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REVIEW

Gable Beams with Multiple Openings Subjected to Static Load: As a Review

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ABSTRACT

To reinforce and support long-span roofs, gable beams can be used. In order to reduce weight and to meet the requirements of modern construction in terms of passing electrical, sanitary and mechanical services, multiple openings must be created inside the gable beams. With those multiple openings in the gable beams, the structural performance of those beams and their architectural appearance will certainly improve. This research reviews the historical development, modeling methods, experimental research and design considerations of multiple-opening gable beams under the influence of static loads. This research is of particular interest to the cracking pattern, failure pattern, load-deflection curves, and reinforcement details related to gable beams with multiple openings. It also explains and reviews the modern and old techniques and strategies used to strengthen reinforced concrete gable beams with multiple openings and their importance in restoring the load-bearing capacity of gable beams and eliminating the negative impact of the presence of those openings. This review study recommends key design principles for reinforced concrete gable beams without openings, using the same design equations as for conventional reinforced concrete beams. However, if the reinforced concrete gable beams contain openings, they must be analyzed using appropriate software and treated like trusses to determine the internal forces within the beam. The beam is then designed based on the critical section between the support and the beginning of the first opening. This review study also identified the most significant parameters affecting the behavior of reinforced concrete gable beams: the presence of openings. Openings reduce the beam's load-bearing capacity by 3% to 18% and increase deflection by 6% to 70%.
Keywords: Non-Prismatic Beams; Gable Beams; Static Load; Multiple Openings; Reinforced Concrete; Review

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1. Introduction

In civil engineering, structural, service, and architectural requirements are among the most important factors in developing beam systems [1,2]. Among the most important of these systems, reinforced concrete gable beams have gained great importance due to their design, where their cross-section is non-prismatic, i.e., variable depth, as shown in **Figure 1**. This design balances bending moments and beam strength. Therefore, reinforced concrete gable beams achieve economy in the use of materials by reducing the depth at the supports and increasing it in the middle without reducing the beam strength. At the same time, modern buildings require the passage of plumbing and electrical services through structural beams, such as sewage pipes, water pipes, and electrical conduits. Therefore, it has become necessary to create openings in the reinforced concrete beams [3,4]. These openings reduce the building's floor height and the overall dead loads. However, the presence of these openings causes stress concentration in the reinforced concrete beams, especially in reinforced concrete gable beams, posing a challenge for structural designers due to the combination of stress concentration and depth variation [5,6].

The structural behavior of prismatic reinforced concrete beams with openings has been extensively studied, but research on reinforced concrete gable beams with multiple openings remains very limited. This represents a research gap that this study addresses. Therefore, this study aims to provide and summarize a set of available research concerning reinforced concrete gable beams, review historical developments, highlight the contributions of researchers in this field, and address the problems related to the design and analysis of this type of beam.

Figure 1. Reinforced concrete gable beam with multiple openings [5].

2. Research Methodology

This section outlines the general framework and systematic steps followed in studying this topic, starting with problem definition and reviewing previous research on gable beams, their differences from conventional beams, design recommendations, and key factors affecting the behavior of this type of beam, such as the presence of openings. This review study examined previous research on concrete beams with openings and their analytical principles. It also investigated the effect of multiple openings in gable beams, studied the geometry and structural characteristics of gable beams, and examined the structural behavior of gable beams under static loading. Furthermore, it explored reinforcement, detailing, and strengthening techniques for gable beams, compared gable beams with prismatic beams, and finally, identified the most important conclusions related to this type of beam.

3. Literature Review of Research on Reinforced Concrete Beams with Web Openings

3.1. Early Investigations (1950s–1970s)

In the 1950s, experimental studies began on reinforced concrete beams with web openings due to their necessity in commercial and industrial buildings to pass water pipes, sewage pipes, air conditioning and heating pipes through them, as well as fuel transport pipes in industrial buildings and other essential services in buildings. In 1968 [7], Prentzas investigated the structural behavior of reinforced concrete beams with web openings by conducting an experimental study in laboratories and measuring the maximum load, the deflection in the middle span at the maximum load, and the service load, which represents 70% of the maximum load. They concluded that the presence of openings alters the cracking pattern and significantly reduces the shear strength of beams. They also concluded that the presence of openings in the reinforced concrete beams used in this study has a negative effect on their load-bearing capacity, and they confirmed that traditional beam theory cannot be applied to reinforced concrete beams with large web openings.

In 1973, Somes and Corley [8] studied the distribution of shear forces around openings and the concentration of stresses. Furthermore, they investigated the cracking pattern and the growth of diagonal cracks. They reached a number of important conclusions, the most important of which is the presence of stress concentrations at the corners of the opening, which causes the beginning of cracking, and this cracking continues until it leads to failure. In 1977, Salam [9] investigated the structural behavior of reinforced concrete beams with web openings of varying shapes and locations. This was done by conducting an in-depth experimental study and casting and modelling several laboratory test samples of reinforced concrete beams containing openings. He reached a crucial conclusion: the shape and position of the opening relative to the neutral axis directly influence the failure pattern. Therefore, these studies are considered fundamental to understanding the structural behavior of reinforced concrete beams with web openings.

3.2. Development of Analytical Concepts (1980s–Present)

In the late 20th century, the theory of strut-and-tie modeling (STM) was widely used in the design and analysis of discontinuous areas in reinforced concrete beams and applied to reinforced concrete beams with openings to understand how loads are transferred around these openings through compression struts and tension ties [10]. The publication of Mansur and Tan's 1999 book [11], "Concrete Beams with Openings: Analysis and Design," revolutionized the field of analysis and design of reinforced concrete beams with web openings. This book compiled a large number of experimental and analytical studies spanning decades and established the design and analytical foundation for reinforced concrete beams with web openings. Although the book focuses on prismatic beams, its principles have been applied to the design and analysis of reinforced concrete gable beams with multiple openings.

According to Baykov and Seagal [12], the guidance for defining the position and size of openings was known. The researchers suggested the following for their research: (1) Openings must not be positioned closer to the supports than half of the total beam height (H). This is to evade sudden shear failure and reinforce congestion in the critical area. The location of an opening near to half of the total height of the beam should also be avoided at any concentrated load. (2) In the I-beam or T-beam, the openings should be located level with the flange. Square or rectangular beams frequently include openings centered on cross-section of beam, while these openings are essential for eccentric height locating. The reinforcing steel bars in the chord components below or above the opening must have adequate concrete cover. There has to be suitable height to the element to strengthen touching shear stresses efficiently and there needs to be adequate concrete areas in the compression region to provide the ultimate compression block during flexure. (3) The distance between one opening and another must be greater than or equal to the total height of the reinforced concrete beam in order to ensure that the opening behaves individually when using a number of openings spread over a specific length of the reinforced concrete beam. (4) The height of opening should not exceed 55.0% of the total beam height. (5) Using several openings is better than using one large opening. This leads to improved structural properties of the areas above and below the openings, as well as the formation of columns between the openings that transfer the stresses generated by external loads.

An experimental study was conducted by Abdalla and Kennedy [3] on prestressed reinforced concrete beams with tetrahedral openings to investigate the cracking patterns caused by prestressing and external loads applied perpendicularly to the beam plane. The study focused on determining the cracking patterns and deflection rates in two phases: the initial loading phase and the service load phase. This study involved casting and testing thirteen prestressed reinforced concrete beam specimens with subsequent tension. The prestressed concrete beam specimens were divided into three groups: the first group consisted of two I-shaped beams; the second group consisted of five T-shaped beams; and the third group consisted of six rectangular beams. The study aimed to find a method for calculating the initial crack load for different crack patterns, with two illustrative examples demonstrating the application of this method. Laboratory test results revealed five different crack patterns, as shown below and in **Figure 2**. a) First crack pattern: These cracks are horizontal, extending along the longitudinal axis of the beam at the edges of the openings. They are caused by prestressed tensile forces applied to the prestressed reinforced concrete beams. b) Second crack pattern: These cracks are located at the corners of the openings and are inclined at a specific angle to the horizontal, starting from the corner of the opening. This type of crack is caused by the concentration of stresses at the corners of the four-sided openings due to the application of external vertical loads to the prestressed reinforced concrete beams. c) Third cracking pattern: These cracks occur due to the development and increase of shear forces generated by the application of vertical external loads. They are inclined at an angle to the horizontal and are generated in the middle of the opening's side. d) Fourth cracking pattern: These cracks occur at the corners of openings and along the length of the opening's side. They are vertical in shape and start from the bottom, extending upwards. The cause of this cracking pattern is the generation of bending moments due to external loads applied to prestressed reinforced concrete beams. e) Fifth and final cracking pattern: This cracking pattern extends along the length of the lower side of the beam. The cracks are either vertical or start vertically and then incline at a certain angle. The cause of this cracking pattern is the combined effect of bending moments and shear forces generated by external loads applied to prestressed reinforced concrete beams. The last four cracking patterns occur during the service loading phase of prestressed reinforced concrete beams, while the first cracking pattern occurs during the initial loading phase. The study reached several conclusions, the most important of which are: 1) The fifth cracking pattern (e) occurs in prestressed reinforced concrete beams containing openings, where the layer below the opening is thin, and the presence of bending moments near the edges of the openings causes flange cracking even when under compression. 2) The third cracking pattern (c) and the fifth cracking pattern (e) cause complete failure of prestressed reinforced concrete beams. 3) Deep openings in prestressed reinforced concrete beams cause the occurrence of the third cracking pattern (c) and the fourth cracking pattern (d).

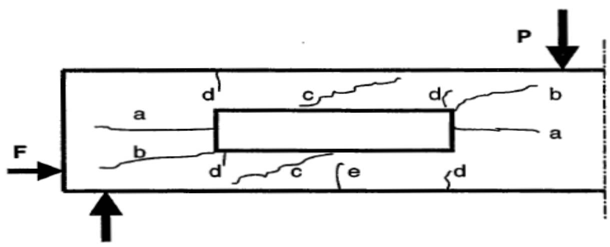


Figure 2. Crack patterns in prestressed reinforced concrete beams containing openings.

Source: Abdalla and Kennedy (1995) [3].

Amiri and Alibygie [13] conducted a laboratory study on the structural behavior of reinforced concrete beams with circular openings. The variables studied were the size of the opening, the location of the opening, the placement of reinforcement around the opening to strengthen it, and finally, the type of concrete used, from ordinary-strength to high-strength concrete. The experimental program consisted of casting 15 reinforced concrete beam test specimens, divided into two groups. The first group included one reinforced concrete beam without openings, cast in ordinary-strength concrete, and nine reinforced concrete beams with openings, also cast in ordinary-strength concrete. The second group included five reinforced concrete beams with openings, cast in high-strength concrete. All reinforced concrete beam specimens were tested under two-point loads with simple supports. The most important conclusion reached by the researchers in this study is that the diameter of the opening has a negative impact on the load-bearing capacity of the tested reinforced concrete beams. This effect is particularly pronounced when the opening diameter exceeds one-third of the total height of the reinforced concrete beam. They also concluded that the location of the opening has a significant impact on the ultimate load of the tested reinforced concrete beams. Furthermore, the researchers observed that using reinforcement around the opening is highly beneficial for reducing crack propagation and narrowing the crack width around the openings. They recommended its use as a method of strengthening openings, especially those that are inclined or perpendicular to the direction of the shear crack. They also noted that increasing the strength of the concrete and improving its mechanical properties plays a significant role in enhancing the load-bearing capacity of reinforced concrete beams containing openings and mitigating the negative impact of the openings on the load-bearing capacity of these beams. The experimental results obtained from this study were compared with equations found in several codes.

In 2013, Oukaili and Shammari [14] conducted an experimental study on reinforced concrete beams with openings and a T-shaped cross-section (**Figure 3**). The results showed that strengthening the area around the openings compensated for the decrease in shear strength caused by these openings. Reinforced concrete beams with a T-section containing six or four openings, strengthened with steel bars, exhibited a 27% and 45% increase in shear strength, respectively, equivalent to 86% and 89% of the shear strength of reinforced concrete beams without openings. Meanwhile, carbon fiber reinforced polymer (CFRP) beams showed increases of 32% and 92%, equivalent to 92% and 114% of the load-bearing capacity of reinforced concrete beams without openings, respectively.

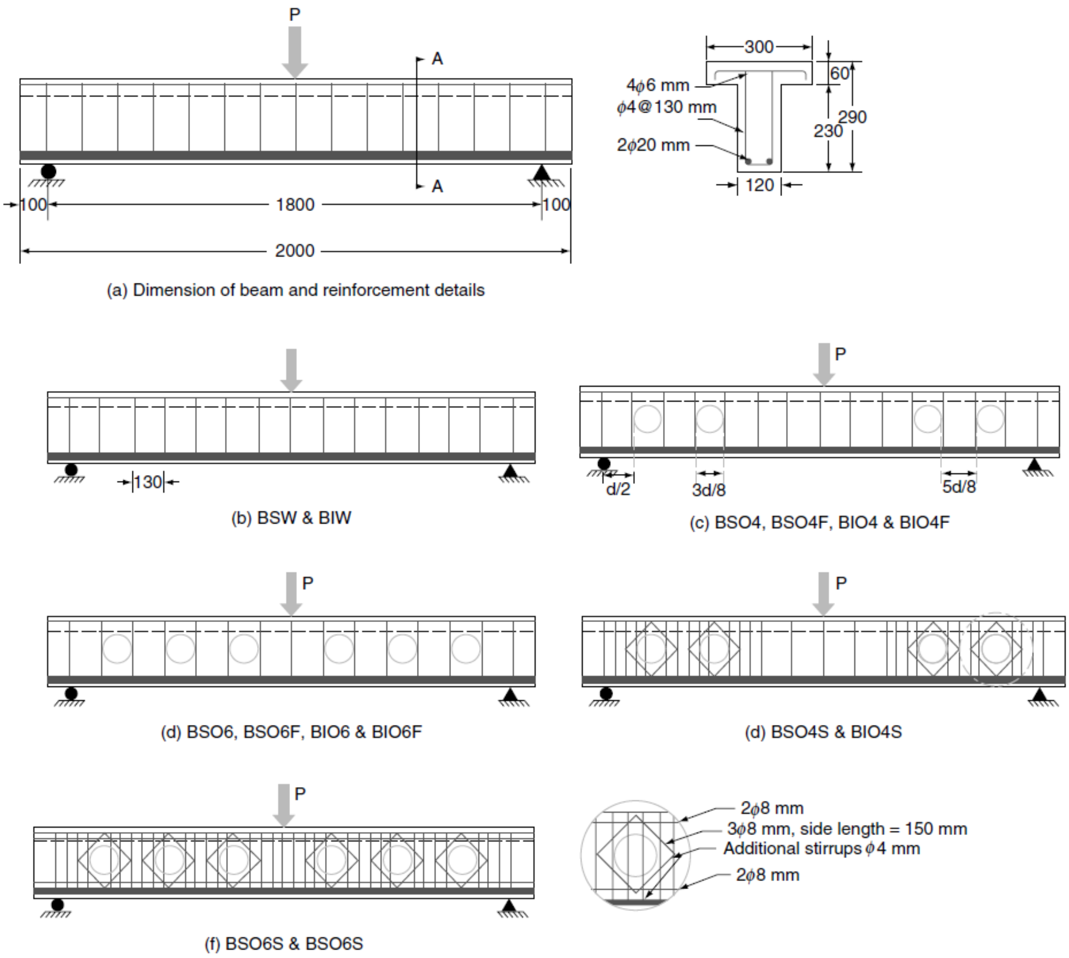


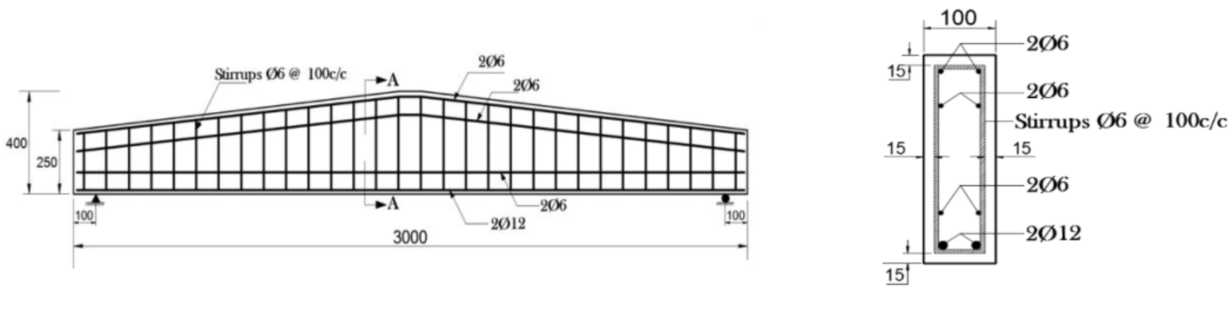
Figure 3. Details of beam specimens.

Source: Oukaili and Shammari (2013) [14].

Al-Sheikh [15] conducted a laboratory investigation into the structural behavior of reinforced concrete beams containing openings, tested under two-point loads and simple support. The laboratory program for this investigation consisted of casting and pouring twenty-seven reinforced concrete beam specimens, one of which did not contain openings, while the remaining twenty-six reinforced concrete beam specimens contained openings. The variables studied in this investigation were: 1) the size of the opening in the reinforced concrete beams; 2) the change in the position of the opening along the length of the reinforced concrete beam; and 3) the change in the shape of the openings. The test specimens of the reinforced concrete beams were evaluated based on the value of the ultimate load, the cracking pattern, and the type of failure. Load-deflection curves were also plotted for all the tested reinforced concrete beam specimens. Based on the experimental results of the tested reinforced concrete beams, it was observed that the reduction in the ultimate load of reinforced concrete beams with openings in the shear zone is greater than the reduction in the ultimate load of reinforced concrete beams with openings in the bending zone. This indicates that the optimal location for openings in reinforced concrete beams is in the bending zone, and openings in the shear zones are not recommended. Furthermore, the researchers concluded that the reduction in the ultimate load of reinforced concrete beams due to the presence of openings is directly proportional to the size of the opening; that is, increasing the size of the opening increases the reduction in the ultimate load. They also concluded that rectangular openings are better than square openings, given a constant total opening area. They observed that rectangular openings reduce the reduction in the ultimate load by 4% compared to square openings. They also found that circular openings are better than both square and rectangular openings, and they represent the best choice for the shape and geometry of openings in reinforced concrete beams, as they reduced the percentage of decrease in the ultimate load by 8% compared to square openings. In 2018, Jassim and Jarallah [16] conducted a scientific experiment to study the structural behavior of reinforced concrete beams with large openings. The variables in this study were the size of the opening, its location along the length of the beam (sometimes in the bending zone, sometimes in the shear zone), and the number of openings (e.g., beams without openings, beams with one, two, or three openings). The researchers also sought to mitigate the negative impact of the opening on the load-bearing capacity of the reinforced concrete beams. To achieve this, they reinforced the opening area using high-performance powder concrete: once below the opening (in the tension zone), once above the opening (in the compression zone), and finally, once both below and above the opening (in the tension and compression zones). To study these variables, they cast 12 reinforced concrete beam specimens. All the beam specimens were tested under two-point loads and simple support. The tested reinforced concrete beam models were evaluated based on the failure load, mid-span deflection, crack pattern, crack width, load-deflection curve, failure type, and strains in the reinforcing steel and concrete. From the experimental results, the researchers concluded that increasing the opening size leads to a greater reduction in the failure load of the reinforced concrete beam. They also found that openings in the shear zone are significantly more detrimental than those in the bending zone. Furthermore, the laboratory results showed that the number of openings is directly proportional to the rate of load-bearing capacity reduction in the reinforced concrete beams, regardless of whether the openings are located in the shear or bending zones. They also found that using reactive powder concrete in the opening zone has a very significant effect on increasing the load-bearing capacity of reinforced concrete beams containing openings. This increase in load-bearing capacity almost negates the effect of the opening, meaning that the failure load of reinforced concrete beams containing openings and strengthened with reactive powder concrete is approximately equal to the failure load of reinforced concrete beams without openings. The results also showed that the increase in load-bearing capacity of reinforced concrete beams containing openings in the shear zone and strengthened with a layer of reactive powder concrete in both the tension and compression zones was 47%, compared to homogeneous reinforced concrete beams containing two openings in the shear zone. However, the increase in load-bearing capacity was very small in reinforced concrete beams containing openings and strengthened with a layer of reactive powder concrete only in the tension zone. This confirms the necessity of strengthening openings using reactive powder concrete in both the tension and compression zones. Shubbar et al. [17] conducted a theoretical analytical study using the ABAQUS software to investigate the structural behavior of reinforced concrete beams with circular openings. The study focused on the effect of opening size and location on load-bearing capacity and deflection of these beams. Overall, the researchers concluded that the opening size is directly proportional to the decrease in load-bearing capacity of the reinforced concrete beams due to the negative impact of the opening; that is, the larger the opening size, the greater the decrease in load-bearing capacity of the reinforced concrete beams. They also concluded that the optimal location for the opening is in the bending zones, and this was confirmed by the results, as the resistance of the reinforced concrete beams decreased by 6% to 13% when the opening was found in the bending zone, and this percentage increased to reach 36% when the opening was found in the shear zones. Likewise, the percentage increase in deflection in the middle of the beam space at the maximum load was 19.7% compared to the reinforced concrete beams without openings.

3.3. Emergence of Gable Beam Research (2000s–Present)

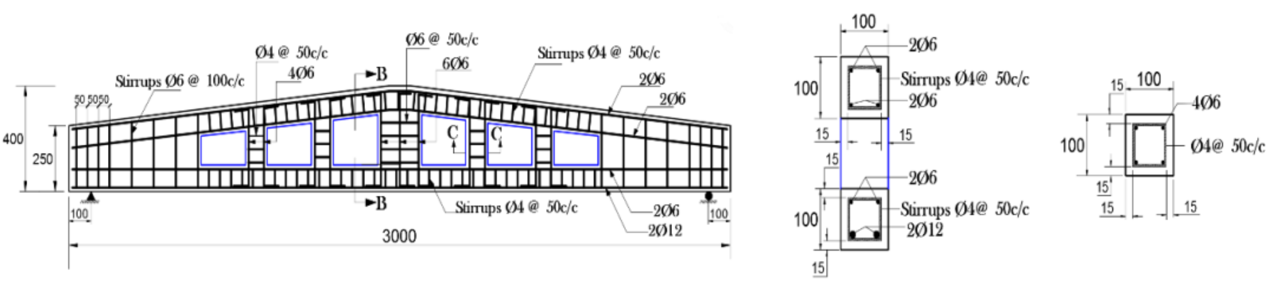
At the beginning of the first decade of the 21st century, research on reinforced concrete gable beams increased due to the significant rise in the use of large-span roofs. However, scientific studies combining multiple openings with gable architecture remained limited. Notably, Hassan and Izzet [18] conducted one of the first systematic experimental and numerical investigations on reinforced concrete gable roof beams with multiple openings under static loads (**Figures 4** and **5**). Their work demonstrated that opening shape (circular vs. quadrilateral) significantly influences load capacity, stiffness, and crack development. The experimental results on the models showed that the presence of openings in the gable beams reduced the maximum load-carrying capacity by approximately 2.3% to 17.9%, while the mid-distance deflection increased in the three load stages evaluated, increasing in the case of uncracking elastic loading, in the case of cracking loading, and in the case of maximum loading by approximately 6.1% to 53.4%, 3.7% to 75.7%, and 9.8% to 74.1%, respectively.



a- Reinforcement details **b- Section A-A**

Figure 4. Details of reinforcement for solid gable beam (all dimensions are in mm).

Source: Hassan and Izzet (2019) [18].



a- Reinforcement details` **b- Section B-B c- Section C-C**

Figure 5. Details of reinforcement for gable beam with openings (all dimensions are in mm).

Source: Hassan and Izzet (2019) [18].

Parallel research on steel cellular beams, notably by Tsavdaridis, provided valuable insights into opening interaction effects and vierendeel mechanisms, which, although material-specific, offer conceptual parallels applicable to reinforced concrete gable beams.

4. Geometry and Structural Characteristics of Gable Beams

4.1. Non-Prismatic Geometry

Gable beams are characterized by a linearly varying depth or a parabolic shape. This geometric shape aligns bending resistance with bending moment demand, reducing dead loads and it gives an irregular rigidity across the space. In 2022, researchers Dawood and Nabbat [19], from the Civil Engineering Department at the University of Babylon, conducted an experiment to investigate the effect of increasing the depth of reinforced concrete beams, once at the mid-span and again at the supports, on the failure mode of the beams. They cast a model with a total length of 1,500 mm, a depth of 220 mm at the supports, and a mid-span depth of 155 mm. A second model was of the same length but with a depth of 140 mm at the supports and 240 mm at the mid-span, as shown in **Figure 6**. The researchers found that the first model failed under a load of 59.79 kN, exhibiting flexural failure, while the second model failed under a load of 182.3 kN, exhibiting shear failure. The researchers concluded that increasing the depth at the mid-span is more effective than increasing the depth at the supports, and that the beam's geometry has a significant effect on its load-bearing capacity.

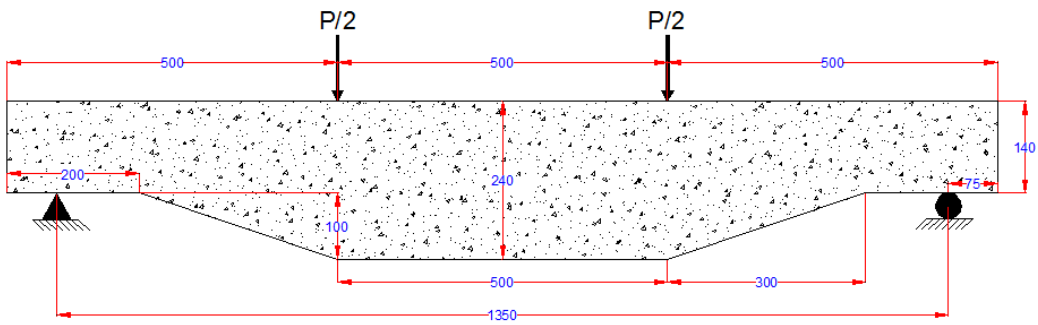


Figure 6. Details of non-prismatic reinforced concrete beams by researchers.

Source: Dawood and Nabbat (2022) [19].

However, the varying depth makes the analysis of stresses and strains very complicated, especially in areas where the faces of inclined beams intersect with openings.

4.2. Influence of Geometry on Internal Forces

The main differences between gable beams and prismatic beams, in terms of internal forces, are that gable beams are subject to a change in neutral axis, an uneven distribution of shear stresses and the presence of inclined compression supports near the bracing. The presence of openings amplifies these effects, resulting in highly complex paths for internal forces [20]. Investigating the behavior of reinforced concrete gable beams with and without openings by casting four specimens, each 3,000 mm long and 400 mm deep at the mid-span and 250 mm deep at the supports. The first specimen was solid (no openings), the second had eight quadrant openings (four on each side), the third had the same openings but with a change in the angle of inclination from 90° to 60°, and the last had a change in the angle of inclination to 45° while maintaining the total area of the openings as shown in **Figure 7**. All specimens were tested under a concentrated load. The researchers concluded that the presence of openings reduces the beam's weight by 12.5%, reduces its load-bearing capacity by 6.1% to 12.9%, and increases mid-span deflection by 13% to 52%. They also concluded that reducing the slope of the opening has a positive effect on the load-bearing capacity.

To further clarify the effect of different parameters on the structural characteristics of gable beams, **Table 1** was created.

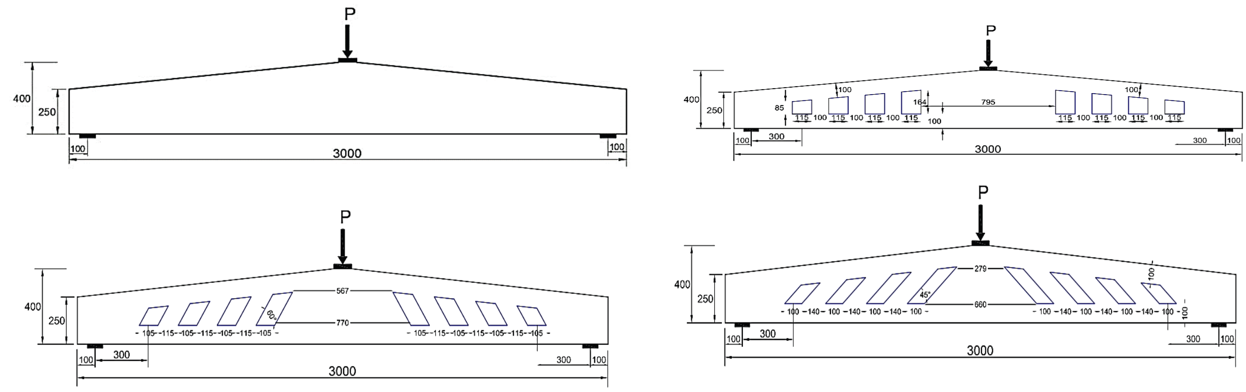


Figure 7. Details of reinforced concrete gable beams by researchers.

Source: Mohammed and Izzet (2023) [20].

Table 1. The effect of certain parameters on the structural characteristics of gable beams.

Parameters	Effect of Parameters on the Structural Characteristics
Increasing the depth at the mid-span	A 260% increase in failure load.
Increasing the depth of the supports	A 20% increase in failure load.
Change in beam depth	Change in neutral axis, an uneven distribution of shear stresses.
Presence of openings	Reduces the gable beam's weight by 12.5%, reduces its load-bearing capacity by 6.1% to 12.9%, and increases mid-span deflection by 13% to 52%.
Reducing the slope of the opening	A positive effect on the load-bearing capacity.

5. Openings in Gable Beams

5.1. Classification of Openings

Reinforced concrete gable beam openings are classified based on Shape: circular, rectangular, square, trapezoid, or irregular. Size: large >40% beam depth, medium size and small <25% beam depth. Location: near to the supports, midspan, or inclined regions. Number: single open or multiple openings. Multiple openings may interact structurally, resulting in the formation of weak-in-web zones. Hassan et al. [21] conducted a scientific study in the laboratories of the Civil Engineering Department at the University of Baghdad on reinforced concrete gable beams containing openings of different shapes and sizes. This study included six dimensionally identical models. The first model was without openings to represent a control model, while the second, third, and fourth models contained tetrahedral openings, and the fifth and sixth models contained circular openings, as shown in **Figure 8**. The researchers reached a very important conclusion: circular openings are better than tetrahedral openings because circular openings do not concentrate stresses at the corners of the opening. Therefore, the reduction in load-bearing capacity due to the presence of openings is less in circular openings than in tetrahedral openings.

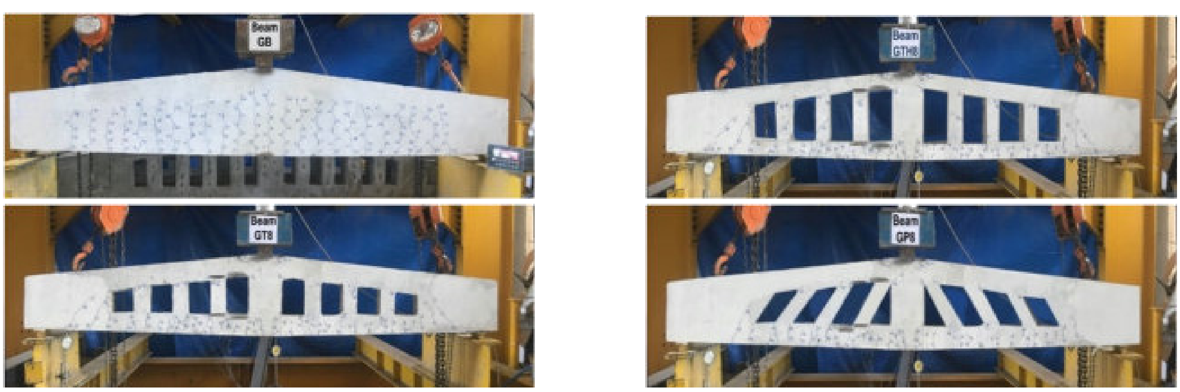


Figure 8. *Cont.*

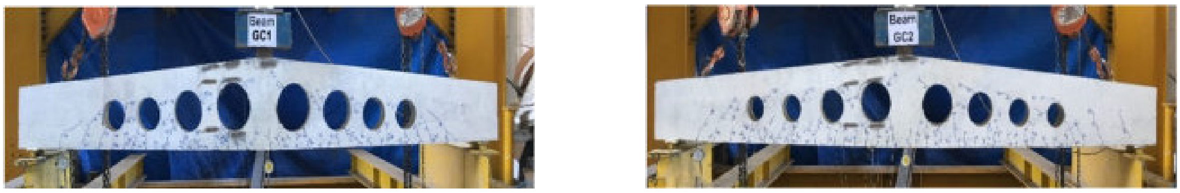


Figure 8. Tested models of reinforced concrete gable beams.

Source: Hassan et al. (2021) [21].

5.2. Interaction Effects of Multiple Openings

Investigations have shown that closely spaced openings cause stress overlap, increasing the likelihood of diagonal cracking and premature failure. In gable beams, this interaction is exacerbated by varying depths. Researchers Meyoof et al. [22] found that increasing the number of openings distributed along a given length of reinforced concrete gable beams is more effective than increasing the area of a single opening. They conducted a study on reinforced concrete gable beam models containing six and eight openings, as shown in **Figure 9**. They found that the failure load for the model with eight openings was 83.6 kN, while the failure load for the model with six openings was 76.04 kN.

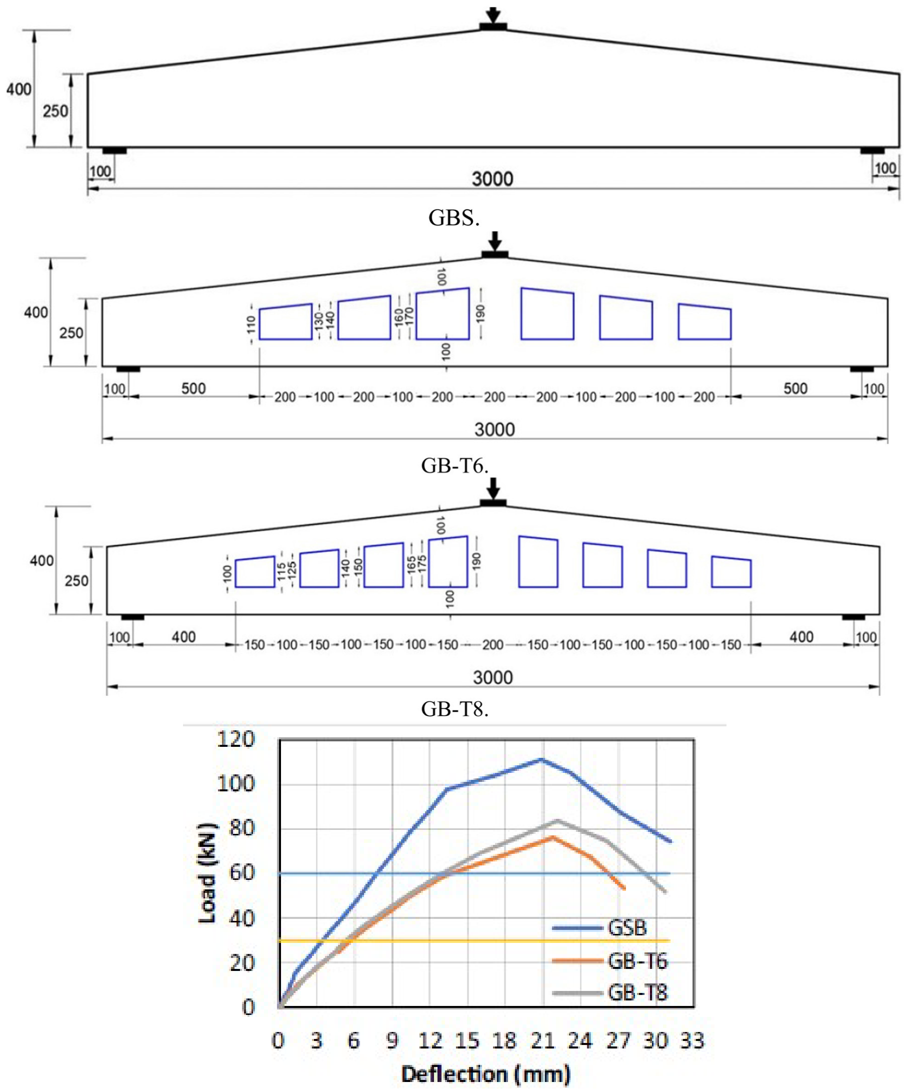


Figure 9. Tested models of reinforced concrete gable beams.

Source: Meyoof et al. (2022) [22].

6. Structural Behavior under Static Loading

6.1. Load–Deflection Behavior

Experimental results consistently show that multiple openings in gable beams exhibit the following: reduced initial stiffness, increased deflection in midspan, and early appearance of crack [23]. Reductions in stiffness of up to 35–50% have been reported compared to solid gable beams, depending on the opening configuration. It was also observed that the presence of openings in reinforced concrete gable beams reduces load-bearing capacity by 11% to 17%, depending on the distribution of the openings along the beam. Furthermore, it increases the maximum deflection by 41% to 55%, as illustrated in **Figure 10**.

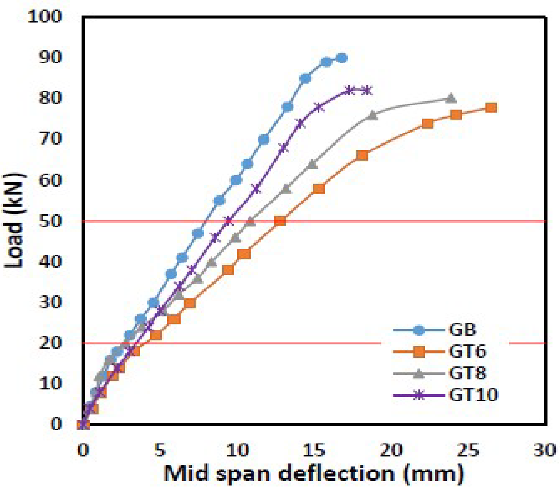


Figure 10. Load-deflection curves of tested models of reinforced concrete gable beams.

Source: Hassan and Izzet (2019) [23].

Al-Hilali et al. [24] conducted an experimental study on non-prismatic prestressed concrete beams with eight openings. The study included testing the effect of the presence of openings, the effect of prestressing force, and the shape of the opening (circular and quadrilateral) on the load-deflection curves. **Figure 11** shows the load-deflection curves for the tested samples bearing the following symbols: (NPB) for (non-prismatic prestressed beam), (NPQ8) for (non-prismatic prestressed beam with eight quadrilateral openings) and finally (NPC8) for (non-prismatic prestressed beam with eight circular openings).

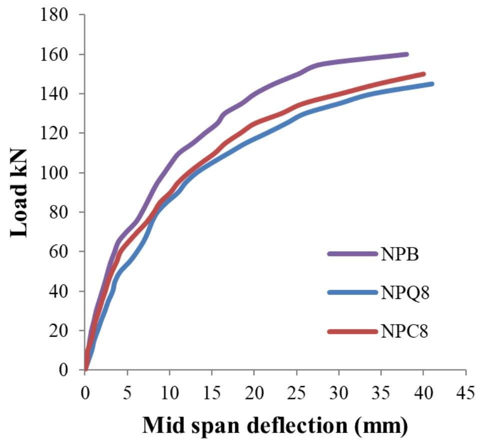


Figure 11. Load-deflection curves of tested samples of non-prismatic prestressed beam.

Source: Al-Hilali et al. (2022) [24].

6.2. Stress Redistribution and Load Path Disturbance

The openings disrupt the natural flow of compressive and tensile stresses. In gable beams, compression struts are forced to deviate around the openings, tensile stresses concentrate at the opening corners, and the inclined beam geometry alters stress trajectories. Al-Hilali and Izzet [25] conducted an analytical study using the ABAQUS program to investigate the stress distribution along the length of the reinforcing bars in the tension zone of reinforced concrete gable beams containing vertical or inclined quadrant openings. **Figure 12** shows stress concentration at the corners of the openings, whether vertical or inclined, but inclined openings in the direction of the load result in lower stress values and a better stress distribution.

Finite element studies confirm the presence of high stress concentrations at the intersection of the opening edges and the inclined beam surfaces. Examples of such studies include the structural analysis conducted by Maryam [26] using the ABAQUS/CAE version 2018 program, where the analysis confirmed the validity of this information, as shown in **Figure 13**. The stress concentration is very clear in the area of intersection of the opening edge and the inclined surface of the gable beam.

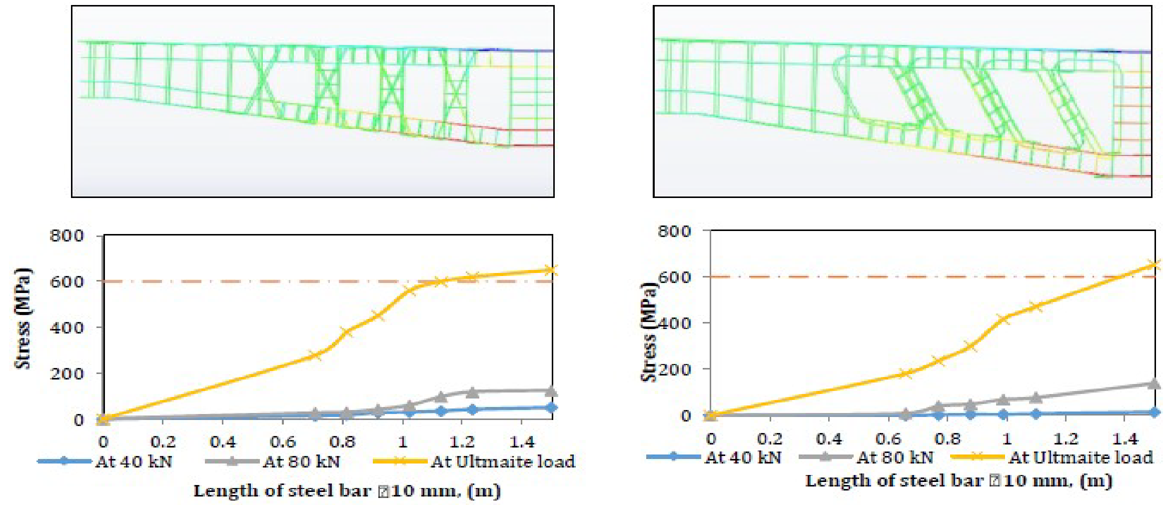


Figure 12. Concentrating stresses at the corners of the openings and distributing stresses along the reinforcing steel bars in the tension zone.

Source: Al-Hilali and Izzet (2023) [25].

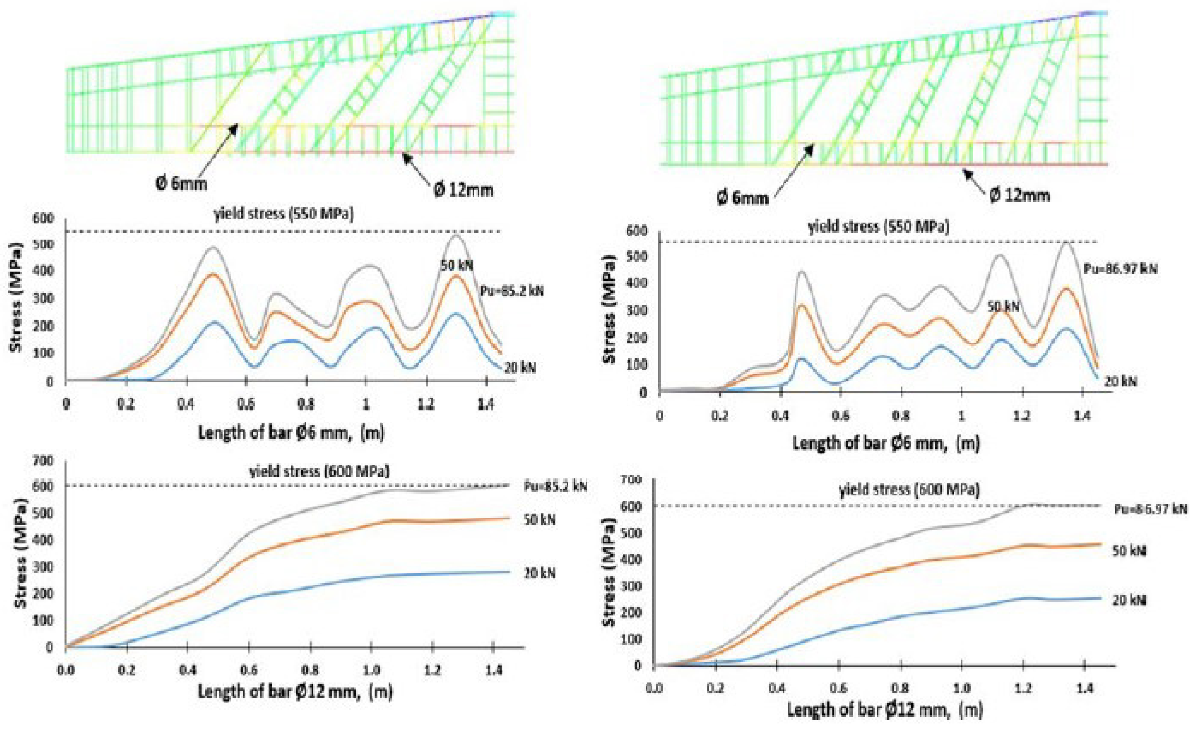


Figure 13. Stress distribution along the bottom reinforcement of the gable beam.

Source: Maryam (2024) [26].

7. Cracking Behavior and Failure Modes

7.1. Crack Initiation and Propagation

Cracks typically initiate at the opening corners, reduced-depth regions, and high-shear regions near supports. The spread of cracks is generally diagonal, reflecting the combined effect of bending and shearing. This is the conclusion reached by researchers Aykac et al. [27] after conducting an experimental study to test the effect of multiple openings on the structural behavior of reinforced concrete beams. In this study, the researchers attempted to strengthen the area around the openings using various techniques to reduce their impact. One such technique is adding reinforcing steel around the openings, as illustrated in **Figure 14**.

Abdulkareem and Izzet [28] studied the cracking pattern and the load that causes the first crack in fire-exposed, multi-opening, reinforced concrete gable beams. They found that all the specimens began to crack after being exposed to fire, but the load at the first crack ranged from 18% to 24% of the maximum load. **Figure 15** illustrates the cracking pattern of the specimens examined in this study, where the distance between cracks ranged from 65 to 50 mm for beams burned at a temperature of 700 °C and from 60 to 80 mm for unburned beams.

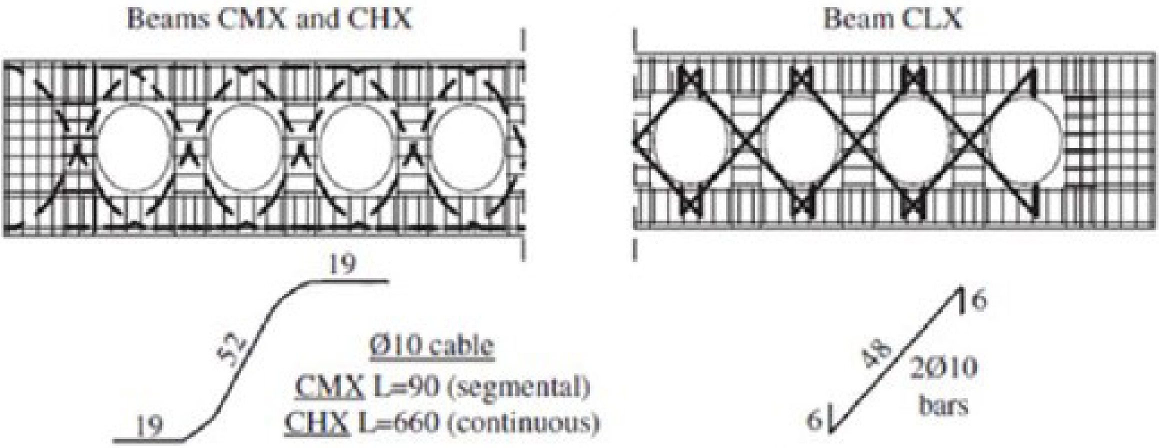


Figure 14. Details of strengthening openings using reinforcing steel bars.

Source: Aykac et al. (2023) [27].

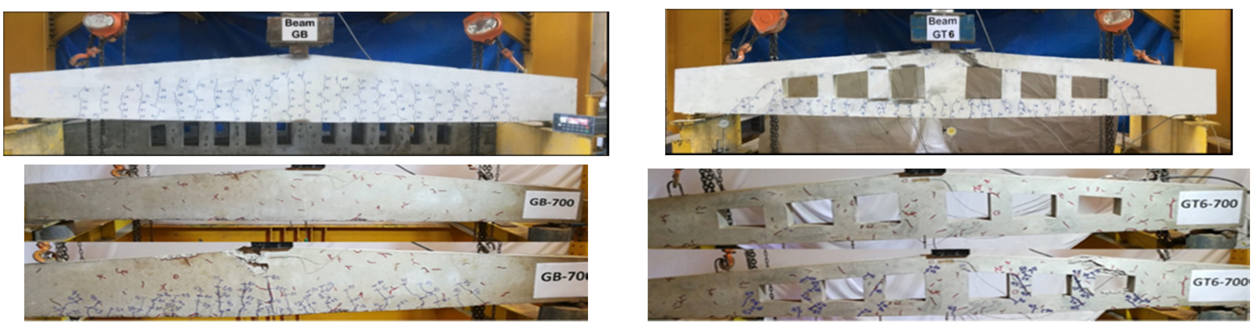


Figure 15. The pattern of cracking and the appearance of the first crack in the reinforced concrete gable beams with multiple openings and exposed to fire.

Source: Abdulkareem and Izzet (2022) [28].

7.2. Failure Modes

Reported failure modes include: Flexural failure due to yielding of longitudinal reinforcement and Shear failure near supports. These patterns of failure were evident in the study conducted by AlAli et al. [29] and as illustrated in **Figure 16**.

Or failure occurs in shallow areas of reinforced concrete gable beams, as happened in the study by El-Hacha and Gaafar [30] and as shown in **Figure 17**.

Opening-induced failure, characterized by diagonal cracking between openings. This type of failure occurs when reinforced concrete beams have openings spread along a certain length, as illustrated in **Figure 18** of the study conducted by researchers Aykac et al. [31]. They also reached the conclusion that beams with inadequate reinforcement around openings tend to fail suddenly.

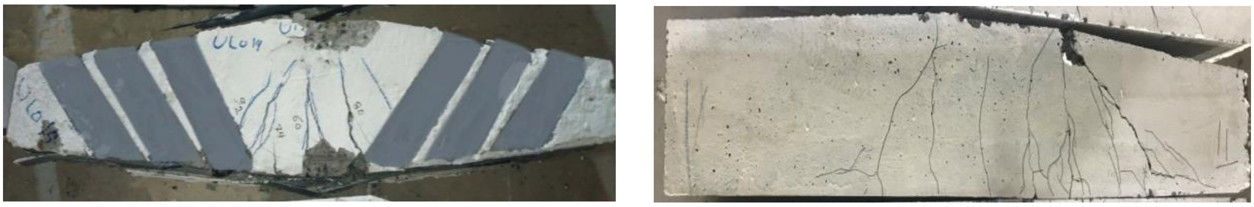


Figure 16. Flexural failure and shear failure of reinforced concrete gable beams.

Source: AlAli et al. (2022) [29].

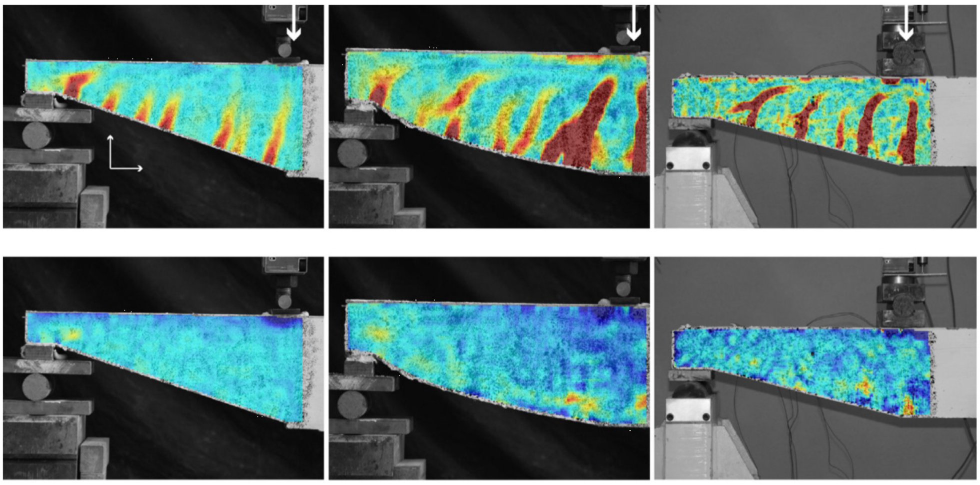


Figure 17. Reinforced concrete gable beams fail in shallow-depth areas.

Source: El-Hacha and Gaafar (2011) [30].

Figure 18. Failure between openings in reinforced concrete beams.

Source: Aykac et al. (2014) [31].

8. Reinforcement Detailing and Strengthening Techniques

8.1. Conventional Reinforcement Strategies

Effective reinforcement techniques include: diagonal bars around the openings, closed stirrups near the opening edges, and additional longitudinal bars above and below the openings. These measures work to restore load paths and enhance ductility. These strategies can be observed in the study conducted by the researchers Oukaili and Shammari [14], as shown in **Figure 19**.

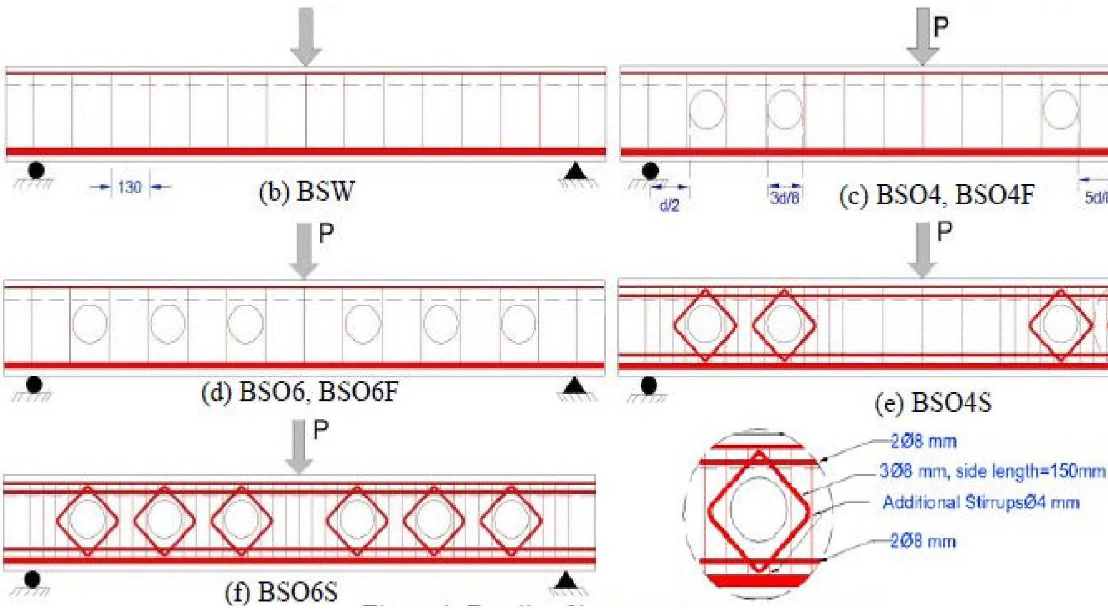


Figure 19. Strategies used to strengthen openings in the study .

Source: Oukaili and Shammari (2013) [14].

8.2. Advanced Strengthening Methods

Recent studies have explored: fiber reinforced polymer (FRP) sheets bonded around the openings, steel plate for strengthening, and composite techniques systems for strengthening. These technologies allow for greater load-bearing capacity and control the shape and pattern of cracks. These techniques can be observed in the study conducted by the researchers Khatam and Nasser [32], as shown in **Figure 20**.

Figure 20. Techniques used to strengthen openings in the study.

Source: Khatam and Nasser (2022) [32].

Based on this review and the literature review of previous research on gable beams, we can draw important conclusions regarding their design. For gable beams without multiple openings, the design equations found in various codes, such as the American Concrete Institute (ACI) code, the European code, or the Chinese code, which are used for designing prismatic beams, can be applied. However, there are no specific design equations for gable beams with multiple openings.

9. Comparison of Gable Beams with Prismatic Beams

With the presence of openings in gable beams, compared to prismatic beams, gable beams with openings exhibit the following characteristics: higher stress concentration, more complex crack patterns, and the location of the opening is highly influential. For these reasons, applying the design principles of prismatic beams is unsuitable for the design of gable beams. Most of the studies mentioned previously have confirmed these characteristics of reinforced concrete gable beams containing multiple openings.

10. Research Gaps and Future Directions

Identified gaps include: insufficient experimental results, the absence of standardized design criteria, and very limited research focused on improving the design of openings. The need for design rules based on practical performance. For these reasons and requirements, we recommend and urge our esteemed researchers to pursue this important research path to enrich it and bridge this significant research gap. We also emphasize that reinforced concrete gable beams are highly beneficial in large spaces, thus sparing structural designers the need for costly intermediate concrete columns that obstruct views and impede free movement in open areas. Because openings are essential in reinforced concrete gable beams, extensive scientific research is required to develop design equations for this important type of reinforced concrete beam.

11. Conclusions

This study demonstrates that reinforced concrete gable beams with multiple openings exhibit highly complex structural behavior under static loads, influenced by the shape of the openings and the reinforcement details. While significant progress has been made in experimental and analytical studies, these are still limited, and there remains a pressing need for a design guide for this type of beam. Therefore, further research in this area is essential, and numerous studies and research projects are needed to establish fundamental principles for the design and analysis of this type of structural element.

Author Contributions

Conceptualization, W.H.N. and H.T.N.; methodology, H.T.N.; software, W.H.N. and H.T.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. and H.T.N.; writing—original draft preparation, W.H.N.; writing—review and editing, H.T.N.; visualization, W.H.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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Informed Consent Statement

Not applicable.

Data Availability Statement

All data relating to this research are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

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