Research Article

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Performance of reinforced concrete non-prismatic beams having multiple openings configurations

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Abstract: This experimental study demonstrates the gable-reinforced concrete beams' behavior with several number of openings (six and eight) and posts' inclination, aimed to find the strength reduction in this type of beam. The major results found are: for the openings extending over similar beam length it is better to increase the number of posts (openings), *i.e.*, increasing opening number led to decrease in opening area, which allows us to transmit stresses and act as lever arms between the upper and the lower chords. Also, findings revealed that the inclined posts have larger loading at the mid-point relative to vertical ones. For gables with vertical posts having six and eight openings, the ultimate strength reduction was 31.5 and 25.6%, whereas it was 29 and 17.3% for those with inclined posts, respectively.

Keywords: reinforced concrete, gable roof, roof beams, roof openings, ultimate strength, inclined posts

1 Introduction

Through the last few decades, the global literature witnessed significant enrichment with several research publications that address the analysis and design of beams with openings under a group of shear and bending stress circumstances. For instance, an experiment was conducted to determine what significant questions can be posed about constructing or existing openings in the created beam, as well as how to cope with these openings. Some scholars reported that the design technique for beams with big openings, as outlined by Somes and Corley [1] and Mansur and Tan [2], can be reduced further without sacrificing rationality or incurring excessive costs. Hassan and Izzet [3] presented a numerical simulation using the ABAQUS/CAE version 2018 finite element program to investigate the flexural behavior of 13 existing simply supported reinforced concrete (RC) gable roof beams with openings of various sizes and configurations under monotonic loading. Several studies, including Ehmann and Schnellenbach-Held [4], Al-Shaarbaf *et al.* [5], Oukaili and Shammari [6], Shubbar *et al.* [7], Jabbar *et al.* [8], and Hassan and Izzet [9], used the finite element approach to explore the problems of openings in the beams. Aykac *et al.* [10] presented an experimental investigation that looked at the impact of several openings along the length of a concrete beam on its flexural performance. Three groups of nine concrete beams were tested, each with various reinforcement degrees (low, moderate, and heavily reinforced). Every group had a control solid beam having two sets of 12 equal space openings running along the length of the beam (square or circular). To avoid "beam type shear failure," longitudinal reinforcement was employed with stirrups close to the opening sides, as well as small stirrups along the upper and lower chords to avoid "frame type shear failure." In addition, the circular-shaped openings in the beams were diagonally reinforced. All of the beams that were tested were simply supported and subjected to four-point loading until they failed. This article presents the main outcomes of these tests. The diagonal steel bars used to support the area around the circular-shaped openings were an active solution to avoid shear stresses causing Vierendeel collapse of the posts between the openings. In 2014, the author cast and investigated ten more RC beams with multiple openings, using the identical steel reinforcement specifications as before, with the exception that light reinforcement was not used. The use of stirrups in the posts increased ductility and load capacity, prevented shear failure, and avoided Vierendeel action, according to the findings. Using carbon fiber-reinforced polymer, Dawood and Nabbat [11] attempted to delay failure caused by cracks that begin at the openings' corners. The study's key findings were that in flexure beams, the CFRP sheet technology

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provides greater performance than near surface mounted. When compared to unstrengthened solid beams, the ultimate loading potential of strengthened solid beams rose to 16% for flexural behavior and to 15% for shear behavior. When compared to a solid beam, the existence of openings in non-prismatic beams near the support reduces the ultimate loading capacity by 12.56%, while beams with openings at the interior point loading reduce the ultimate loading capacity by 59.44%. Compared to a solid beam, the existence of an aperture in a non-prismatic beam positioned at mid-span above neutral axis and in neutral-axis reduces the ultimate loading capacity by 10.75 and 2.84%, respectively. Jassim and Jarallah [12] conducted an analysis to explore the RC beams' behavior with larger web openings formed in various places and strengthened with reactive powder composite at the massive compression and tension zones (under the bottom border of the openings and above the top edge of the opening). Izzet *et al.* [13] carried out research to investigate approaches that can improve the load carrying potential of gable beams with openings with prestressing force, accepted results were found with respect to beam stiffness and its strength. However, Abdulkareem and Izzet [14] examined the serviceability of post fire on the gable beams behavior that have several configurations and sizes. It was concluded that fire has the worst wide range effects on the strength and deformability of this type of beams. The prismatic RC beams' behavior investigation with openings was the focus of previous research. This work aims to present an experimental examination of the flexural behavior of RC gable roof beams that have openings, as well as a numerical comparison study to determine the best section for this type of roof beam.

2 Experimental work

Five simple supported gable roof beams were fabricated and experimentally evaluated. Table 1 exhibits the symbols and definitions used in this study, and Table 2 presents the main variables investigated. All beams were 3,000 mm long, with 100 mm width and 400 mm depth at the mid of the span, whereas it was 250 mm at the beam ends. The schematic beam features are shown in Figures 1–3. Two groups of beams were tested, the number and size of the created openings, as well as the posts' inclination between the holes, were used to classify these groups in this study.

2.1 Material properties

The major steel and concrete properties utilized in this work are illustrated in Table 3. Standard tests according to ASTM were executed to figure out the hardened concrete and steel reinforcement properties.

2.1.1 Setup and testing procedure

A static one-point load test was performed on all gable specimens. To apply the load to the test gable, a hydraulic jack with a capacity of 800 kN was used. The load was implemented with a value of 4 kN/min in load control mode, with the test stopping every 5 kN to record the progression of cracks and deflections along the gable. The crack pattern was drawn on the gable's front face to make it easier to locate and identify cracks during and after the test. Figure 4 shows a schematic perspective of the steel reinforcing features as well as the specimen's test setup.

3 Results and discussion

3.1 Gable cracking resistance load

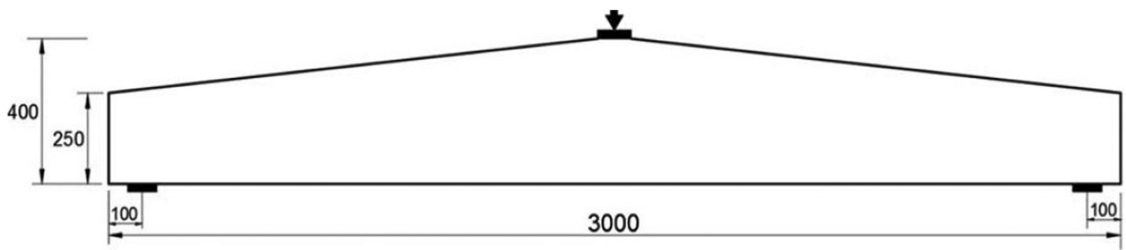
All gable beams with openings cracked at 18.6–19.7% of the relevant failure load during loading stage, whereas the solid gable beam cracked at 22.5% of its ultimate load,

Table 1: Definitions of symbols

Symbol	Definitions
GB	Control gable beam
S	Solid beam
T	Trapezoid-shaped openings with dimensions of 100 mm deep upper and lower chords linked with vertical posts having 100 mm width
P	A beam having parallelogram-shaped openings with dimensions of 100 mm deep lower and upper chords and 100 mm wide posts inclined at a 60° angle to the lower chord

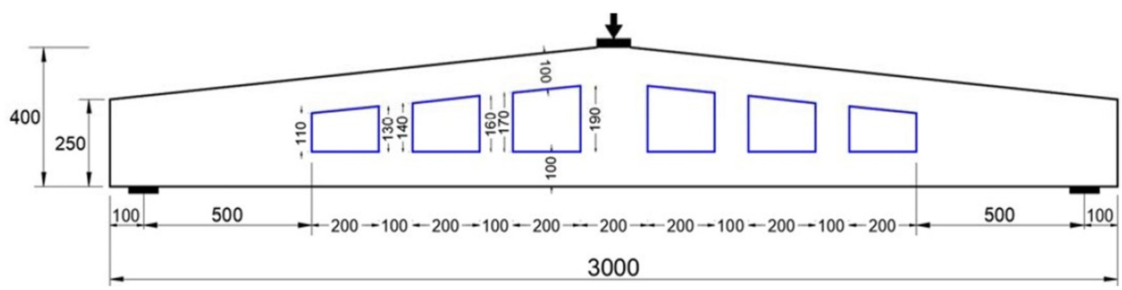
Table 2: Details of tested beams

Group	Beam ID	Opening's configuration	Number of opening	Overall opening's area (mm^2)	Opening's width (mm)	$Weight_{beam}$/$Weight_{gb}$
Control	GBS	—	—	—	—	1.00
A	GB-T6	Trapezoid shaped	6	180,000	200	0.81
	GB-T8		8	174,000	150	0.82
B	GB-P6	Parallelogram shaped	6	154,000	200	0.84
	GB-P8		8	151,000	150	0.85

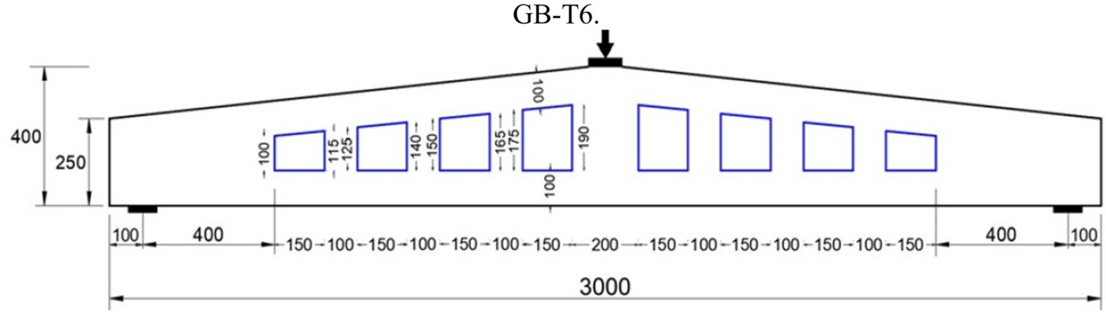


GBS.

Figure 1: An architecture of solid gable beam (all dimensions are in mm).



GB-T6.

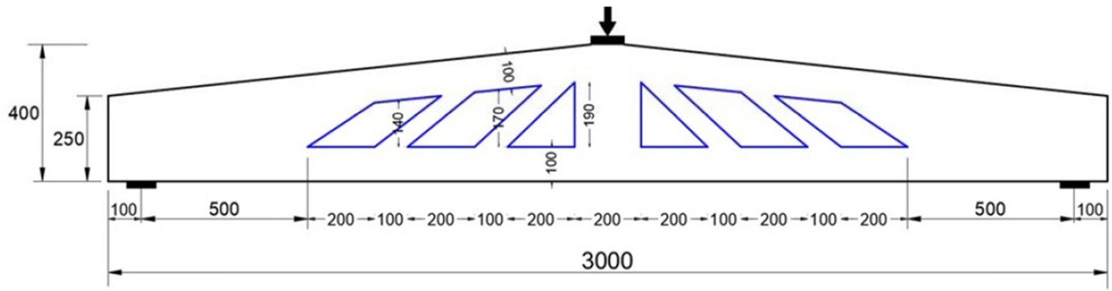


GB-T8.

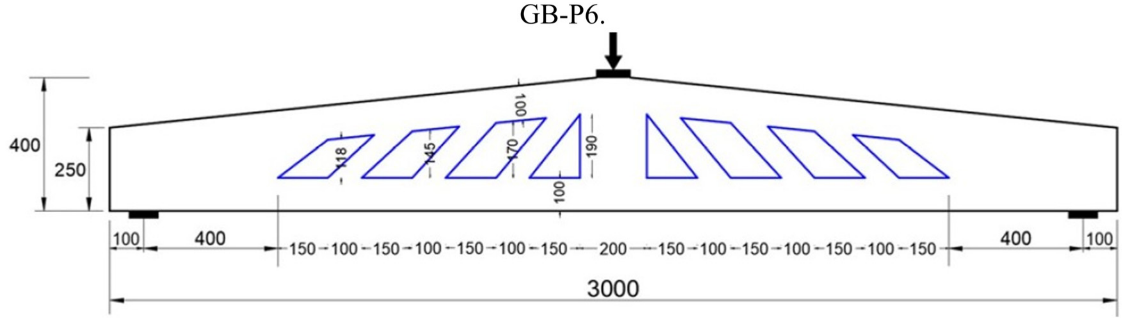
Figure 2: An architecture of group A (all dimensions are in mm).

as shown in Table 4. This indicates that all gable beams that have openings cracked before the solid ones, and that all beams cracked before reaching beams' service load. It is worth noting that only flexural cracks developed in the solid gable beam, whereas flexural-shear cracking appeared accompanying flexural cracking in the other gable beams that have openings. In addition, results revealed that the inclined flexural-shear cracking almost entirely expanded at the solid endings of the gable beams, with openings near the supports.

Virtually, vertical flexural cracking formed in the massive tensile fibers of the lower chords in the region of the higher bending moment sections as the implemented loading resulted in remarkable flexural stresses



GB-P6.



GB-P8.

Figure 3: An architecture of group B (all dimensions are in mm).

Table 3: Tensile characteristics of the investigated steel reinforcing bars

Material	Diameter (mm)	Mean yield tensile stress (MPa)	Mean ultimate tensile strength (MPa)	Elongation (%)	Average compressive strength
Steel reinforcement	4	370	567	—	—
	6	550	629	—	—
	12	570	677	11.0	—
Concrete	—	—	—	—	38.05

in the lower chord. With increasing applied load, vertical flexural cracks began to expand, extended, and took on a more horizontal pattern (*i.e.*, flexural-shear cracks) at the extreme top fibers of the lower chords (at the lower edge openings). The inclined shear cracking formed at the openings top corners closest to the applied force in all of the examined specimens with higher applied loads. Meanwhile, the aforementioned inclined cracks continued to progress when the force was applied, with their orientation orientated toward the applied load. The number, size, and location of openings all have an effect on the first cracks loading of the gable beams which were tested. Table 4 shows that gable beams having six openings had the greatest reduction in cracking load value, which was 60% less than the solid one.

Generally, the gradual rise in cracks size associated with the beam soffit at the lower chord with an increasing amount of openings is higher for gable beams with eight openings compared to the specimens with six openings. The crack size of the lower chord was found to be higher in specimens with parallelogram-shaped openings than in specimens that have trapezoid-shaped openings. This aspect is noted because of the accumulation of flexural stress in the concrete along the sharp corners (which has an angle less than 90^{o}) of these openings.

3.2 The tested beams' deformability

The relationships between mid-span applied load and mid-span deflection for the tested beams are illustrated in Figures 5 and 6. The relevant mid-span deflections for loading stages of 30 and 60 kN, and the ultimate applied loads are illustrated in Table 5. Reaching a loading of approximately 17 kN that contributes to the mean cracking loads of gable beams with openings, overall investigated beams, except GBS, had deflected linearly with the progress of applied loading. Additionally, they

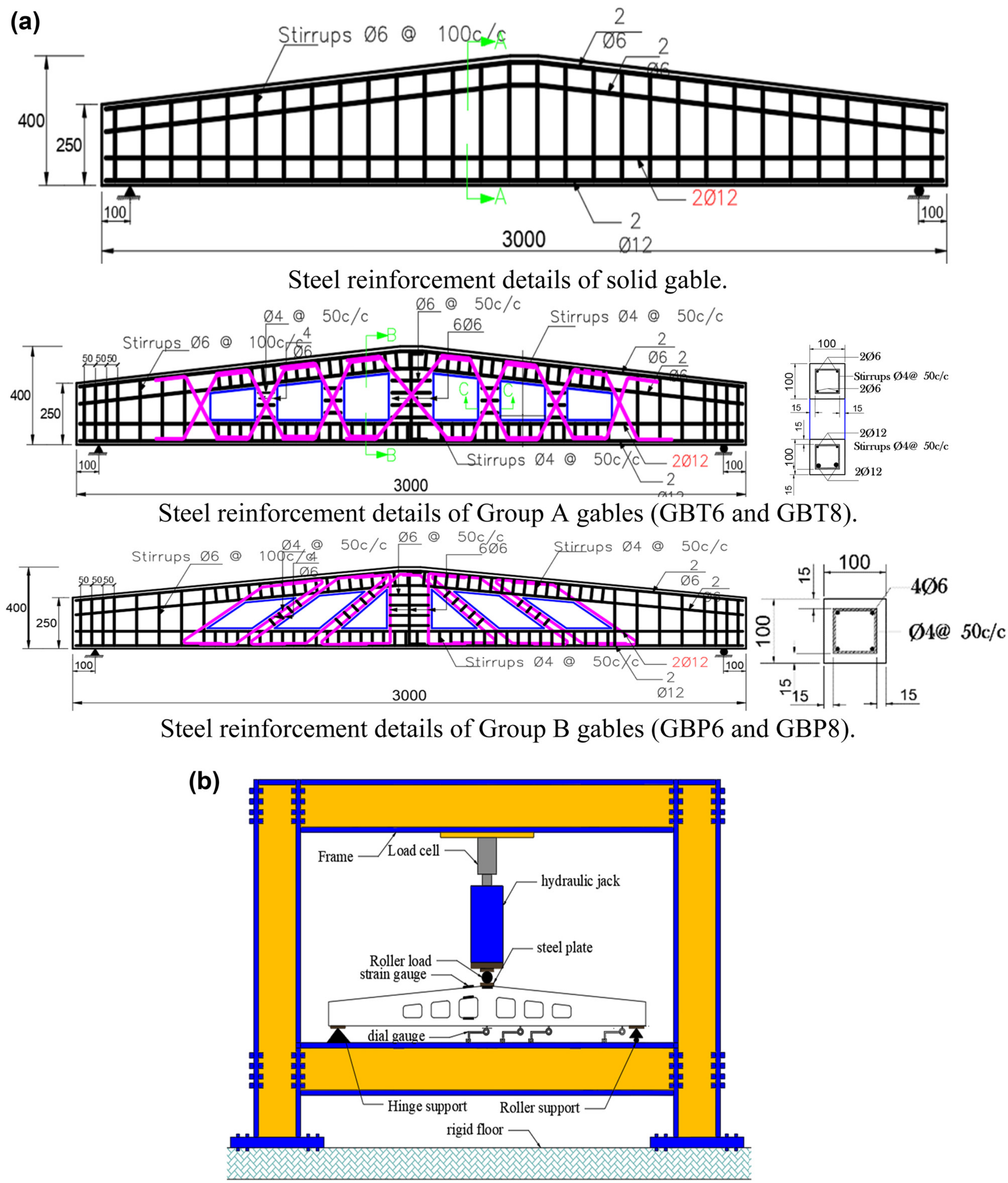


Figure 4: (a) Gables steel reinforcement details (all dimensions are in mm). (b) Test setup.

had approximately similar amounts of mid-span deflections. Furthermore, the deflection curves related to the specimens from the similar groups more or less corresponded. The investigated beams had deflected through a linear behavior with the load increase after the crack loading reached an amount of roughly 60 kN. However, the slope of the lines was remarkably lower than before cracking, and the deflection curves diverged depending

Table 4: Failure and cracking loads

Group	Beam ID	Number of openings	First cracking load P_{cr} (kN)	$\frac{P_{cr}}{P_{cr,ct}}$ (%)	Failure load P_{ult} (kN)	$\frac{P_{cr}}{P_{ult}}$ (%)
Control	GBS	–	25	–	110.97	22.5
A	GB-T6	6	15	60	76.04	19.7
	GB-T8	8	16	64	83.60	19.1
B	GB-P6	6	15	60	78.50	19.1
	GB-P8	8	17	68	91.45	18.6

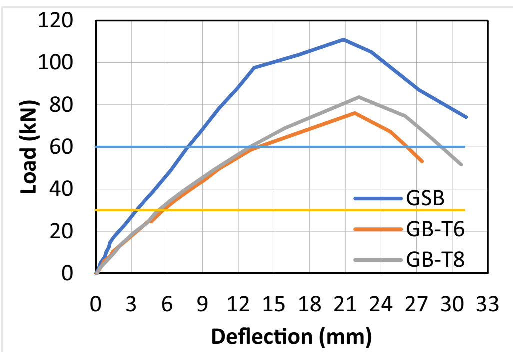


Figure 5: Load–deflection curves of Group A.

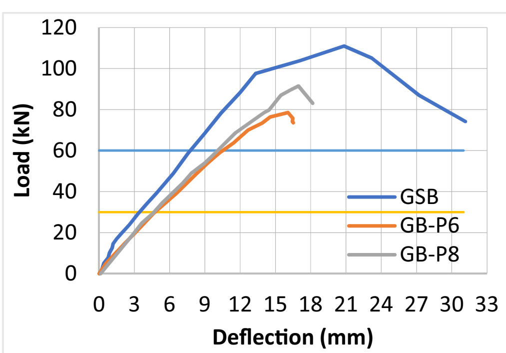


Figure 6: Load–deflection curves of Group B.

on the degree of stiffness degradation and the cracking severity. Within each group, the slope of the linear parts varied proportionally to the number of openings that extended along the length of the beam span.

The investigated gable beams initiated to deflect *via* nonlinear behavior with the load increase, at loads higher than 60 kN, exhibiting deflection curves that differ significantly from the solid gable beam deflection curve. As indicated in Figures 7 and 8, the degree of this divergence is determined by the configuration rather than the number or total area computed for the generated openings. Cracks began to occur in various areas of the tested beams during the nonlinear stage. No new cracks occurred with applied loads greater than 70 kN; however, the existing cracks progressively extended and expanded. The installation of openings in almost all flexural concrete parts causes the structural member to deflect more due to the sudden variation in dimensions related to the cross-section, reducing the total stiffness. Table 5 shows that, whether the sections cracked or not, the stiffness increases with the increase in the number of openings through the same beam length at linear stages up to 60 kN (*i.e.*, increasing posts number). On the other hand, inclined posts show an increase in beam stiffness.

Table 5 and Figures 5 and 6 show that as the opening number and posts increase, the load carrying potential of the beam increases and the corresponding deflection decreases. This could be due to an increase in beam

Table 5: Beams mid-span deformability at different loading stages

Group	Beam ID	Number of openings	At 30 kN		At 60 kN		At ultimate load		P_{ult} (kN)	% [(2)]
			Δ mm	% [(1)]	Δ mm	% [(1)]	Δ mm	% [(1)]		
Control	GBS	–	3.29	–	7.59	–	20.84	–	110.97	–
A	GB-T6	6	5.59	69.9	13.09	72.46	21.79	4.6	76.03	31.5
	GB-T8	8	4.62	40.42	11.76	54.94	20.14	3.36	83.63	24.6
B	GB-P6	6	4.64	41.03	10.23	34.78	16.07	22.9	78.5	29.3
	GB-P8	8	4.57	38.91	9.88	30.17	16.95	18.7	91.45	17.6

Note: (1) $\frac{\Delta_{beam} - \Delta_{GBS}}{\Delta_{GBS}}$; (2) $\frac{P_{beam} - P_{GBS}}{P_{GBS}}$.

Table 6: Beams mid-span deformability at different loading stages

Group	Beam ID	Number of openings	At 30 kN		At 60 kN		At ultimate load		P_{ult} (kN)	%$^{(2)}$
			Δ mm	%$^{(1)}$	Δ mm	%$^{(1)}$	Δ mm	%$^{(1)}$		
Control	GBS	—	3.29	—	7.59	—	20.84	—	110.97	—
A	GB-T6	6	5.59	69.9	13.09	72.4	24.79	18.8	76.03	31.5
	GB-T8	8	5.5	67.17	12.93	70.4	22.15	6.3	83.63	24.6
B	GB-P6	6	4.82	46.5	10.64	40.18	25.7	23.32	78.5	29.3
	GB-P8	8	4.8	45.9	10.37	36.6	23.73	13.87	91.45	17.6

Note: (1) $\frac{\Delta_{beam} - \Delta_{GBS}}{\Delta_{GBS}}$; (2) $\frac{P_{beam} - P_{GBS}}{P_{GBS}}$.

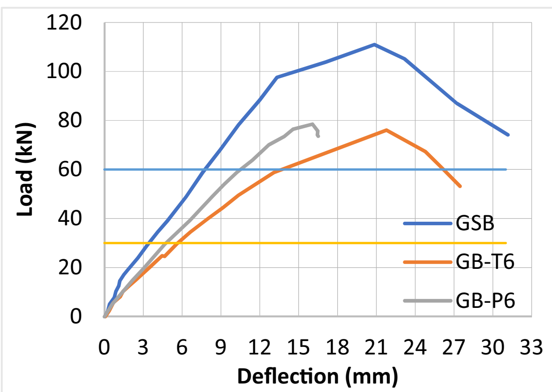


Figure 7: Load–deflection curves for beams having six openings.

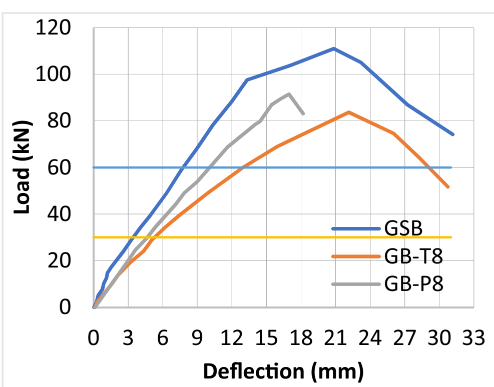


Figure 8: Load–deflection curve for beams having eight openings.

stiffness caused by minimizing the total area of openings while increasing the solid elements represented by the posts between the openings. Figures 7 and 8 exhibit gable beams with various opening configurations (post inclinations), but with the same number of openings of six and eight, respectively.

3.3 Failure behavior and the load carrying capacity

In spite of the formulation of shear cracking at the solid components near the beam ends and the openings' top corners closest to the mid-span implemented load, the investigated beams GBS, GBT8, and GBP8 failed through the same manner of tension-controlled flexural behavior attributed to the formation of multiple flexural cracking areas at the tension side, which pass across tension steel reinforcing, causing yielding, and ultimately damage of concrete at the compression areas closer to the applied load, as illustrated in Figures 9 and 10.

The failure modes of GBT6 and GBP6 differ from the behavior of failure related to the other investigated beams. This aspect is because the larger openings' size impact associated with the implemented load. These beams fail in tension-controlled flexural behavior due to the higher steel reinforcement yield.

There was no significant buckling phenomenon closer to the compression reinforcing bars attributed to the sufficient confining impact accomplished *via* the closed steel stirrups at the upper chords. In addition, the flexural cracking associated with the beams expanded through the overall depth of the lower chord, explaining that there was no compressive strain formulated at this section, ensuring the solid behavior of the gable beams with openings, as illustrated in Figures 9 and 10. This observation can be attributed to the high-performance operation of obtaining the shear strength by using closed steel stirrups with openings at the lower and upper chords related to the gable beam. In the posts between the openings, there were no plastic hinges. Meanwhile, only low number of posts were subjected to fine diagonal cracking at the later loading phases, and a low number of diagonal cracking at the support area had little influence on the way of failure.

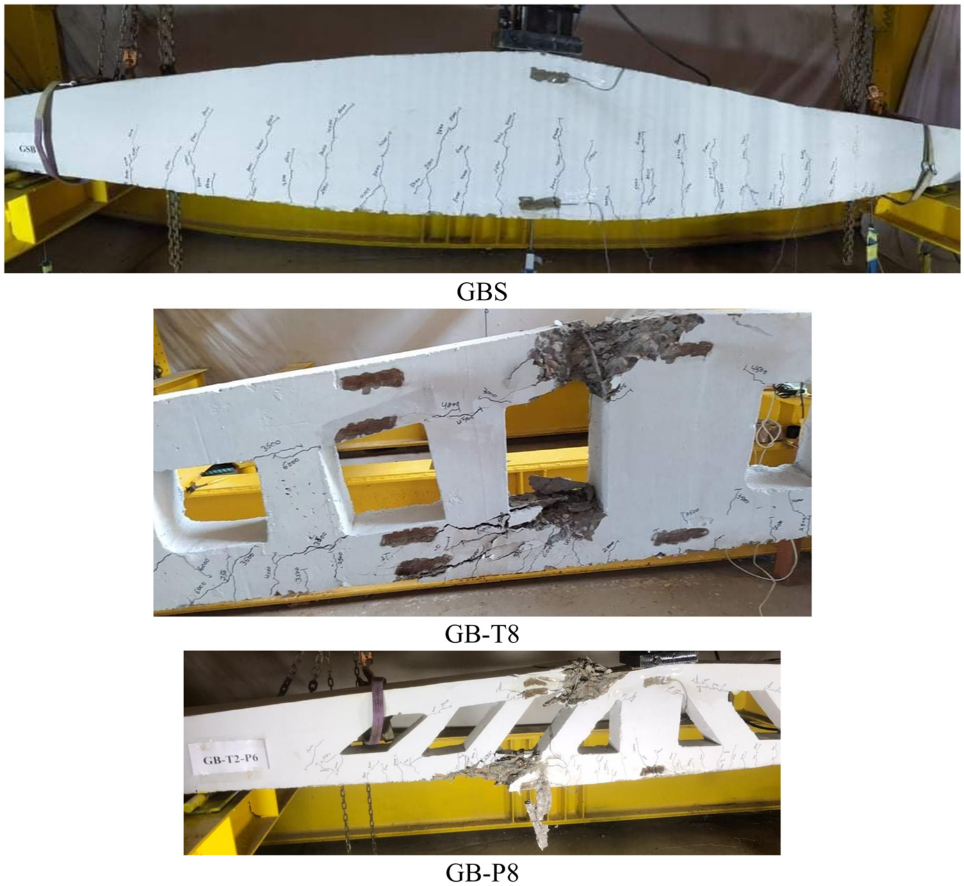


Figure 9: Failure of gable beam with openings.

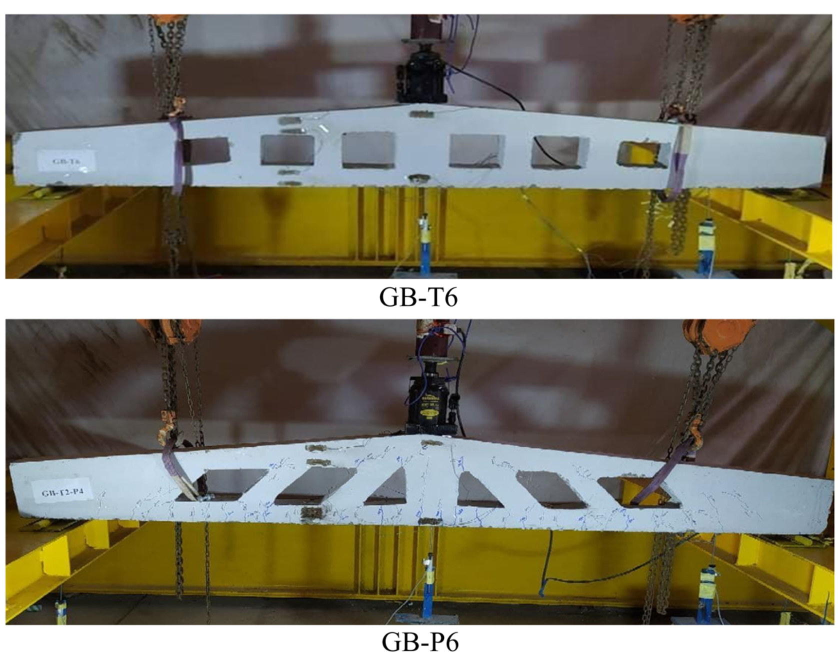


Figure 10: Tension-controlled flexural mode failure.

The ultimate strength of a gable beam is reduced by 17.59–31.50%, when insertion openings exist (Table 5). In greater detail, increasing the opening number through the same beam span length (*i.e.*, lowering opening area due to increasing post number) minimizes gable beam load carrying capacity to decline. The load resistance of inclined posts toward the loading point was higher than that of vertical posts (Table 6).

4 Conclusions

The following major findings can be listed depending on the experimental program designed to explore the behavior associated with the gable RC beams with openings:

1. Gable beams with insertion openings have a lower ultimate load carrying potential. This reduction is in the range of 17.6–31.5%.
2. Conversely, increasing the opening amount from six to eight using the similar distance (*i.e.*, increasing the number of posts) reduces the deterioration in ultimate load carrying potential by 10% for vertical posts and 16% for inclined posts toward the mid-loading point.
3. When compared to solid gable beams, insertion openings increase deflection. For beams with openings relative to the solid one, the increasing ratio related to the mid-span deflection at elastic, service, and ultimate loads can range from 38 to 70%, 16 to 72%, and 4.6 to 23%, respectively.
4. Inclined posts have a higher load carrying capability than vertical posts because they are more efficient at transmitting stresses. The ultimate strength reduction for gables with six and eight openings was 31.5 and 25.6%, respectively, whereas it was 29 and 17.3% for those with inclined posts.

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