinforced Beam, Designed for Flexure):

Similar to SRBV1, this beam was retrofitted using alternating 4-inch CFRP strips at a distance of 3-inch and 18-inch wrap at the bottom, designed primarily to improve flexural performance.

viii. GRBV2 (GFRP Reinforced Beam, Designed for Flexure):

The beam follows the same retrofitting pattern as GRBV1, using a 6-inch CFRP wrap alternatively at a distance of 6-inch and 18-inch wrap at the bottom, focusing on flexural reinforcement. The post-retrofitted beams were retrofitted after developing cracks, with reinforcement applied to address existing structural damage. In contrast, pre-retrofitted beams were reinforced before cracking occurred, ensuring higher load capacity and preventing future damage. The use of CFRP wraps and strips in both groups improves the beams' ability to resist shear and flexural failures. The dimensions of CFRP strips and

wraps were carefully applied based on the anticipated structural stresses in different beam areas. This strategic placement of reinforcement helps manage bending moments and shear forces, ensuring that both steel and GFRP reinforced beams perform well under static and dynamic loading conditions.

4.13.2 Post-Retrofitted Beams (Cracked Specimens)

The Following beams were retrofitted after Flexure test.

i. SRB1 (Steel Reinforced Beam 1):

This beam was retrofitted with alternating CFRP wraps of 4 inches, at a distance of 3-inch, followed by 18-inch CFRP strip in the middle section.

ii. SRB2 (Steel Reinforced Beam 2):

An alternate 6-inch CFRP wrap was applied to the central portion of this beam at a distance of 6-inch, with additional 18-inch CFRP strip at the bottom in the middle section. This configuration focuses on providing increased shear and bending capacity in the middle, where the beam is likely to experience maximum deflection under load.

iii. SRB3 (Steel Reinforced Beam 3):

Retrofitted with a large 18-inch CFRP wrap in the middle, accompanied by 18-inch CFRP strip at the bottom. The use of a larger wrap in the central section indicates an intention to significantly enhance shear capacity in this region.

iv. GRB1 (GFRP Reinforced Beam 1):

Similar to SRB1, this GFRP-reinforced beam was retrofitted with alternating 4-inch CFRP wraps at a distance of 3-inch, accompanied by 18-inch CFRP strip at the bottom. The reinforcement is designed to strengthen the cracked zones, particularly around the flexural areas.

v. GRB2 (GFRP Reinforced Beam 2):

An alternate 6-inch CFRP wraps were applied at a distance of 6-inch, accompanied with 18-inch CFRP strip at the bottom in the middle section. This beam follows a similar strategy to SRB2 in targeting flexural and shear improvement.

vi. GRB3 (GFRP Reinforced Beam 3):

The beam has a central 18-inch CFRP wrap as well as CFRP strip of same length at the bottom, focusing on enhancing the shear capacity. This is similar to SRB3 but applied to a GFRP-reinforced beam.

vii. SRBV1 (Steel Reinforced Beam, Designed for Flexure):

This beam was retrofitted using alternating 4-inch CFRP wrap at a distance of 3-inch, accompanied by 18-inch wrap at the bottom. It was specifically retrofitted to address flexural issues without major concerns for shear strength.

viii. GRBV1 (GFRP Reinforced Beam, Designed for Flexure):

The beam was retrofitted with a two alternate 6-inch CFRP wraps with the distance of 6-inch, accompanied by 18-inch CFRP wrap at the bottom. Like SRBV1, this beam was retrofitted to address flexure-related concerns.

4.13.3 Special Beams

i. SRB 2

In the SRB2 beam, which was retrofitted after cracking (post-retrofitted), a major diagonal crack was observed originating from the bottom edge and extending upward toward the compression zone, indicating a shear failure mode. Along the crack path, the concrete surface exhibited signs of spalling—a condition where fragments or flakes of concrete detach from the surface. This deterioration is typically caused by internal stresses that exceed the tensile strength of the concrete, often aggravated by pre-existing damage, corrosion, impact, or poor bonding between repair materials and the original concrete (ACI 546R, 2004). In SRB2, spalling was likely triggered by a combination of factors: pre-existing damage prior to CFRP application, which weakened the bond interface; incomplete stress redistribution following retrofitting; and inadequate confinement or anchorage near the crack zone. The externally bonded CFRP strips failed to restore the beam's shear capacity effectively, largely due to reduced adhesion on the already cracked surface. As such, the localized material loss not only diminished load-carrying capacity but also compromised the bond between CFRP and concrete, exposing internal steel reinforcement to environmental effects such as corrosion.

This case highlights a key limitation of post-damage strengthening: CFRP systems are most effective when applied to un-cracked or properly prepared surfaces as pre-existing

damage compromises adhesion and structural performance [118]. SRB2 therefore represents a special case among the tested specimens, emphasizing the importance of surface integrity and proper retrofit detailing for effective post-damage strengthening in achieving successful retrofitting outcomes. It serves as an example of how inadequate preparation and anchorage can lead to poor retrofit performance, particularly in specimens with prior damage.





ii. GRB 4

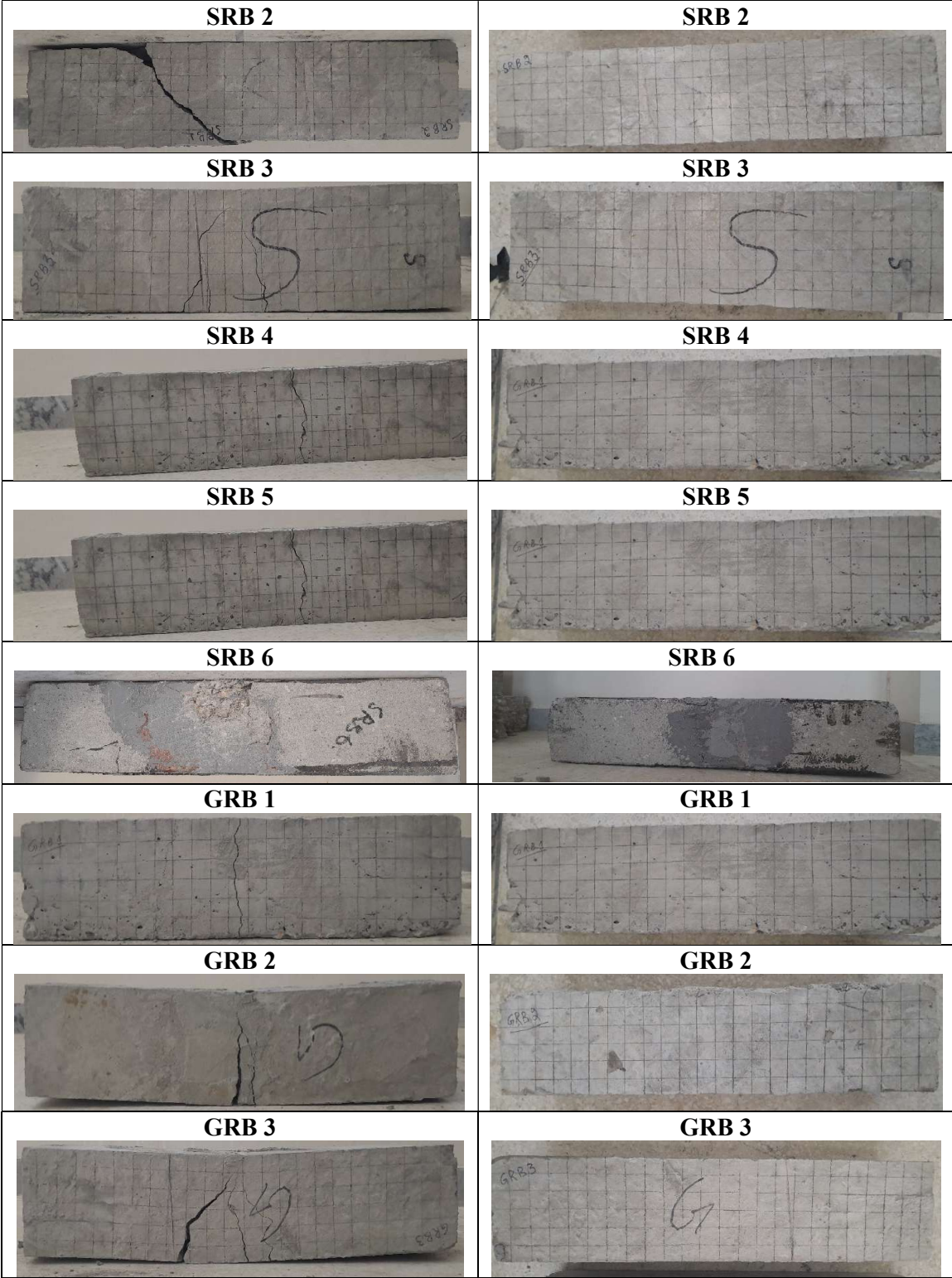
This beam also clearly demonstrates a significant spalling effect, characterized by the detachment and loss of substantial portions of its concrete cover, most notably exposing the underlying reinforcement. This spalling occurred alongside prominent cracks in various regions of the beam, including areas retrofitted with CFRP strips. The extent and distribution of the damage suggest that the applied loads during testing induced severe internal stresses, leading to both cracking and the progressive failure of the concrete surface. The presence of spalling in retrofitted zones highlights potential limitations in bond performance between the CFRP and the pre-damaged substrate, ultimately compromising the beam's structural integrity under load.

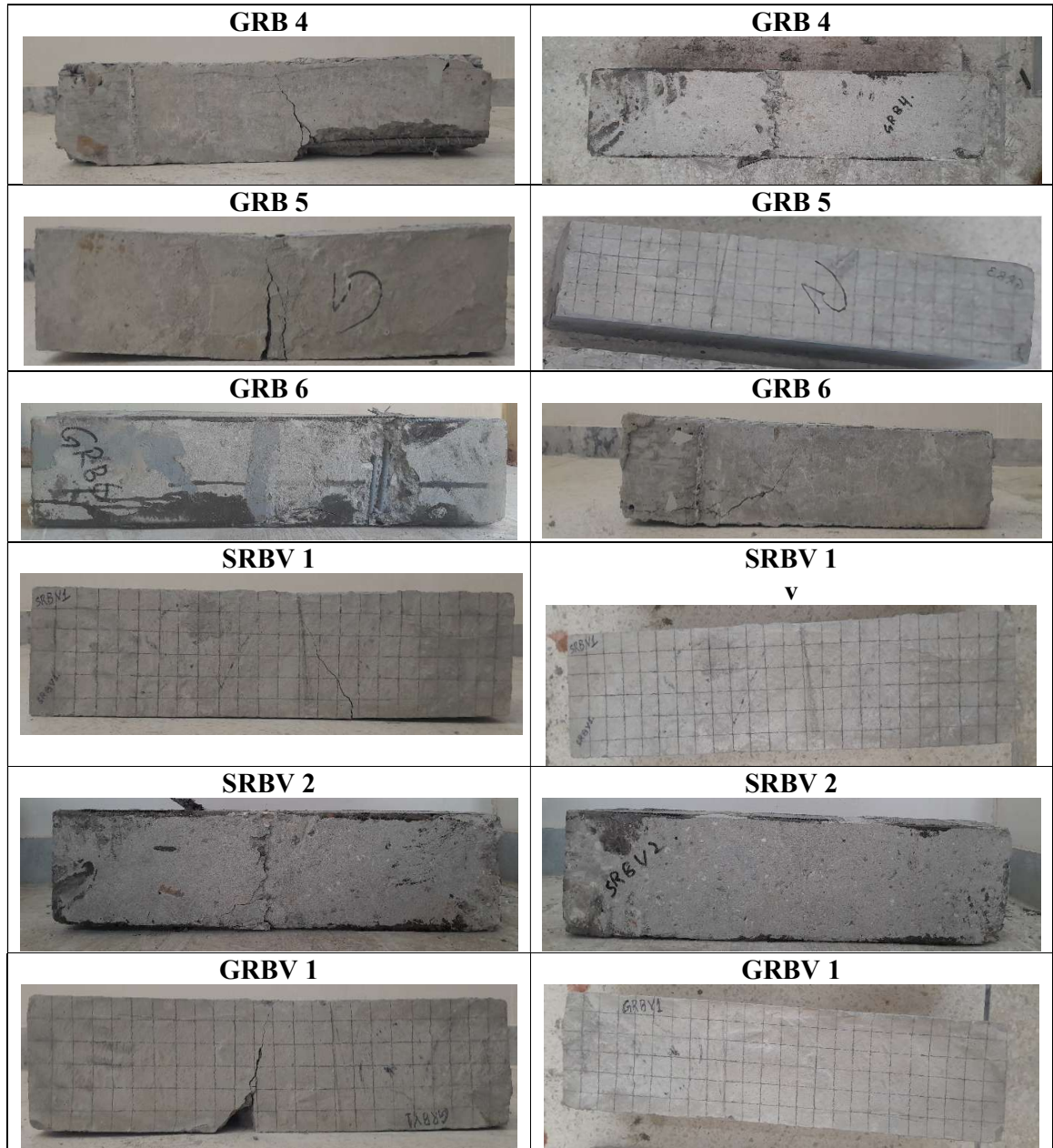
4.14 Non-Retrofitted Beams Before and After Flexure Test

This section shows non-retrofitted beams divided into cracked and un-cracked categories. It includes unreinforced and reinforced beams tested under static loading conditions, highlighting the crack patterns and structural responses for evaluation as shown and discussed below;

Table # 4.14-1 Non Retrofitted Beams Before and After Testing

Cracked	Un-Cracked
<p data-bbox="537 1486 711 1518">Unreinforced</p> 	<p data-bbox="1105 1486 1279 1518">Unreinforced</p> 
<p data-bbox="581 1675 667 1707">SRB 1</p> 	<p data-bbox="1149 1675 1235 1707">SRB 1</p> 





4.14.1 Cracking Behavior in Non-Retrofitted Beams after Testing

During the experimental testing of the beams, various types of cracks were observed in the cracked specimens depending on their reinforcement configuration and loading behavior. In steel reinforced beams (SRB), particularly in specimens SRB 1 to SRB 6, the most prominent cracks were flexural in nature. These cracks initiated from the tension face at mid-span and propagated vertically upward due to bending moments exceeding the

tensile strength of the concrete. The formation and widening of these vertical cracks with increasing load are characteristic of ductile behavior and are typical in beams reinforced with steel bars, which provide good tensile resistance and bond strength. In addition to flexural cracks, some diagonal shear cracks were observed in specimens SRB 2, SRB 3, and SRB 5, mainly near the supports or within the shear span. These cracks formed at an angle of approximately 30° to 45° to the horizontal axis and resulted from high shear stresses in regions where the moment is relatively low but shear force is high. These cracks indicated the transition toward a more brittle shear failure mechanism, particularly in beams where the stirrup spacing or shear reinforcement was relatively less effective.

In Glass Reinforced Beams (GRB), GRB 1 to GRB 6, showed a different cracking pattern due to the inherent brittleness and lower bond strength of GFRP bars. In these specimens, flexural cracks also developed at mid-span, but they appeared more suddenly and were accompanied by a sharper increase in crack width. In GRB 2 and GRB 4, splitting cracks were observed along the reinforcement path, suggesting inadequate bond between the GFRP bars and the surrounding concrete. These longitudinal cracks are critical as they can lead to debonding and bar slip, ultimately compromising the anchorage performance.

In SRBV 1 and SRBV 2, the cracking pattern showed a combination of flexural and shear characteristics. Initial vertical cracks at mid-span gradually extended diagonally as loading progressed, indicating the presence of flexural-shear cracks. These cracks are a result of the simultaneous action of bending and shear, often forming a curved path from the tension zone toward the supports. The behavior in SRBV beams was more progressive and ductile compared to GRBV specimens.

In contrast, to SRBV beams the GRBV specimen, GRBV 1, exhibited sudden diagonal cracking, which was sharper and more brittle. The cracks formed rapidly under increasing load and were less distributed, a behavior typical of FRP-reinforced beams under combined flexural and shear action. The lack of ductility in this specimen led to a localized failure mechanism dominated by brittle cracking.












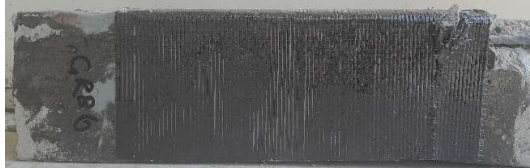
Moreover across several specimens including SRB 4, GRB 3, and SRBV 2, localized cracks directly beneath the loading points were observed. These cracks were short, vertical, or slightly inclined, and occurred due to the high compressive stress

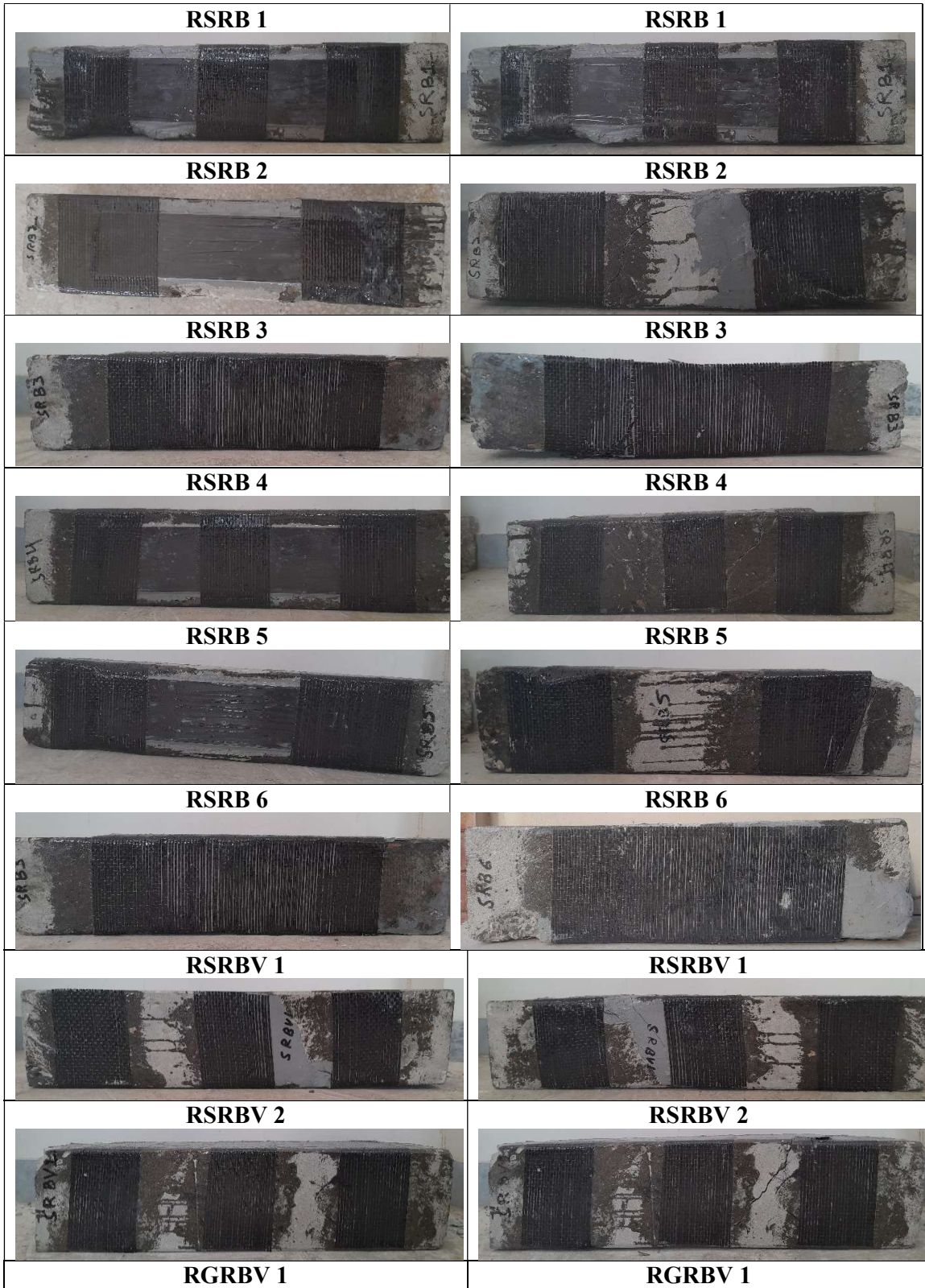
concentrations from the applied point loads. While these did not directly contribute to the overall failure mode, they marked zones of localized crushing and surface distress.

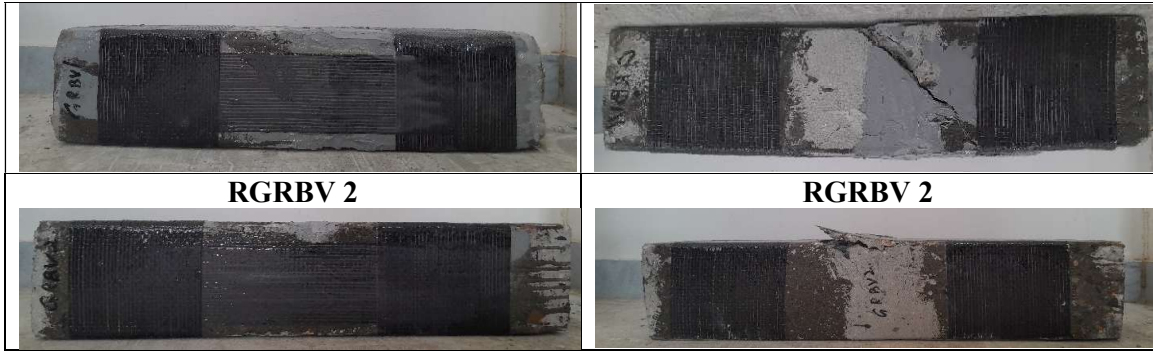
4.15 Retrofitting of Beams Before and After Flexure Test

The CFRP retrofitted beams with strips and wraps before and after the testing, emphasizing the distribution and alignment of the strengthening material are shown below. It highlights the retrofitting design for improving load-bearing capacity under static and impact loads and energy dissipation.

Table # 4.15-1 Retrofitted beams before and after testing

Before Testing	After Testing
<p style="text-align: center;">RGRB 1</p> 	<p style="text-align: center;">RGRB 1</p> 
<p style="text-align: center;">RGRB 2</p> 	<p style="text-align: center;">RGRB 2</p> 
<p style="text-align: center;">RGRB 3</p> 	<p style="text-align: center;">RGRB 3</p> 
<p style="text-align: center;">RGRB 4</p> 	<p style="text-align: center;">RGRB 4</p> 
<p style="text-align: center;">RGRB 5</p> 	<p style="text-align: center;">RGRB 5</p> 
<p style="text-align: center;">RGRB 6</p> 	<p style="text-align: center;">RGRB 6</p> 





4.15.1 Cracking Behavior in Retrofitted Beams after Testing

The retrofitted specimens, including GRB 1–6, SRB 1–6, SRBV 1–2, and GRBV 1–2, exhibited distinct cracking behaviors compared to their non-retrofitted counterparts. Prior to testing, these beams were externally retrofitted using fiber-reinforced polymer (FRP) wraps, steel jackets, or similar strengthening techniques intended to enhance flexural and/or shear resistance. After retrofitting and testing under the same loading conditions, the effectiveness of these interventions became evident in both the initiation and propagation of cracks.

In the GRB series, retrofitting contributed to a noticeable delay in the onset of cracking. For example, in GRB 2 and GRB 4, which had shown premature brittle failure in the non-retrofitted state, the cracks after retrofitting were more controlled and appeared at higher load levels. The retrofitted GRB beams still exhibited flexural cracks at the mid-span region due to bending, but their widths were significantly reduced, and the cracks were more uniformly distributed. Additionally, splitting cracks observed along the GFRP reinforcement in un-retrofitted samples were either minimized or completely eliminated post-retrofit, indicating improved bond characteristics.

Similarly, the SRB specimens (SRB 1 to SRB 6) showed enhanced ductility after retrofitting. The development of diagonal shear cracks, particularly in SRB 3 and SRB 5, was postponed, and in some cases, their angles were flatter — suggesting that the retrofitting helped redistribute stresses more effectively. In SRB 2 and SRB 6, where prior tests showed early shear-induced cracking, the retrofitted beams exhibited dominant flexural cracking modes instead, implying a shift in failure mechanism due to increased shear resistance.

The SRBV specimens, SRBV 1 and SRBV 2, benefited from retrofitting by presenting a more ductile failure behavior. The presence of flexural-shear cracks was still evident, but they progressed gradually and required higher loads to initiate. The crack paths in these specimens were more curved and extended slowly toward the supports, suggesting that the retrofit not only delayed failure but also allowed for better energy dissipation during loading.

In the GRBV series, which included GRBV 1 and GRBV 2, the effect of retrofitting was most evident in controlling the brittleness of failure. These beams previously showed sudden and unstable diagonal cracking. Post-retrofit, the cracks appeared more stable and limited in length and depth. Although diagonal shear cracks still developed under vertical loads, they were narrower and less extensive than in un-retrofitted GRBV specimens. Moreover, some cracks initiated as flexural and transitioned to diagonal, a sign of hybrid crack mechanisms being better restrained by the retrofitting layers.

Across all retrofitted beams, cracks beneath the loading points—seen in specimens such as SRB 4 and GRB 5—were less severe, suggesting that surface confinement provided by retrofitting materials helped dissipate point load stresses. The uniformity and reduced severity of cracking in all tested retrofitted beams clearly indicate the beneficial role of the retrofit measures in enhancing crack control, shifting failure modes from brittle to ductile, and improving overall structural performance.

4.16 Discussion

The experimental study on RC beams retrofitted with CFRP under static loading conditions demonstrated that CFRP significantly improves load-bearing capacity, energy dissipation, flexure strength, shear strength and ductility. These findings highlight CFRP's effectiveness as a retrofitting material, aligning with research objectives, scope and existing literature while offering valuable insights into its structural benefits.

4.17 Energy Dissipation and Load-Bearing Capacity

The results demonstrate that CFRP-retrofitted beams exhibit higher energy dissipation compared to non-retrofitted control beams. This is evident from the load-deflection curves, where retrofitted beams showed a larger area under the curve, indicating greater energy

absorption. For instance, retrofitted steel-reinforced beams (RSRB) showed energy dissipation improvements ranging from 35% to 507% compared to their non-retrofitted counterparts (SRB). Similarly, retrofitted glass-reinforced beams (RGRB) exhibited energy dissipation improvements between 15% and 253% compared to non-retrofitted beams (GRB). This enhancement in energy dissipation is crucial for structures subjected to dynamic loads, such as earthquakes or blasts, where the ability to absorb and dissipate energy can prevent catastrophic failure. These findings align with previous studies; [23]; [119]; [24]; [22] that have highlighted CFRP's ability to improve the ductility and energy dissipation capacity of RC structures

4.18 Comparison between Pre-Retrofitted and Post-Retrofitted Beams

The study compared pre-retrofitted (un-cracked) and post-retrofitted (cracked) beams to evaluate the effectiveness of CFRP application at different stages of structural deterioration. Pre-retrofitted beams consistently outperformed post-retrofitted beams in terms of load-bearing capacity and energy dissipation. For example, pre-retrofitted steel-reinforced beams (SRB4, SRB5, and SRB6) showed higher load capacities and energy dissipation compared to post-retrofit beams (SRB1, SRB2, and SRB3). This suggests that early intervention with CFRP retrofitting can prevent structural damage and enhance performance, reinforcing the importance of proactive maintenance in structural engineering. However, post-retrofitted beams still showed significant improvements compared to non-retrofitted beams, indicating that CFRP can effectively restore lost structural capacity even after damage has occurred. This finding is particularly relevant for aging infrastructure, where retrofitting is often performed after the onset of deterioration.

4.19 Flexural and Shear Enhancement

The application of CFRP wraps and strips significantly enhanced the flexural and shear strength of the beams. Beams retrofitted with CFRP strips at the bottom and wraps along the sides showed improved resistance to bending and shear forces, especially in mid-sections prone to deflection and cracking. For example, beams with CFRP strips and wraps (e.g., RSRB3 and RGRB3) had higher load capacities and reduced deflection compared to those with only CFRP strips or wraps. This supports previous research on CFRP's

effectiveness in improving RC beam performance [82]; [83]; [84]; [85]; [86]. Proper CFRP placement, particularly with larger wraps and strips in critical areas, was key to maximizing structural improvements.

4.20 Debonding and Failure Modes

One challenge observed during testing was the debonding of CFRP from the concrete surface, especially in post-retrofitted beams. This primarily occurred at the CFRP-concrete interface, leading to premature failure, particularly in beams with existing cracks. Stress concentrations at crack tips contributed to the debonding. To address this, future retrofitting designs could incorporate additional anchorage systems, like U-wraps or mechanical anchors, to enhance the bond between CFRP and concrete, as suggested by previous studies [109]; [106]; [104]; [105]

4.21 Comparison between Steel and GFRP Reinforced Beams

The study also compared the performance of steel-reinforced beams (SRB) and glass fiber-reinforced polymer (GFRP) reinforced beams (GRB) retrofitted with CFRP. Steel-reinforced beams generally exhibited higher load capacities and energy dissipation compared to GFRP-reinforced beams. For example, retrofitted steel-reinforced beams (RSRB) showed energy dissipation improvements compared to non-retrofitted steel beams (SRB), while retrofitted GFRP beams (RGRB) showed improvements of up to 253%. This difference can be attributed to the higher modulus of elasticity and tensile strength of steel compared to GFRP. However, GFRP-reinforced beams still demonstrated significant improvements after retrofitting, making CFRP a viable option for structures where steel reinforcement is not feasible due to corrosion concerns, particularly in coastal or marine environments. Overall, the research effectively fulfills its aim, scope, and objectives by providing empirical data and comparative analysis that validate CFRP as an effective retrofitting solution for enhancing the structural performance of RC beams.




4.22 Cracking Behavior in Pre and Post Retrofitted Beams

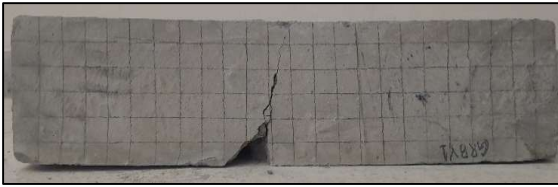


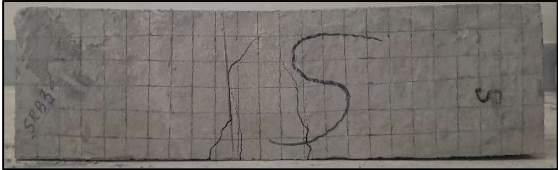
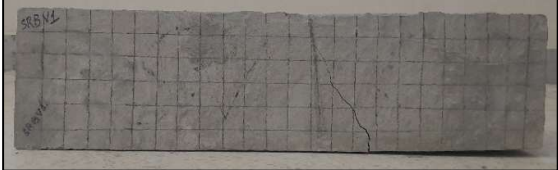
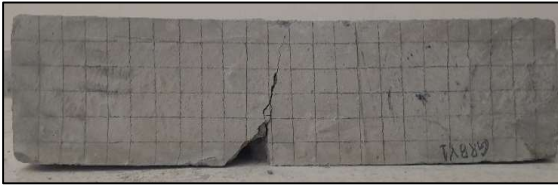
The comparative analysis of cracking behavior in non-retrofitted and retrofitted beams reveals a substantial improvement in structural performance post-retrofitting. In non-retrofitted specimens, SRB beams (SRB 1 to SRB 6) primarily exhibited vertical flexural

cracks at mid-span due to bending, along with diagonal shear cracks near the supports in some cases (e.g., SRB 2, SRB 3, and SRB 5), indicating a partial transition toward brittle shear failure in the absence of sufficient shear reinforcement. GRB beams showed sudden flexural and splitting cracks along the reinforcement path, while GRBV specimens displayed abrupt diagonal cracks with brittle characteristics. In contrast, retrofitted beams exhibited delayed crack initiation, with flexural cracks mostly concentrated at mid-span and more stable diagonal cracks forming at shallower angles within the shear span. Cracks in retrofitted SRB and GRB beams were narrower, more uniformly distributed, and less severe under the same loading conditions, while SRBV and GRBV specimens showed improved ductility and gradual crack progression. The improved bond characteristics and surface confinement provided by FRP wraps, steel jackets, or hybrid retrofitting systems significantly mitigated premature cracking, shifted failure modes from brittle to ductile, and enhanced overall structural integrity.

4.23 Failure Modes of Non Retrofitted Beams.

Table # 4.23-1 Beam Failure Mode Remarks

Beams	Beams Failure Mode Pictures	Remarks
GRB1		Exhibits flexural failure. Vertical cracks confirm flexural tension.
GRB2		Displays classic flexural failure. A prominent vertical crack at mid-span indicates tensile rupture due to bending moment exceeding concrete's flexural capacity.
GRB3		Shows dominant flexural failure. Central crack indicates tensile rupture under bending stress.

GRBV1		Displays flexural failure with a vertical crack initiating from the tension zone. Crack propagation aligns with bending stress concentration.
SRB1		Indicates shear failure near support zones. Diagonal and vertical cracks close to beam ends suggest principal tensile stress-induced rupture due to shear forces.
SRB2		Diagonal crack near mid-span suggests flexural-shear interaction. Crack initiates in the tension zone and propagates diagonally, indicating combined bending and shear stresses.
SRB3		Shear failure occurred. Diagonal Cracks appear at mid span.
SRBV1		A mini diagonal crack near mid-span indicates minor shear-flexural interaction.
GRBV1		Exhibits pure flexural tension failure. A single vertical crack originates at the bottom tension face near mid-span and

		propagates upward, indicating bending moment exceeded beam's tensile capacity.
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Chapter 5 Conclusions and Recommendations

5.1 Conclusion

It is concluded that the effectiveness of CFRP retrofitting depends strongly on the type of reinforcement used. Steel-reinforced beams benefited the most, with CFRP significantly increasing global energy dissipation, ductility, and stability by transforming brittle behavior into ductile performance. GFRP-reinforced beams also improved after CFRP retrofitting, but their inherent brittleness limited the overall gains, leaving them less efficient than steel-CFRP systems. Non-retrofitted beams provided the weakest response, with low energy absorption, concentrated paver energy, and rapid brittle failure. Taken together, these findings confirm that CFRP retrofitting is an effective method for strengthening reinforced beams, especially those with steel reinforcement.

The results also highlight the need for further research into hybrid or alternative retrofitting techniques to enhance the performance of GFRP systems. This sets the stage for the concluding chapter, which summarizes the study's contributions, practical implications, and recommendations for future research. This research aimed to explore the energy dissipation behavior of reinforced concrete (RC) beams retrofitted with carbon fiber reinforced polymer (CFRP) under static loading conditions. The experimental study involved testing both pre-retrofitted and post-retrofitted beams to assess the effectiveness of CFRP in enhancing the structural integrity of RC beams. The analysis and discussion highlights the effectiveness of CFRP retrofitting in enhancing the structural performance of RC beams.

The study demonstrated that the application of CFRP significantly improves the load-bearing capacity and energy dissipation capabilities of the beams, especially under static loading. The retrofitted beams, whether pre-retrofitted or post-retrofitted, exhibited increased stiffness, reduced deflection, and improved overall performance compared to the control beams. Post-retrofitted beams, which had been previously cracked, benefited from CFRP reinforcement in terms of restoring lost structural capacity. The pre-retrofitted beams, on the other hand, prevented damage and exhibited superior load resistance. This comparison shows that CFRP retrofitting is a viable method for prolonging the life of deteriorating concrete structures and preventing catastrophic failure under both static and dynamic loading conditions.

Moreover, Load-deflection analysis further confirmed that CFRP application improved both flexural and shear resistance, particularly in critical stress regions. However, challenges such as CFRP debonding, especially in post-retrofitted beams, indicate the need for optimized bonding techniques.

These findings provide valuable insights into the role of CFRP in structural retrofitting, supporting its adoption for enhancing the resilience and longevity of RC structures. The analysis and discussion highlights the effectiveness of CFRP retrofitting in enhancing the structural performance of RC beams.

The comparison between different beams under static load revealed that retrofitted beams performed well under static conditions, though they dissipated more energy under impact loads. This suggests that CFRP retrofitting is an effective solution for structures exposed to dynamic forces such as earthquakes or blasts. The use of different configurations of CFRP reinforcement, such as alternating strips and wraps, was found to be effective in addressing specific structural weaknesses.

The application of CFRP, particularly in beams subjected to different types of loads, proved to be a cost-effective solution for strengthening and retrofitting RC structures. In conclusion, CFRP is an effective material for retrofitting RC beams, offering substantial improvements in energy dissipation, stiffness, and overall load-bearing capacity. These recommendations aim to enhance the overall effectiveness of CFRP retrofitting techniques and ensure the longevity and safety of reinforced concrete structures. The findings of this study can be applied in real-world scenarios, particularly in coastal regions and areas prone to environmental deterioration, where infrastructure longevity is critical.

5.2 Recommendations

1. **CFRP Application:** Structural engineers should adopt CFRP for retrofitting RC beams, particularly in structures exposed to dynamic forces or environmental degradation.
2. **Pre-emptive Retrofitting:** Retrofitting should be performed before structural damage occurs. Pre-retrofitted beams demonstrated higher energy dissipation and load-bearing capacity, emphasizing the importance of early intervention.

3. **Environmental Research:** Additional research is necessary to evaluate the long-term impact of environmental factors on CFRP performance, ensuring its durability under real-world conditions.
4. **Optimized CFRP Placement:** Strategic positioning of CFRP wraps and strips should be considered in future designs. Placing larger wraps at critical points, such as mid-sections, can greatly enhance shear and flexural performance.
5. **Cost-Benefit Analysis:** Though CFRP may be expensive, the long-term benefits of structural safety, reduced repair costs, and extended service life make it a worthwhile investment. Decision-makers should account for these factors when selecting retrofitting materials.

5.3 Future Implications:

The findings on energy dissipation in beams have several real-world applications, particularly in the fields of civil and structural engineering. Here are some key applications: The findings have broader implications for retrofitting practice. They confirm that CFRP is a highly effective strengthening material, especially for steel-reinforced concrete beams, as it improves energy dissipation, ductility, and crack behavior. For GFRP-reinforced systems, CFRP retrofitting provides measurable improvements but does not fully overcome their brittle tendencies. Hybrid retrofitting strategies may be required for greater effectiveness. From a practical perspective, the results suggest that retrofitting existing steel-reinforced infrastructure with CFRP can enhance seismic performance, extend service life, and mitigate brittle failures under cyclic and static loading. For GFRP systems, CFRP serves as a partial solution, but further innovations are needed to ensure resilience comparable to steel-CFRP systems.

Seismic Retrofitting: Structures in earthquake-prone areas can benefit from beams with high energy dissipation capabilities. These beams can absorb and dissipate the energy from seismic waves, reducing the impact on the structure and enhancing its resilience against earthquakes.

1. **Building Construction:** In high-rise buildings, energy dissipation beams can be used to improve the building's ability to withstand wind loads and other dynamic forces. This can lead to safer and more durable structures.

2. **Industrial Machinery:** In industrial settings, beams with high energy dissipation can be used in machinery and equipment to reduce vibrations and noise, leading to smoother operation and longer equipment life.

These applications highlight the importance of energy dissipation in beams for creating safer, more durable, and more efficient structures in various real-world scenarios.

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