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Experimental Investigations on Reinforced Concrete Gable Beams Strengthened with CFRP Sheets

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ABSTRACT

This study presents an experimental investigation on the structural performance of reinforced concrete (RC) gable beams strengthened with carbon fiber reinforced polymer (CFRP) sheets. A total of six RC gable beams were cast and tested under static loading applied at mid-span. One specimen served as a solid control beam, while two unstrengthened specimens incorporated eight circular or trapezoidal openings to reduce self-weight. The remaining three specimens featured identical geometries but were strengthened using CFRP sheets to enhance their bending and shear resistance. Evaluated parameters included load-deflection curves, ultimate load capacities, cracking patterns, failure modes, and structural strains. This research addresses a critical gap regarding the structural behavior and CFRP strengthening of perforated RC gable beams. Results demonstrated that incorporating openings successfully decreased beam self-weight by 14%, though inducing a minor 6.25% reduction in ultimate capacity. However, CFRP configurations significantly improved the load-carrying capacity by approximately 35% and substantially delayed crack propagation. Specifically, CFRP sheets delayed the first crack appearance, increasing its associated load by up to 82.35% when comparing the gable beam strengthening with CFRP sheets (GBS) specimen with the control gable beam (GB) specimen. Furthermore, the strengthening technique efficiently minimized concrete and steel strains across all specimens, reducing maximum concrete strain by 33.3%. Ultimately, the findings confirm that CFRP strengthening is highly efficient in eliminating the adverse structural effects of weight-reducing openings, ensuring structural integrity.

Keywords: Reinforced Concrete Gable Beams; Variable Cross-Sections; Non-Prismatic Beams; Multiple Openings in Web; Strengthened with CFRP Sheets; Static Load

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1. Introduction

Reinforced concrete gable beams are important members characterized by a variable depth in cross-sections that typically increases from the supports toward the mid-span, as shown in **Figure 1** [1]. The building of present structures needs numerous ducts and pipes to accommodate important services such as water supply, sewage, electricity, air conditioning and a communication network. Creating openings in the reinforced concrete gable beam network facilitates the passage of these electrical conduits, pipes, and tubes through the structural elements. Therefore, it will reduce the floor height, lighten the weight, enhance spatial efficiency and future maintenance, as well as the possibility of replacing services and establishing new ones [1]. However, the inclusion of multiple openings presents complex stresses and disturbances. In reinforced concrete construction, gable beams achieve structural efficiency and architectural suitability. Despite the numerous advantages of aesthetics and the use of services, gable beams are exposed to complex stress distribution due to their non-prismatic geometry and the presence of multiple openings in them [2]. These variations in cross-sectional depth along the length of the beam, in addition to the existence of openings in the web, cause changes in moment of inertia, negatively affecting stiffness and deformation characteristics. Furthermore, high shear forces near the supports may lead to brittle failure patterns if adequate reinforcement is not provided and openings are not created near the supports [3]. With the development of advanced composite materials, carbon fiber reinforced polymer (CFRP) is becoming widely used in many buildings and structures. It is also considered an effective solution for structural reinforcement [4]. This type of polymer is characterized by high tensile strength, corrosion resistance, light weight, and ease of use. It can also be used for post-construction maintenance. Externally bonded CFRP sheets and proper epoxy are commonly used to enhance both flexural and shear strength in reinforced concrete beams [5]. There are many scientific studies that specialize in investigating the use of CFRP as a strengthening material for prismatic reinforced concrete beams against bending or shear stresses. For example, Hussein [6] investigated the structural behavior of simply supported reinforced concrete beams exposed to loads in the third of the span and containing openings in the shear region. The openings were strengthened using CFRP sheets in different arrangements and configurations: some were placed around the opening, others on either side of the opening, and a third technique involved placing the CFRP sheets on either side of the opening at an oblique angle. All CFRP sheet configurations improved shear strength and also eliminated the negative impact of the openings. Azeez [7] considered the cause of CFRP detachment from the concrete surface of reinforced concrete beams. Their investigational program included casting and testing 17 specimens. The experimental results showed a 54.3% increase in failure load when comparing concrete beams reinforced with CFRP and epoxy and concrete beams reinforced with CFRP, 1.2% polyvinyl alcohol (PVA), and 1% steel fibers. Abdulkareem and Izzet [1] studied the service requirements of reinforced concrete gable beams after fire exposure. The study consisted of 12 reinforced concrete gable beam specimens containing 6 or 8 circular or trapezoidal openings. A mechanism was developed to calculate the deflection and crack width under concentrated loads at the mid-span length during the elastic phase, based on the uncracked section. The results obtained from this study were compared with the American Concrete Institute (ACI) code, and a very high degree of agreement was found. Mohammed and Izzet [8] investigated the structural performance of reinforced concrete gable beams containing eight trapezoidal openings (four on each side of the gable beam). The control sample was free of openings, while the three remaining samples contained openings. The study focused on the effect of opening tilt toward the load on the ultimate load-bearing capacity of the gable beams. The main findings of this study are that the presence of the openings reduces the weight of the gable beam by 12.5%, and increasing the tilt of the opening sides from 90° to 45° increases the ultimate load of the gable beam by 28.4%. Numerous studies have explored the use of carbon fiber reinforced polymer (CFRP) to strengthen prismatic reinforced concrete beams. However, studies focusing on strengthening gable beams have been insufficient. Therefore, experimental research is essential. This study focuses on the experimental evaluation and comparison of the performance of reinforced concrete gable beams strengthened with carbon fiber polymer (CFRP) and unstrengthened gable beams under static loads. It aims to provide a precise understanding of the structural behavior of strengthened gable beams, addressing a current research gap in this area. The general framework of this study involves the casting and laboratory testing of six reinforced concrete gable beam samples. This study aims to study the effect of CFRP strengthening on reinforced concrete gable beams containing two types of openings: circular and trapezoidal. It also aims to determine the optimal shape of the opening and the negative effect of these openings on the load-bearing capacity of reinforced concrete gable beams. It explores how to overcome this effect using CFRP sheet reinforcement. The novelty of this study addresses a critical research gap concerning the structural behavior and retrofitting of non-prismatic sections with web configurations. In addition, this paper answers how externally bonded CFRP sheets can eliminate structural degradation and change stress distributions, while testing the hypothesis that cross-shaped CFRP configurations can recover lost capacity and shift failure modes away from premature Vierendeel failure. Theoretically, this study provides empirical data on stress disturbances and internal strain profiles in variable-depth elements. Practically, it offers an optimized design scheme to reduce dead weight by up to 14% via web openings for utility passages without risking structural integrity. To achieve these objectives, this paper is organized as follows: Section 2 details the experimental program, material properties, and instrumentation; Section 3 comprehensively discusses the experimental results, load-deflection behavior, ultimate capacities, and cracking patterns; while Section 4 presents the main conclusions and future research recommendations, respectively.

Figure 1. Reinforced concrete gable beams [1].

2. Experimental Work

2.1. Research Methodology

To achieve the research objectives of understanding the structural performance of reinforced concrete gable beams, studying the effect of openings, changing the shape of the opening while maintaining a constant total size, and studying the effect of strengthening with CFRP sheets, and to provide a comprehensive overview of the experimental sequence, a general flowchart illustrating the systematic methodology steps followed in this investigation—from casting to final destructive testing—is presented in **Figure 2**.

Six reinforced concrete gable beam specimens were cast and tested. The specimens were divided into two groups. The first group, dedicated to studying the effect of changing the shape of the openings, consisted of three specimens: the first (GB) had no openings; the second gable beam with circular openings (GBC) had eight circular openings evenly distributed on both sides of the beam; and the last gable beam with trapezoidal openings (GBT) had eight trapezoidal openings, also evenly distributed on both sides of the beam, while maintaining a constant total opening size between the second and third specimens. The second group, dedicated to studying the effect of strengthening with CFRP sheets, also consisted of three specimens gable beam strengthening with CFRP sheets (GBS), gable beam with circular openings and strengthening with CFRP sheets (GBCS), gable beam with trapezoidal openings and strengthening with CFRP sheets (GBTS), identical to those in the first group but strengthened using CFRP sheets. To provide a comprehensive overview of the research matrix, a detailed summary of the experimental design, including the specific allocation of specimens, testing groups, opening geometries, and strengthening configurations, is systematically organized in **Table 1**.

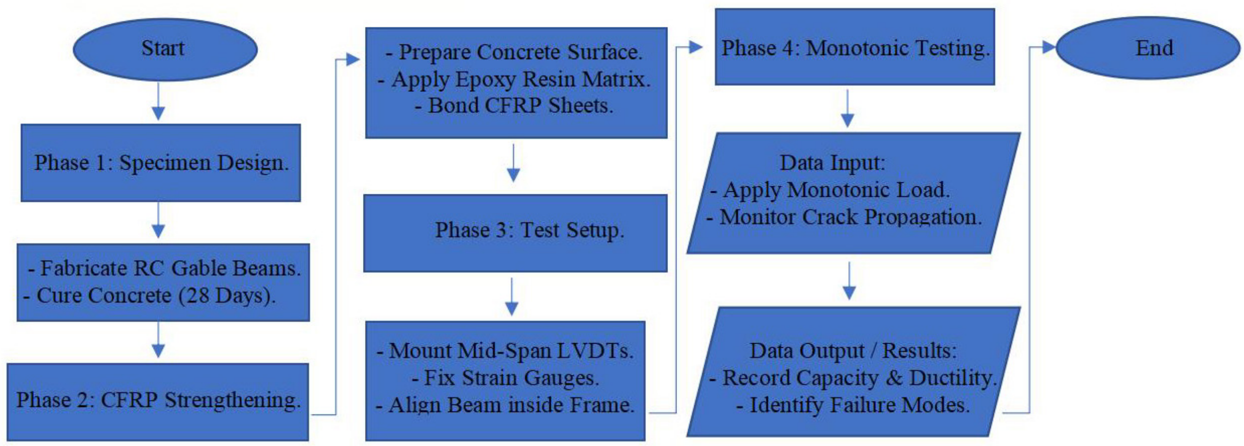

Figure 2. General flowchart illustrating the sequence of experimental methodology steps followed in the study.

Table 1. The experimental design, including the allocation of specimens and testing groups.

Specimens Symbol	Web Opening Shape	Total Self-Weight Reduction (%)	Strengthening Scheme (CFRP Sheets)
GB	None (Solid)	0	Unstrengthened
GBS	None (Solid)	0	10 cm wide strip from the bottom
GBT	Trapezoidal	14	Unstrengthened
GBTS	Trapezoidal	14	Cross-Shaped CFRP and a 10 cm wide strip from the bottom
GBC	Circular	14	Unstrengthened
GBCS	Circular	14	Cross-Shaped CFRP and a 10 cm wide strip from the bottom

2.2. Construction Materials Used

All construction materials used in this study (cement, sand, gravel, water, high range water reducing admixture (HRWRA), Ø4 mm, Ø6 mm, and Ø12 mm reinforcing steel, CFRP, and epoxy) were tested, and the results were found to be in compliance with scientific and local specifications [9–12]. The compressive strength of the concrete at 28 days (f_{cu}) was 40 MPa, and the yield strength (f_y) of the Ø4 mm, Ø6 mm and Ø12 mm reinforcing steel was 380 MPa, 520 MPa, and 550 MPa, respectively. The tensile strength of CFRP sheet was 3,500 MPa.

2.3. Reinforced Concrete Gable Beams

All six specimens used in this study had the following dimensions (Length: 3,000 mm, Width: 100 mm, Depth at supports: 250 mm, Depth at mid-span: 400 mm, Linear variation in depth) [13–17]. The details of the reinforcing steel [18] in the test specimens are shown in **Figures 3–5**.

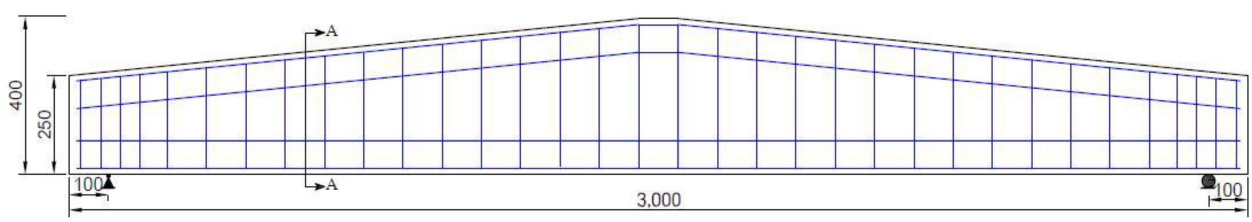

Figure 3. *Cont.*

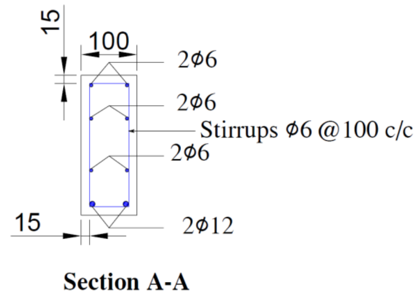

Figure 3. Typical details of steel reinforcement GB (Control), GBS.

Note: All dimensions are in mm.

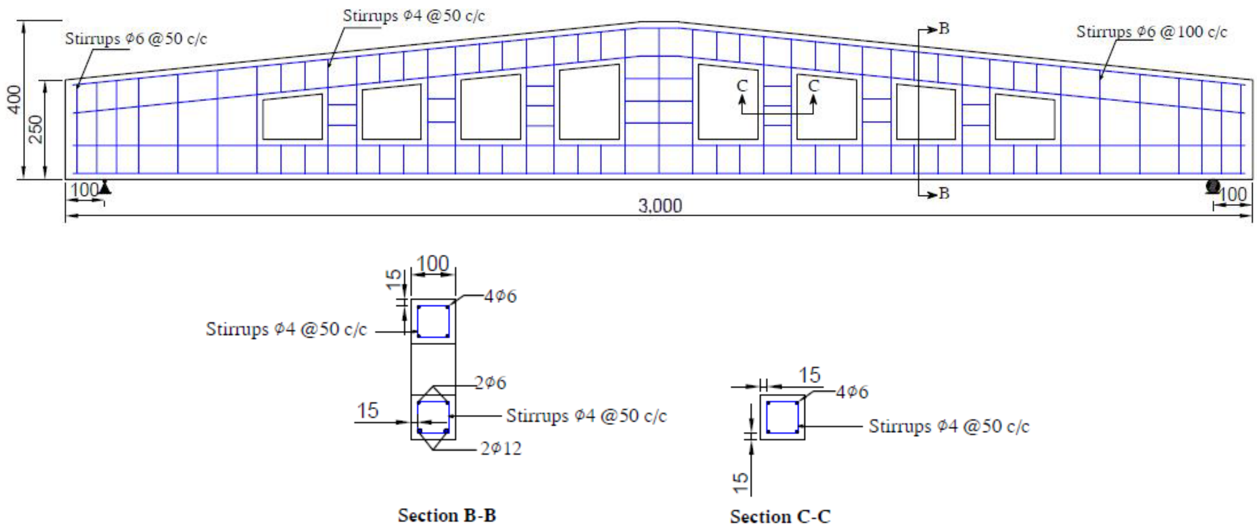

Figure 4. Typical details of steel reinforcement (GBT), (GBTS).

Note: All dimensions are in mm.

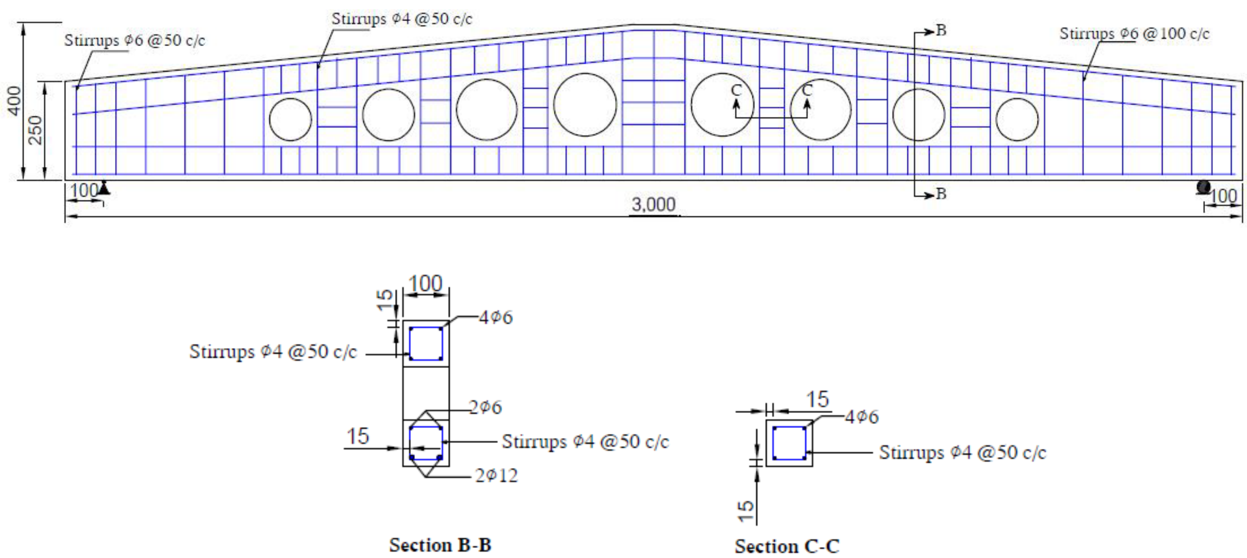

Figure 5. Typical details of steel reinforcement (GBC) and (GBCS).

Note: All dimensions are in mm.

For beam (GBS), strengthen with 100 mm wide for the bottom beams only. While beams (GBTS) and (GBCS) are strengthened with 100 mm wide for the bottom beams and 50 mm wide for the openings in a cross shape around the adjacent openings [19–23], as shown in **Figures 6–9**.

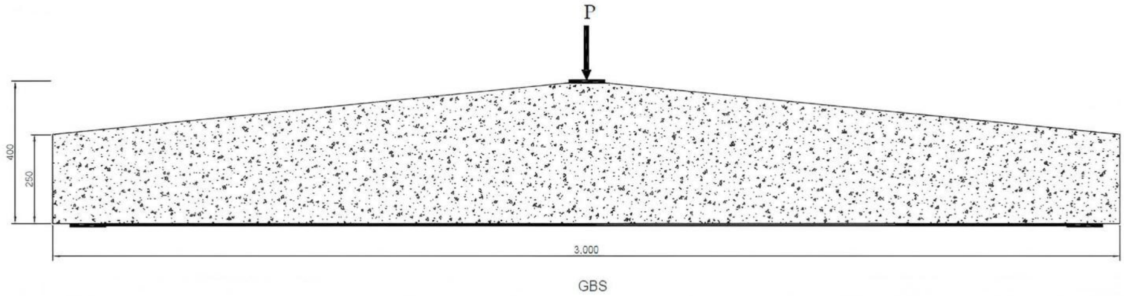

Figure 6. Schematic layout of gable beam (GBS).

Note: All dimensions are in mm.

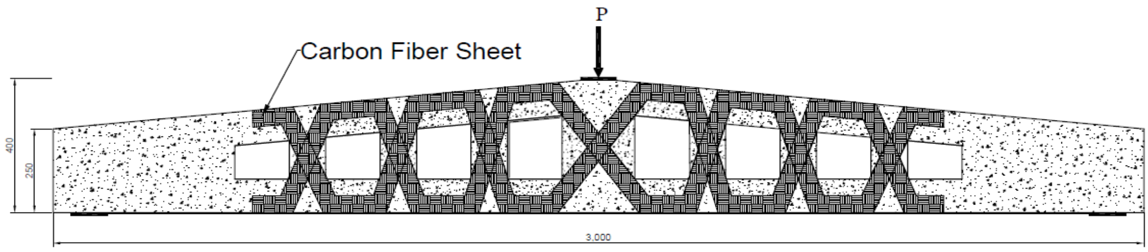

Figure 7. Schematic layout of gable beam (GBTS).

Note: All dimensions are in mm.

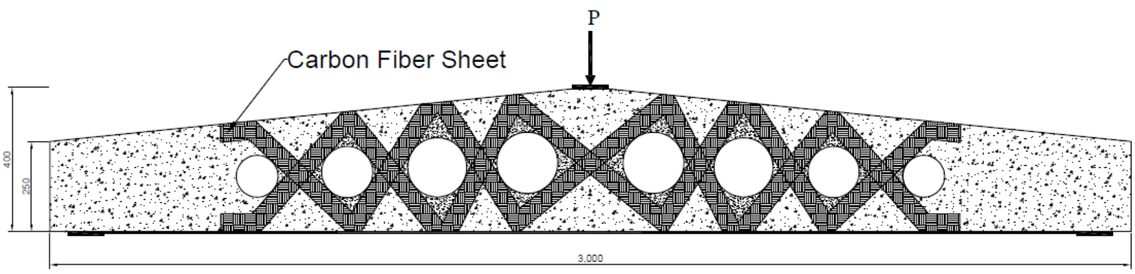

Figure 8. Schematic Layout of Gable Beams (GBCS).

Note: All dimensions are in mm.

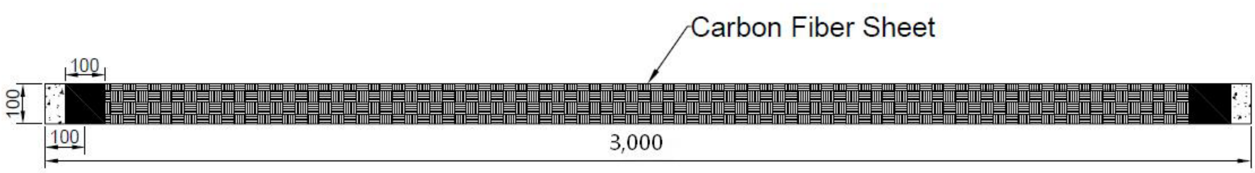

Figure 9. Bottom view of all the gable beams that are strengthened by CFRP.

Note: All dimensions are in mm.

Regarding the specifications of the openings (dimensions, number, location, shape, and distance between them) used in the reinforced concrete gable beam specimens studied in this study, they are illustrated in **Figure 10**.

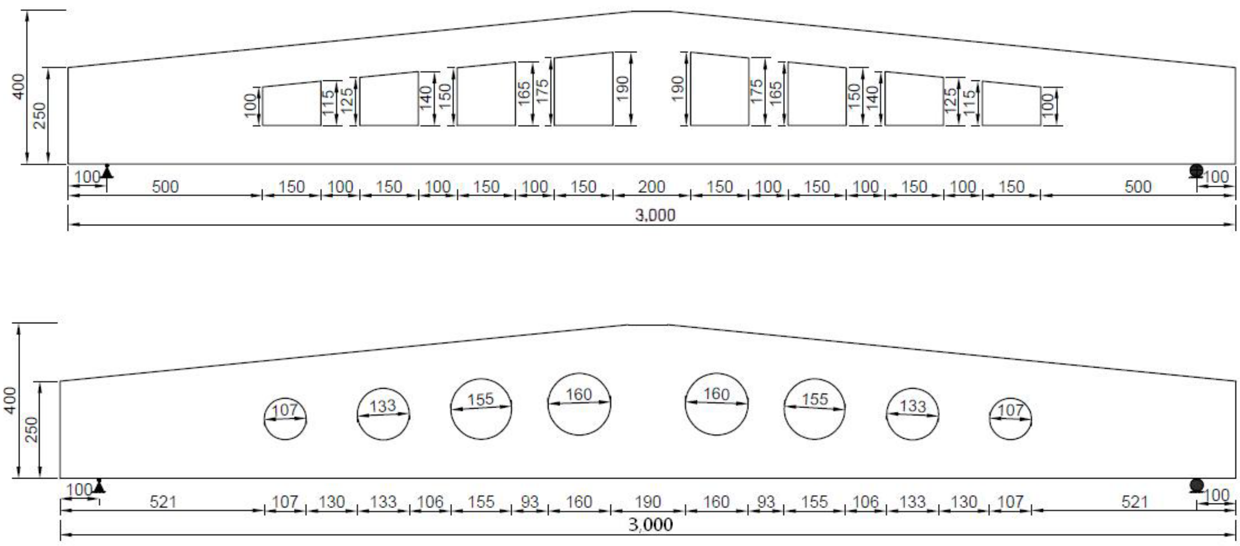

Figure 10. Shapes and dimensions of the openings used in the test specimens.

Note: All dimensions are in mm.

2.4. Casting and Curing of Reinforced Concrete Gable Beams

Before mixing, all quantities were weighed. The crushed gravel, sand, and cement were then mixed in a rotary mixer. Water was added to the mixture, half the total amount, and mixed for two minutes. Next, the superplasticizer was added to the remaining water and poured into the mixer. The concrete was then mixed for three minutes. After mixing, each form was poured in two layers. Fresh concrete was placed in the formwork, and the layer was compacted sufficiently using a laboratory rod vibrator. Vibration was continued for the second layer. A steel trowel was used to level and finish the concrete surface. As shown in **Figure 11**.

Figure 11. The process of casting specimens of reinforced concrete gable beams.

The openings were made using compressed cork cut with a CNC machine, 100 mm thick. The compressed cork pieces were cut according to the dimensions of each of the circular and trapezoidal openings and fixed to the molds using long screws. After pouring the reinforced concrete gable beam specimens, a polyethene (nylon sheet) was placed to cover the formwork to prevent cracking associated with shrinkage and water loss. All gable beam specimens were removed from the sides of the wooden form two days after pouring. Curing was carried out using a damp cloth and continuous soaking in water to ensure proper curing for 28 days [24–26] (**Figure 12**).

Figure 12. Curing of gable beam specimens.

2.5. Applying CFRP Sheet to Existing Reinforced Concrete Surfaces

The following is a summary of the procedures followed in implementing the carbon fiber reinforced polymer (CFRP) system. These steps were followed in accordance with the recommendations of the CFRP manufacturer and ACI Committee No. 440 [27], as shown in **Figure 13**. Scrub the concrete surface at the area where the carbon fiber reinforced polymer (CFRP) panels are attached to the concrete to remove any weak surface. After that, clean the concrete surface and remove dust by spraying it with water. CFRP sheets were cut to the required dimensions: 100 mm wide for the bottom beams and 50 mm wide for the openings in a cross shape around the adjacent openings. Mix epoxy Part A and Part B together according to the manufacturer's recommendations. Applying a thin layer of mixed epoxy to the concrete surface approximately 1.5 mm will result in the carbon fiber reinforced polymer sheets being impregnated after being placed on the concrete surface. Epoxy adhesive was applied to the sheet surfaces. Place carbon fiber reinforced polymer sheet on the concrete surface over the required area, which has been pre-coated with epoxy. Using a ribbed roller toward the sheet to remove air bubbles trapped behind the carbon fiber sheet. Finally, the adhesive was left to cure for at least seven days before testing the gable beam specimens.

Figure 13. Show how to apply the CFRP sheet to concrete surfaces.

2.6. Instrumentation

Testing reinforced concrete gable beams typically involves measuring various parameters related to the beam's behavior under load. The following are some common measurement techniques used in reinforced concrete gable beam testing to obtain accurate experimental data:

1. Linear variable differential transformer (LVDT) sensors are used to measure deflection. In this study, (3 LVDTs) were used, one in the middle of the span and two in the quarter of the gable beam span.
2. An optical micrometer is used to measure crack width.
3. Strain gauges with a strain indicator are used to measure strain in concrete.

2.6.1. Deflection Measurements

The LVDT sensors, as shown in **Figure 14**, were located at the mid-span and two quarter-spans of the gable beam and were used to measure the deflection of the gable beams. It allows for measuring the deflection with the load applied along the length of the gable beam.

2.6.2. Concrete and Steel Strain Measurements

A special type of electronic strain gauge, model (BMB120-80 A A (11) P2000-D), manufactured by Microstar Electric Company Limited, was used to measure the strain in the reinforcement and concrete as follows: Two strain gauges in the bottom reinforcement at the mid-span of the gable beam, where they were placed before the casting of the concrete gable beam's tension zone, one strain gauge was placed on the upper middle part of the concrete gable beam's compression zone. Before installation, the surface was smoothed and cleaned using a carbon-based abrasive cleaner. **Figure 15** shows the location of the concrete strain. Ordinary adhesive was used to fix the strain gauge to the prepared concrete surface.

2.6.3. Microscopic Observation

Crack width is the serviceability requirement for ensuring the integrity of structural concrete elements. Due to the limited tensile strength of concrete, reinforced concrete components are expected to fracture under service stresses. Crack control is crucial for maintaining an acceptable appearance and ensuring the longevity of concrete structures. This high-resolution microscope uses lenses that magnify and image micro-cracks up to ten times; it is equipped with an adjustable light source and high-capacity batteries, as shown in **Figure 16**.

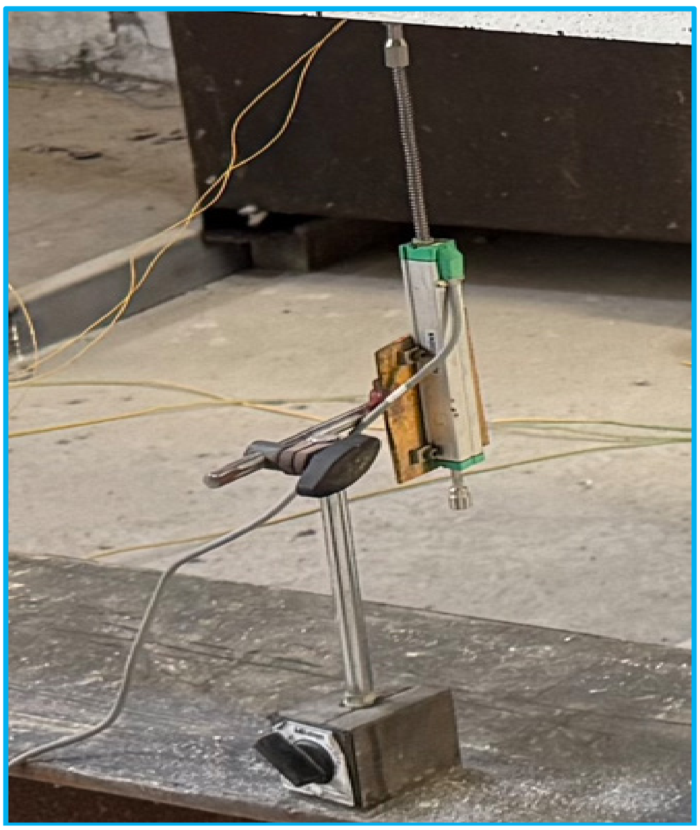

Figure 14. LVDT sensor used for deflection measurement.

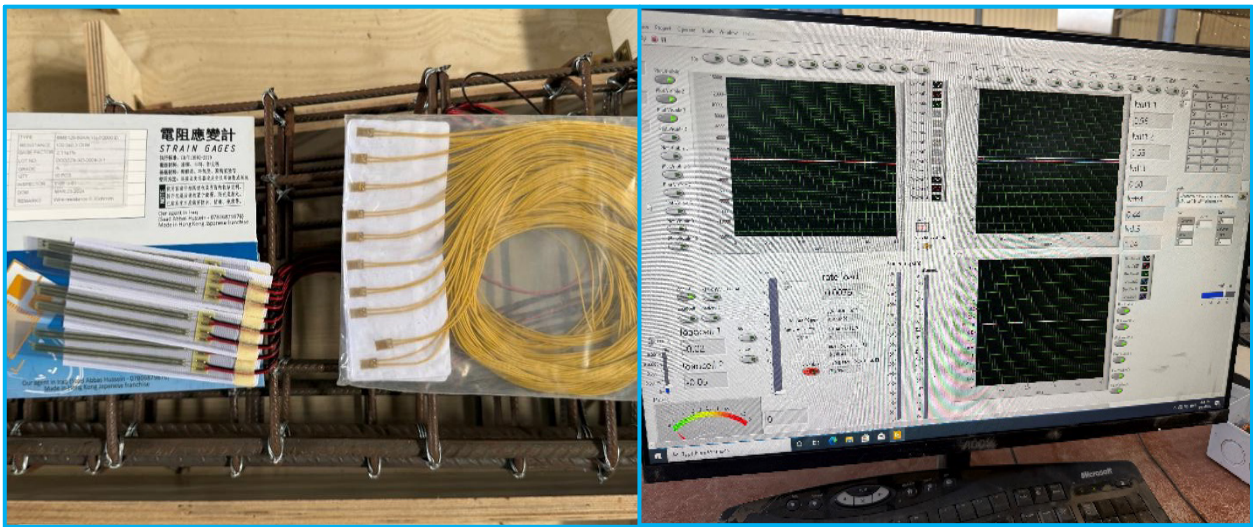

Figure 15. Strain indicator device and software interface window.

Figure 16. The microscope used in this study.

2.7. Testing Procedure

Specimens of the gable beams were placed inside the test frame and adjusted so that the linear variable differential transformers (LVDTs), the point load center at the mid-span, and the simple supports were aligned in their correct positions. All gable beams were tested under a monotonic load until failure [28–30]. The load was applied vertically to the upper middle surface of the reinforced concrete gable beams. The test began with a short initial loading cycle of approximately 2 kN to level the gable beams and maintain their position before the test commenced, then reduced to zero. Initial readings of all gauges were then recorded, and the gable beam was loaded at a constant rate in 5 KN increments, with the load gradually increasing until failure. The time period of each loading increment consisted of 10 min/stage. Strain and vertical displacement (deflection) readings were recorded at each loading stage, as shown in **Figure 17**. Crack formation and propagation were also investigated at each loading stage, and the initial cracking load and the gable beam failure load were recorded. The experiment involved testing gable beams specimens in a simply supported beam configuration. To prevent local bearing failure during testing, steel plates measuring 100 × 100 × 10 mm were placed at the load application and reaction points.

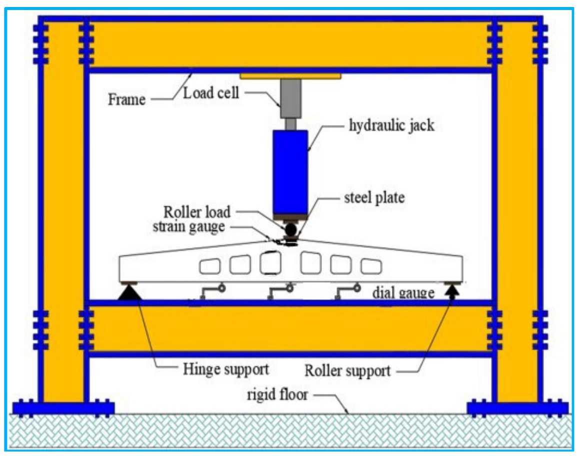

Figure 17. Test setup of gable beam specimen.

3. Experimental Results and Discussion

This section discusses the experimental results of six reinforced concrete gable beam specimens tested in the laboratory. The tested gable beam specimens were compared using load-deflection curves, ultimate load, failure mode and cracking pattern.

3.1. Load-Deflection Curves

3.1.1. Studying the Effect of Strengthening with CFRP

Figure 18 shows the load-deflection curves for reinforced concrete gable beam specimens, both strengthened and unstrengthened with CFRP. We observe that the load-deflection curves for reinforced concrete gable beams strengthened with CFRP (GBS, GBTS, GBCS) are more linear than those for reinforced concrete gable beams not strengthened with CFRP (GB, GBT, GBC). This indicates that CFRP strengthening increases stiffness, thus reducing deflection and increasing the load.

3.1.2. The Negative Effect of Openings in Reinforced Concrete Gable Beams

From **Figure 19**, we can investigate the effect of the existence of openings in reinforced concrete gable beams on the structural behavior. It is noted that the openings have a negative effect on the structural behavior of the gable beams, as they reduce the stiffness of the specimens, increasing deflection and reducing the load-bearing capacity. This is consistent with what the researchers Hassan and Izzet [16] concluded. We also note that circular openings are better than trapezoidal openings in reducing the stiffness of the tested samples, due to the absence of stress concentration in circular openings.

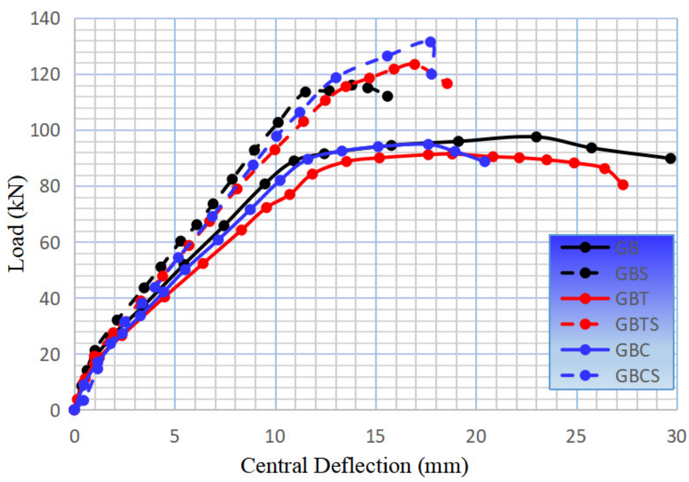

Figure 18. Load-deflection curves for strengthened and unstrengthened gable beam specimens using CFRP.

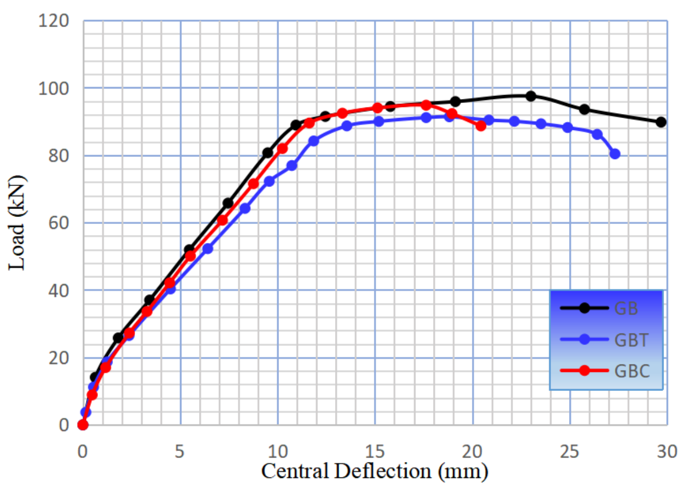

Figure 19. Load-deflection curves for gable beam specimens with and without openings.

3.2. Ultimate Load and Ultimate Deflection

The ultimate load capacities and corresponding deflection values measured at the mid-span, right-quarter span, and left-quarter span of the tested reinforced concrete gable beams are summarized in the following table.

3.2.1. Studying the Effect of Strengthening with CFRP

From the experimental results shown in **Table 2**, we note that the CFRP reinforcement technique is very efficient and effective in increasing the ultimate load and reducing deflection, as the percentage increase in the ultimate load was 19%, 35%, and 38.6% when comparing sample GB with GBS, specimen GBT with GBTS, and specimen GBC with GBCS, respectively. The percentages of decrease in deflection of the mid-length of the specimens under the maximum load were 40%, 10%, and 0.6% when comparing specimen GB with GBS, specimen GBT with GBTS, and specimen GBC with GBCS, respectively.

Table 2. Ultimate load and ultimate deflection for gable beam specimens.

Specimen Symbol	Ultimate Load P_u kN	Ultimate Deflection, mm		
		Left	Center	Right
GB	97.5	14.06	23.01	13.95
GBS	116.1	4.82	13.82	4.75
GBT	91.4	11.56	18.82	11.70
GBTS	123.4	10.18	16.94	10.27
GBC	94.8	10.63	17.62	10.54
GBCS	131.4	8.71	17.73	8.74

3.2.2. The Negative Effect of Openings in Reinforced Concrete Gable Beams

The percentage decrease in the ultimate load was 6.2% and 3% when comparing specimen GB with GBT and GBC, respectively. This decrease indicates the negative effect of the presence of the openings. Also, it is worth noting that the percentage decrease in the ultimate load due to the presence of circular openings is less than that of trapezoidal openings due to the good distribution of stresses in the circular openings. This is consistent with what the researchers Mohammed and Izzet [8] concluded. So as to eliminate the negative effect of the openings in the reinforced concrete gable beams, the gable beams were strengthened with CFRP. If the ultimate load of the GBTS specimen is compared with the GBT specimen, we notice that the ultimate load has increased by 35%, and this indicates the efficiency of the CFRP strengthening technique.

3.3. Cracking Pattern and Failure Mode

In order to discuss the cracking pattern and failure mode of the reinforced concrete gable beam specimens studied in this research, **Figure 20** was created.

3.3.1. Studying the Effect of Strengthening with CFRP

Referring to **Figure 20**, specifically the images of specimens GB and specimen GBS, we observe that the number of cracks in specimen GBS is lower than in specimen GB. This is attributed to the CFRP strengthening technique, which reduces the number of cracks and slows their appearance. The failure mode for specimen GB is flexural failure, as shown in **Figure 20**, where the main crack was located in the middle and under load, i.e., in the area of the maximum bending moment. The failure mode for specimen GBS is CFRP debonding followed by flexural failure. This is because of the CFRP debonding from the concrete layer because of its high tensile strength compared to the epoxy adhesive.

3.3.2. The Negative Effect of Openings in Reinforced Concrete Gable Beams

When comparing the images of specimen GB with those of specimen GBT and specimen GBC, we observe that the number of cracks in specimen GB is lower than in specimens GBT and GBC. This is due to the presence of openings, which increase the number of cracks and accelerate their appearance, thus reducing the stiffness of the reinforced concrete gable beams. The failure mode for specimens GBT and GBC, which contain eight consecutive trapezoidal and circular openings symmetrically distributed around the specimen's centerlines, is Vierendeel failure. This is consistent with what the researchers Hassan and Izzet [16] confirmed. Vierendeel failure, or top chord shear and compression failure, is a common failure in beams with large openings, where the shear forces from the applied loads cannot be transferred through the missing section. The upper and lower sections surrounding the opening resist these forces, generating bending moments called Vierendeel moments. While the failure mode for the two specimens, GBTS and GBCS, was CFRP debonding followed by Vierendeel failure.

3.4. Deflected Shape

In order to understand how reinforced concrete gable beams behave under the effect of external loads, what the shape of the deflected reinforced concrete gable beams was, and to study the variables that affect it, the deflected shape diagrams at ultimate load for all the tested specimens were drawn and their results discussed.

3.4.1. Studying the Effect of Strengthening with CFRP

From **Figure 21**, the effect of CFRP strengthening on the deflection shape of reinforced concrete gable beams can be generally observed. CFRP strengthening reduces deflection. It was also noted that post reinforcement between openings reduces deflection in reinforced concrete gable beams with trapezoidal or circular openings.

Figure 20. Crack pattern and failure mode of the tested gable beam specimens.

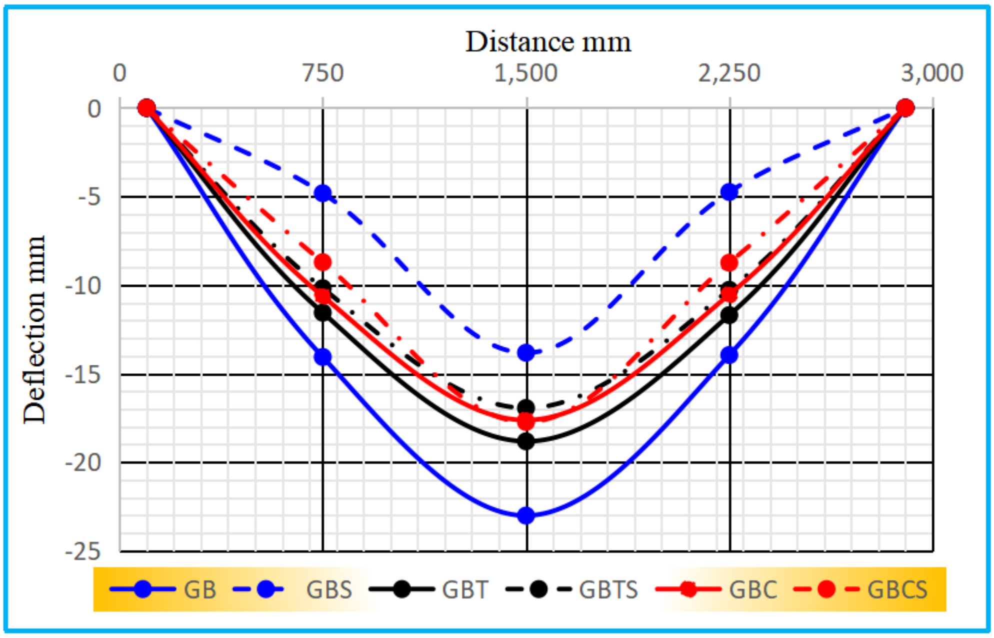

Figure 21. Effect of strengthening with CFRP on deflected shape for reinforced concrete gable beams.

3.4.2. The Negative Effect of Openings in Reinforced Concrete Gable Beams

The ultimate mid-span deflection values for specimens GBC and GBT were compared with those of the control specimen GB, revealing a reduction in deflection of approximately 23.4% and 18.2%, respectively. This behavior is attributed to the presence of post reinforcement between the openings. Furthermore, the experimental results indicate that the circular shape represents the optimal geometry for openings in reinforced concrete gable beams, as demonstrated in **Figure 22**.

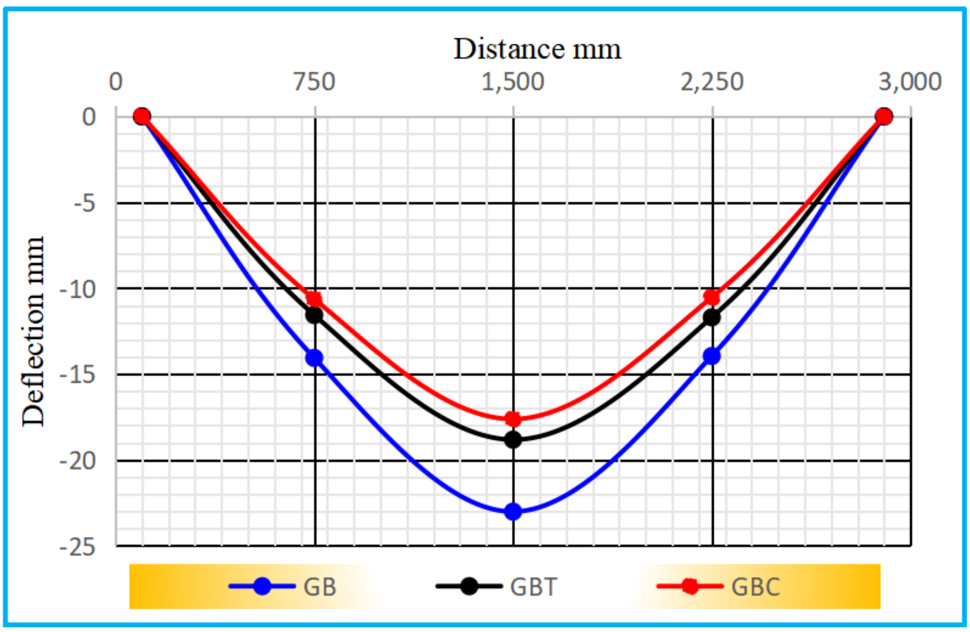

Figure 22. Effect of openings on deflected shape for reinforced concrete gable beams.

3.5. First Crack Load

The first crack load for all tested reinforced concrete gable beam specimens is listed in the following figure. The following two case studies will be discussed separately.

3.5.1. Studying the Effect of Strengthening with CFRP

Figure 23 shows the effect of CFRP reinforcement on the first crack load of reinforced concrete gable beams. CFRP reinforcement delays the appearance of the first crack by increasing the load that causes it to appear. The increase in the load of the first crack is approximately 82.35% when comparing the GBS specimen with the control specimen GB, 66.67% when comparing the GBT specimen with GBTS, and 75% when comparing the GBC specimen with the GBCS specimen. This increase in first crack load for specimens strengthened with CFRP is attributed to the mechanical properties of the CFRP strengthening material.

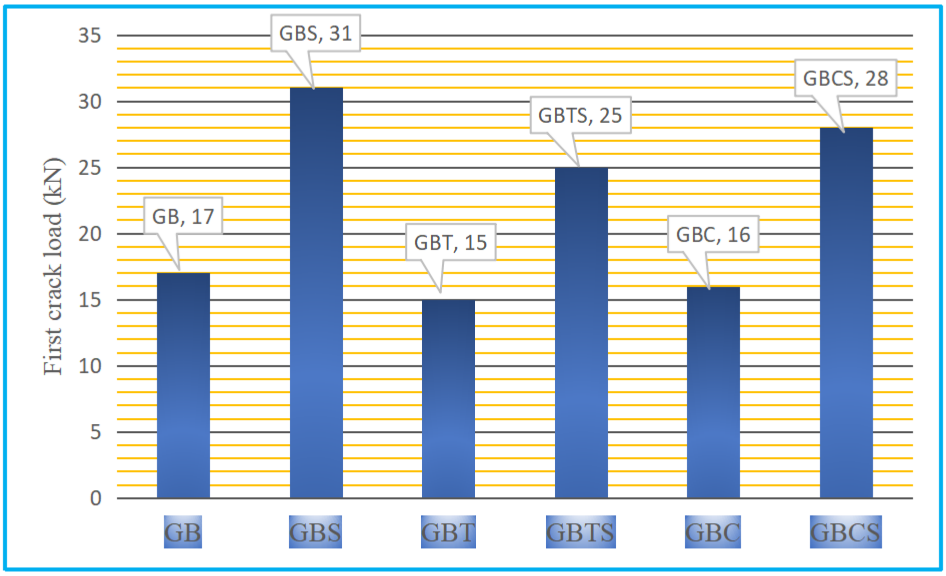

Figure 23. Effect of strengthening with CFRP on first crack load for reinforced concrete gable beams.

3.5.2. The Negative Effect of Openings in Reinforced Concrete Gable Beams

The experimental results of the first crack load for the tested GB, GBC, and GBT specimens, as shown in **Figure 24**, revealed a decrease of 11.76% and 5.88% in the first crack load compared to GBT and GBC specimens, respectively. Therefore, it can be concluded that the openings in reinforced concrete gable beams, whether circular or trapezoidal, negatively affect the first crack load and cause cracks to appear earlier. This is similar to the conclusion of the researchers Mohammed and Izzet [8]. Furthermore, the effect of circular openings on the first crack load is less pronounced than that of trapezoidal openings due to the better stress distribution in circular openings, whereas trapezoidal openings have a stress concentration at the opening corner.

3.6. Concrete and Steel Reinforcement Strain

As mentioned previously in Section 2.6.2, the strain of the concrete was measured in the compression zone, and the strain of the tensile reinforcement steel was measured by attaching strain sensors to two bars and then taking the average reading. We will discuss the effect of the study variables on strain in concrete or in reinforcing steel.

3.6.1. Studying the Effect of Strengthening with CFRP

As shown in **Figure 25**, the flexural strain results for the concrete and reinforcing steel under the failure load of the GBT specimen (91.4 kN) are plotted. From **Figure 25**, we can conclude that the CFRP strengthening technique is very efficient in reducing the strain of the concrete or reinforcing steel for all reinforced concrete gable beam specimens, with or without openings. The reduction in concrete strain reached 33.3% when comparing the GBS specimen with the GB specimen, and the reduction in reinforcing steel strain reached approximately 32.5% when comparing the GBTS specimen with the GBT specimen.

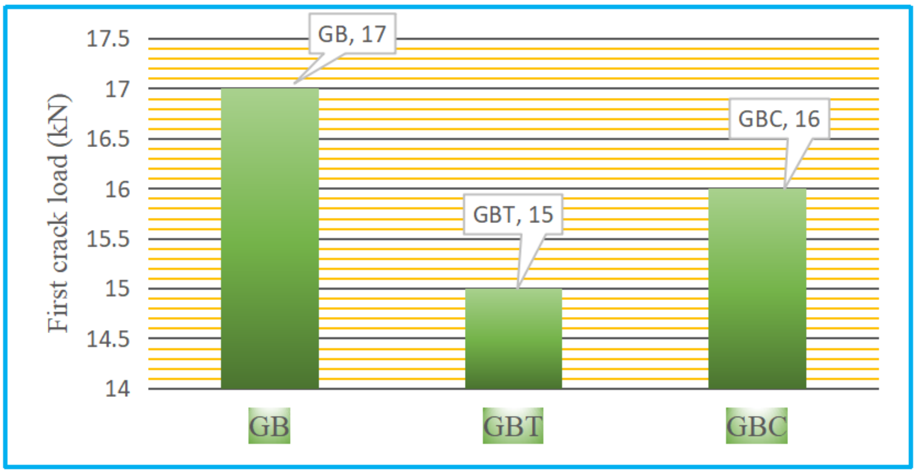

Figure 24. Effect of openings in reinforced concrete gable beams on first crack load.

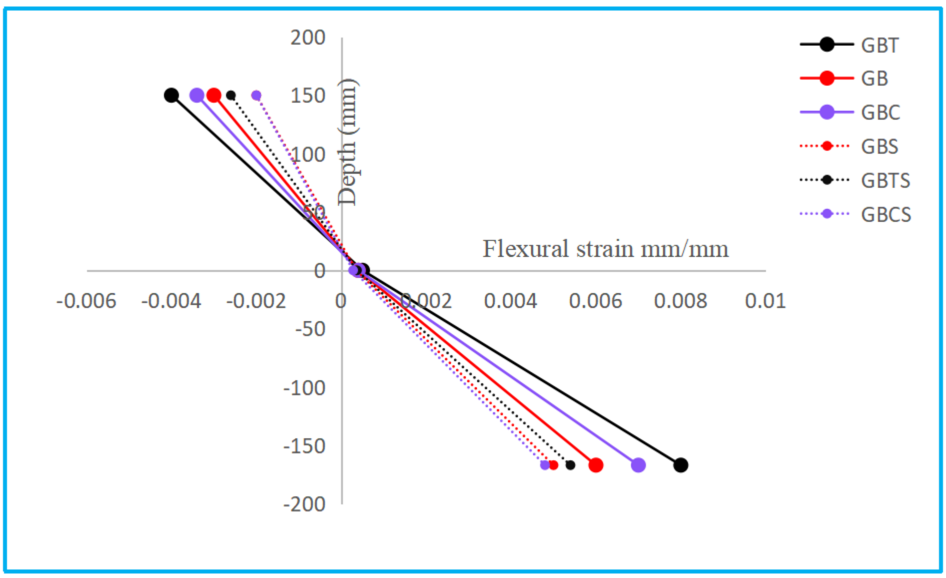

Figure 25. Effect of strengthening with CFRP on flexural strain profiles through the concrete depth of the tested gable beams.

3.6.2. The Negative Effect of Openings in Reinforced Concrete Gable Beams

To determine and study the negative effects of circular and trapezoidal openings on the strains of concrete and tensile reinforcement, **Figure 26** was drawn based on experimental results under the failure load of specimen GBT (91.4 kN).

The results showed that the presence of openings in reinforced concrete gable beams increases the strains in both the concrete and tensile steel reinforcement. This is entirely consistent with the conclusion of the researcher Maryam [17]. Specifically, the concrete strain increased by 13.3% when comparing specimen GBC to specimen GB, and the tensile reinforcement strain increased by 16.7% when comparing specimen GBC to specimen GB.

3.7. Crack Width

Figure 27 shows the cracking widths under the service load for the control specimen GB and all other reinforced concrete gable beam specimens.

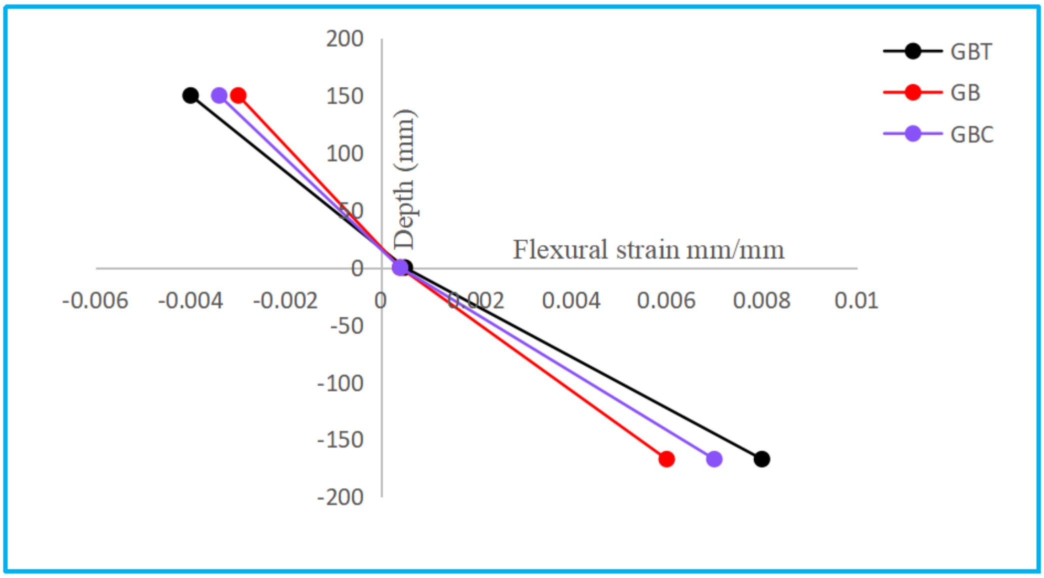

Figure 26. Effect of openings on flexural strain for concrete and steel reinforcement of the tested gable beams.

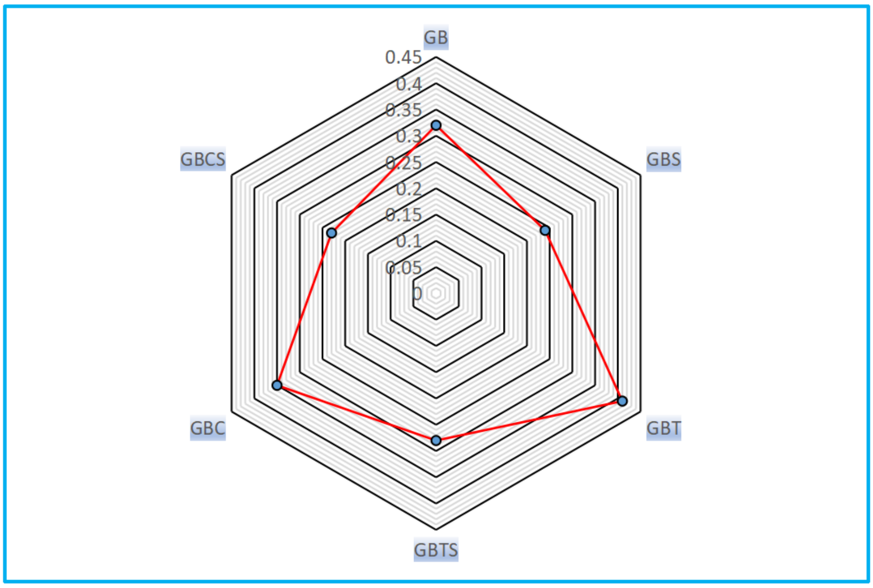

Figure 27. The crack width for all tested gable beam specimens under the service load of the control specimen GB.

Because the crack width is a service requirement, it was studied in relation to the service load. In order to compare the crack width values of the tested gable beam specimens, they were compared to a unified value, which is the service load value of the control specimen GB. For the purpose of studying the variables, they are discussed as follows.

3.7.1. Studying the Effect of Strengthening with CFRP

The results of the tests on the reinforced concrete gable beam specimens showed that the CFRP strengthening technique is very effective in reducing the crack width, as the percentage of reduction in crack width reached about 25% when comparing specimen GB with specimen GBS, 32% when comparing specimen GBT with specimen GBTS, and 34% when comparing specimen GBC with specimen GBCS.

3.7.2. The Negative Effect of Openings in Reinforced Concrete Gable Beams

The laboratory results of this study confirmed that the presence of circular or trapezoidal openings in reinforced concrete gable beams increases the crack width.

The increase was approximately 28% when comparing specimen GBT with specimen GB, and approximately 10% when comparing specimen GBC with specimen GB. Therefore, it can be concluded that circular openings are superior to trapezoidal openings in terms of crack width. This is due to their ability to distribute the stresses generated by the loads applied to the gable beam without creating stress concentrations at their edges.

4. Conclusions

This study investigated the structural behavior and strengthening of non-prismatic reinforced concrete gable beams with web configurations using externally bonded CFRP sheets. Based on the experimental findings and the verification of the research goals, the following sequential conclusions are drawn:

1. The primary objective of this research was successfully achieved by effectively addressing a critical research gap concerning the structural degradation of variable-depth elements induced by web configurations. The experimental program verified that the application of non-destructive strengthening using composite materials can restore the structural integrity and design requirements of perforated gable beam systems.
2. The proposed research hypotheses regarding web perforations were fully confirmed. Incorporating web openings in reinforced concrete gable beams, whether circular or trapezoidal, negatively affects the first crack load and causes cracks to appear earlier. The presence of these openings increases the structural strains in both the concrete and the tensile steel reinforcement, reducing the overall stiffness of the specimens and increasing deflection.
3. The laboratory results confirmed that inducing openings increases the crack width under service loads by approximately 28% for specimen GBT and 10% for specimen GBC when compared to the control specimen GB. However, the circular shape represents the optimal geometry for openings in reinforced concrete gable beams. Circular openings exhibit a lower percentage decrease in ultimate load and superior crack control compared to trapezoidal ones due to their geometric capability to evenly distribute stresses without creating stress concentrations at the edges.
4. The hypothesis regarding the strengthening mechanism was validated, proving that the externally bonded CFRP technique is highly effective. The CFRP sheets successfully mitigated crack propagation, reduced internal strains, and recovered the ultimate capacity. Specifically, the percentage of reduction in crack width at service load reached about 25% when comparing specimen GB with GBS, 32% between GBT and GBTS, and 34% between GBC and GBCS.
5. The investigation successfully verified the failure behavior under monotonic point loading. Specimens GBT and GBC, containing eight consecutive openings symmetrically distributed, exhibited Vierendeel failure due to shear-critical stresses. However, the strategic application of cross-shaped CFRP sheets successfully shifted the failure modes away from premature Vierendeel failure toward a more ductile, flexural-dominated behavior preceded by controlled CFRP debonding.
6. The core novelty of this study lies in providing pioneering empirical data on the mechanical response, stress disturbances, and strain profiles of non-prismatic sections, which are heavily overlooked in traditional prismatic beam literature. The main contribution to the engineering community is the development of an optimized design scheme that safely achieves up to a 14% reduction in dead weight while allowing utility passages through circular web configurations without risking structural integrity.
7. Despite the conclusive findings, certain limitations were encountered during the experimental work. The study was constrained to elements tested under quasi-static monotonic loading at room temperature, without accounting for long-term creep, cyclic fatigue, dynamic loading, or elevated fire exposure. Additionally, the investigation was limited to un-prestressed elements with specific concrete compressive strengths (f_{cu} = 40 MPa). Future research tracks are recommended to explore pre-stressed configurations

and numerical validation.

Recommendations for Future Research

Based on the empirical findings and the inherent physical limitations of this study, the following sequential recommendations are proposed for future research tracks:

1. Future investigations should evaluate the structural response, fatigue life, and micro-crack propagation of CFRP-strengthened perforated reinforced concrete gable beams under dynamic, cyclic, and seismic loading conditions, moving beyond the quasi-static monotonic loading used in this study.
2. Research is highly recommended to investigate the long-term durability of the composite cross-shape CFRP configurations under elevated temperatures, fire exposure, and harsh environmental weathering, as well as the time-dependent effects of concrete creep and shrinkage around the web openings.
3. It is recommended to extend the material matrix beyond the conventional concrete strength (f_{cu} = 40 MPa). Future studies should explore the implementation of Ultra-High-Performance Concrete (UHPC) or alternative composite systems, such as Near-Surface Mounted (NSM) CFRP rods, to optimize weight reduction.
4. Given that this study examined un-prestressed specimens, conducting large-scale or full-scale experimental testing on pre-stressed reinforced concrete gable beams with web configurations is crucial to validate scaling effects and practical industrial boundary conditions.
5. Future works should develop rigorous non-linear Finite Element Method (FEM) models validated by the empirical data of this study. This will allow for extensive parametric investigations on varying web opening ratios, alternative opening shapes, and optimized fiber orientation angles.

Author Contributions

Conceptualization, W.H.N. and H.T.N.; methodology, H.T.N.; software, W.H.N.; validation, W.H.N. and H.T.N.; formal analysis, H.T.N.; investigation, W.H.N. and H.T.N.; resources, W.H.N.; data curation, W.H.N.; writing—original draft preparation, W.H.N.; writing—review and editing, H.T.N.; visualization, H.T.N.; supervision, H.T.N.; project administration, H.T.N.; funding acquisition, W.H.N. Both authors have read and agreed to the published version of the manuscript.

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The data used in this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflict of interest.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

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