Performance of Reinforced Concrete Gable Beam with Quadrilateral Openings of Different Side Inclinations

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Abstract. The existence of openings in a gable beam would have numerous advantages, the most important of which would be a reduction in the overall weight. These advantages include geometric flexibility, ease of handling when erected, and more. This study aims to investigate the flexural behavior of reinforced concrete gable beams with quadrilateral openings of different side inclinations; this goal has been specified with beam stiffness, the maximum load-carrying capacity, and strains of the beams. Beams are identical in their dimensions and reinforcement. The experimental program involved casting and testing four simply supported beams: a solid beam (reference beam) and others with quadrilateral openings. They were 3000mm long, 100mm wide, and 400 mm deep in the middle, tapering to 250 mm on both ends, concentrically loaded. The results demonstrate the load-carrying capacity is reduced by 6.1–12.9%, and the mid-span deflection is increased by 13–52% when openings exist compared to the solid gable beam. Enhancement represented by increases in strength and decreases in deflection was observed when the inclination of the quadrilateral side opening decreased from 90 to 60 and then 45^{o}, respectively. In contrast, the total opening area was maintained. The creation of openings in concrete gable beams can reduce their weight by about 12.5%.

Keywords: Gable; inclination; openings; post.

1. INTRODUCTION

Commonly utilized in commercial and industrial buildings are reinforced and/or prestressed concrete gable roof joists [1, 2]. Due to the limited test results, the effect of opening configuration and opening distribution pattern has been infrequently evaluated in detail. Due to the complexity and lack of physical comprehension, analysis and design of gable roof beams with openings frequently disregard these uncertainties, despite the fact that there are numerous uncertainties associated with the prediction of the service behavior and the load-carrying capacity [3]. Utilizing substantial test data and theoretical results, the serviceability and ultimate performance of these structural concrete members are investigated [4-6].

Gable beams must have openings for service ducts and conduits to pass through easily, and these openings also have the added benefit of reducing the beam's overall weight, which reduces the strain on the building's supporting frames during gravity loading and seismic excitation and saves money in the long run [7]. A solid beam's performance would be adversely affected by the introduction of openings, leading to a more complex behavior since the opening would effectively induce a quick decline in the beam's cross-sectional area and, by extension, the total stiffness. Also, the stress concentration at the opening's edges could cause widespread cracking, which is unacceptable from both an aesthetic and a durability standpoint. Furthermore, the openings would decrease the beam's overall stiffness, which could lead to significant deflections when subjected to service loads [8-10]. Alternatively, a continuous beam's internal pressures and moments would be significantly redistributed. The ultimate strength of such a beam could be reduced to critical grade without sufficient amounts of special reinforcing surrounding the perforation. Therefore, particular care must be taken in designing these beams to limit the crack width and prevent the structural concrete member from failing prematurely due to stress corrosion cracking [11,12].

The main objective of this research is to optimize, for fixed span length, the correlation between the self-weight of the reinforced concrete gable beam with inclined posts of different angles and the maximum load-carrying capacity.

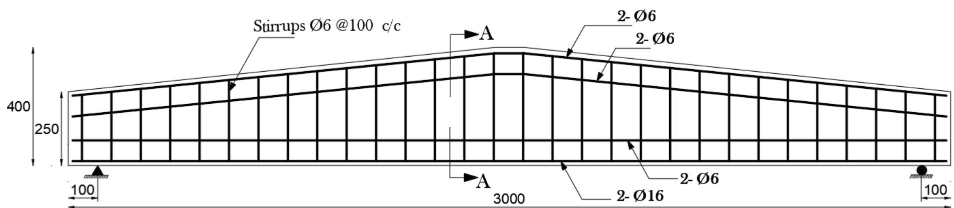
2. EXPERIMENTAL WORK

The behavior of simply supported reinforced concrete gable beams with angled openings of varying degrees under monotonic static stress with their variations up to failure was the focus of a planned and carried-out testing program. Four reinforced concrete gable beams were cast and tested with openings, one without openings (solid) to serve as a control specimen. In contrast, the others consist of varying degrees of slope quadrilateral openings. The concentrated load was applied to the middle of each beam, and all beams were identical in their dimensions (length, width, and height). Steel plates were used to prevent localized failure at the stress point and the supports.

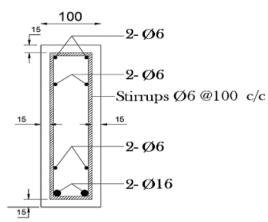
The experimental effort for this study involved creating four miniature versions of a prototype simply supported gable beam, each of which was scaled down by a factor of one-four. Each beam measured 3000 mm in length, 100 mm in width, 400mm in height in the middle, and 250 mm at the ends. All tested beams had the same longitudinal ordinary steel reinforcement: (4Ø6 mm) in two layers along the top chord and (2Ø6 & 2 Ø16 mm) in two layers along the bottom chord (Figures 1 and 2). There was 6 mm steel bar transverse reinforcement in the solid beam GS and the solid ends of the other specimens, with openings spaced at a constant 50 mm for the first four stirrups (at the ends of the beam) and 100 mm for the others. Meanwhile, 4 mm plain bar closed shear stirrups were provided across the tested specimens' entire upper and lower chords, with openings spaced at a constant 50 mm. Additionally, a 4 mm by 6 mm closed bar was arranged in four layers around openings, and a 4 mm by 6 mm closed bar was arranged in two layers in the posts between openings. A straightforward setup was used to test the beams, which had an effective span of 2800 mm. Parametric details of the tested gable beams are shown in Table 1 and Figures 3 to 6, where the symbol G indicates gable and the subsequent symbol S, I90-8, I60-8, and I45-8 denotes solid beam without openings, beam with eight openings, and 90 incline posts, beam with eight openings and 60 incline posts, and beam with eight openings and 45 incline posts, respectively. Upper and lower chords on all truss beams with openings are 100 mm deep, and posts between openings are 100 mm wide.

Table 1: Details of examine beams.

Beam	Beam ID	Number of Openings	Inclination of posts	Existing total beam area mm²	$\frac{\text{Total area of opening}}{\text{Total area GS}}$ %	$\frac{\text{Weight beam}}{\text{Weight GS}}$
Control	GS	-	-	975000	-	1.00
Beams with opening	GI90-8	8	90˚	114300	12.4	0.883
	GI60-8	8	60˚	112000	12.1	0.885
	GI45-8	8	45˚	114300	12.4	0.883

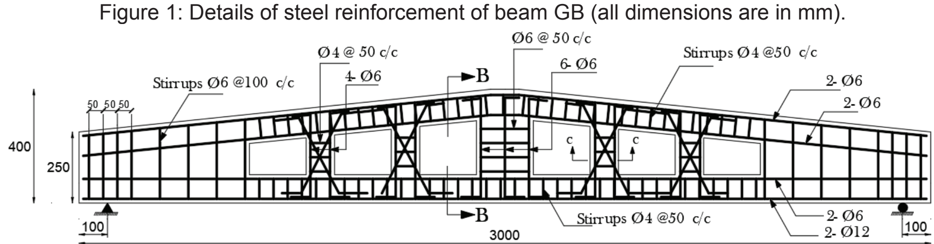


(a) Steel reinforcement Side view.

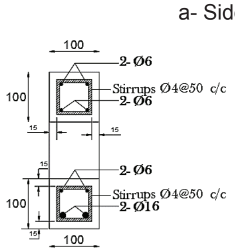


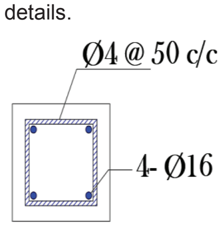
(b) Section A-A.

Figure 1: Details of steel reinforcement of beam GB (all dimensions are in mm).



a- Side view of steel reinforcement details.





b- Section B-B. c- Section C-C.

Figure 2: Details of steel reinforcement of opening beam (all dimensions are in mm).

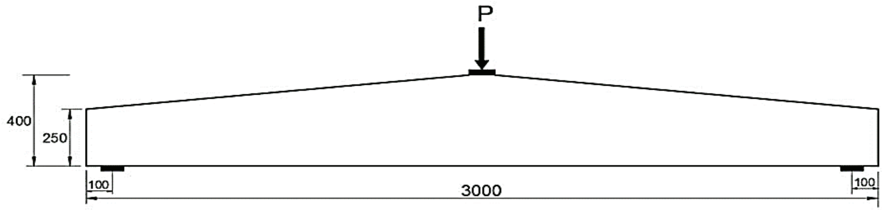


Figure 3: Schematic layout of specimens for GS (all dimensions are in mm).

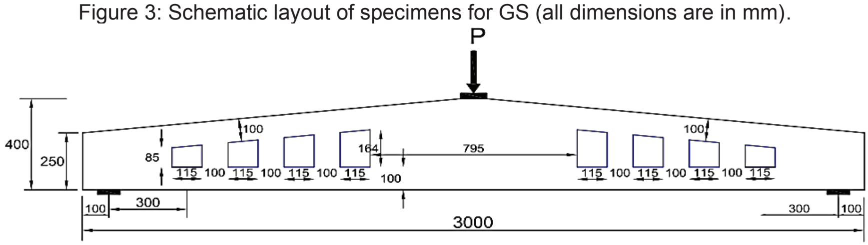


Figure 4: Schematic layout of specimens for GI90-8 (all dimensions are in mm).

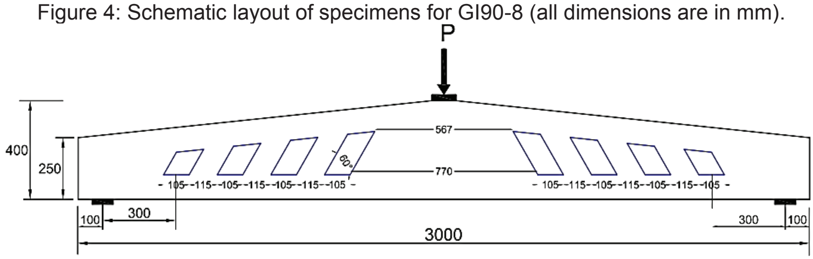


Figure 5: Schematic layout of specimens for GI60-8 (all dimensions are in mm).

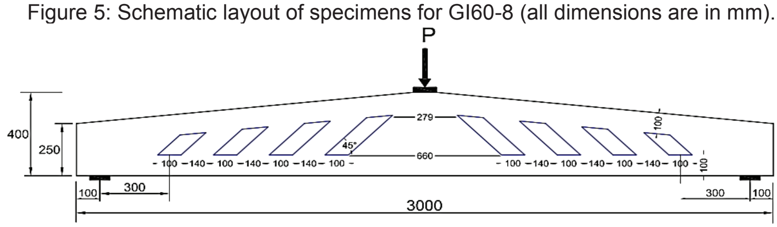


Figure 6: Schematic layout of specimens for GI45-8 (all dimensions are in mm).

The tested beams are cast in wooden molds that have been planned and built. The molds' 18 mm plywood construction and bolted-together side parts make it simple to remove the molds and remove the cast, hardened beams. Before installing the reinforcement cages, the formworks have been cleaned and oiled (Figure 7). The reinforcing cage was placed in the wooden mold once the reinforcing bars were already in place. Two hooked bars, designed to hold the beams, have been included in each steel enclosure. Figure 8 reveals steel bars of varying lengths have been stacked and connected using steel wire measuring 1 mm.

Figure 8: Steel reinforcement.

Figure 7: Wooden mold.

Compacted styropor of 120 mm thickness was used to create the openings, with the styropor being cut to the exact proportions of each opening before being fastened to the molds with long screws, as illustrated in Figure 9.

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Figure 9: Styropor pieces used for constructing the opening.

3. RESULTS AND DISCUSSION

3.1 Resistance to Cracking of the Examined Beams under the Applied Load

The applied load that was present in the tension zone of the tested beam at the point at which cracking became visible (naked eye) is referred to as the initial cracking load. It is often referred to as the load that brought about the crack in the structure. Table 2 illustrates a reduction in first crack load resistance for beams with openings compared to the solid one about 20%. The beam with a 45° inclined opening side (posts inclination) revealed a higher resistance cracking load, followed by the beam with 60° side openings. Meanwhile, the beam with vertical side openings (90 °) had the lesser cracking load resistance. With decreasing inclination posts till 45°, it can be noted that resistance to the first cracking load increased; this may be due to a flattening path to transmit stresses from the mid-loading point to the supports. Furthermore, comparing the loadings of the first cracking with that of the ultimate strength reveals nearby similar differences it was 13.9 and 14.5%.

Table 2: Experimental of examined beams cracking data.

Beams	Beam ID	Number of Openings	Inclination of post between openings	First cracking load P_{cr}, (kN)	$\frac{Pcr}{Pcr,ctrl}$ (%)	Failure load $Pult$, (kN)	$\frac{Pcr}{Pult}$ (%)
Control (ctrl)	GS	------	------	20	------	132	15.2
Beam with openings	GI90-8	8	90°	16	80	115	13.9
	GI60-8	8	60°	17	85	122	13.9
	GI45-8	8	45°	18	90	124	14.5

3.2 Load Versus Deflection

Figure 10 depicts the mid-span deflection with the incremental applied load, compared to the solid control beam. The elastic region is where all beams behave most linearly, and from there on out, a minor deceleration can be seen, which grows in intensity to approach the last stage. The initial stiffness across the elastic zone shows that the beams with angled openings behave similarly to one another, with just a small variation from the reference solid beam. Reinforced concrete gable beams with various holes exhibited clear differences in behavior between the reference solid beam and the reduced moment of inertia beam. The deflection at 30 and 80 kN and the ultimate load are summarized in Table 3. These values have been chosen to represent three loading stages: elastic, near service, and ultimate loading stages. This table shows that at both stages of loading, the stiffness of beams with slanted openings is lower than that of a solid beam (GS). A high decrease was seen at the gable beams with an inclination of 60 and 90 degrees for the posts between the openings, respectively, compared to a 45° inclination. Compared to gable beams with 60- and 90-degree inclination of posts between openings, where concentrated shear stresses at the corners of openings led to a reduction in ultimate carry capacity, the gable beams with 45° inclination of posts between openings were more efficient in load carrying capacity and converged in behavior to that of the reference solid gable beam. However, gable beams with a 45° inclination of posts between openings were marginally more effective than those with a 60-degree or 90-degree inclination of posts. Stresses tend to transmit in the shortest paths from the loading point to the nearest support, which may be why it's important to have the angle of the posts between openings coincide with the direction in which the stresses are flowing, i.e., no turbulent flow in the stress path.

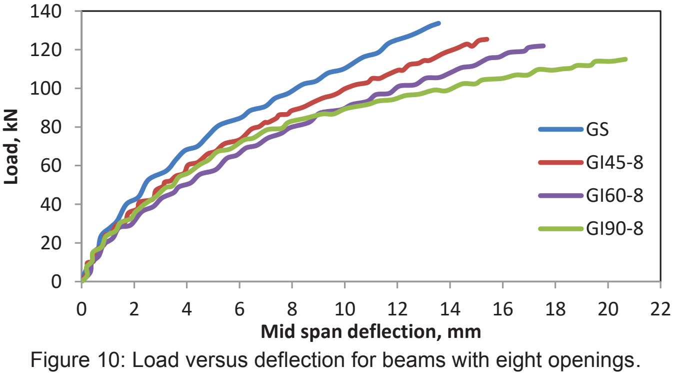


Figure 10: Load versus deflection for beams with eight openings.

Table 3: Results the effect of inclination of posts between openings on the mid-span deflection at three-stages of loading.

Group	Beam	Number of Openings	Inclination of post between openings	At 30 kN		At 80 kN		At ultimate load		Failure load P_{ult} (kN)	Percentage of reduction (%)
				Deflection (mm)	Relative to GS (%)	Deflection (mm)	Relative to GS (%)	Deflection (mm)	Relative to GS (%)		
Control (ctrl)	GS	-	-	1.15	-	5.30	-	13.50	-	132	-
Beams with openings	GI90-8	8	90˚	1.52	132	7.55	142	20.5	152	115	12.9
	GI60-8	8	60˚	1.77	154	8.07	152	17.20	127	122	7.6
	GI45-8	8	45˚	1.40	122	6.60	125	15.20	113	124	6.1

The following comparison demonstrates the increasing percentage in ultimate load with a change in the inclination of posts between openings (Maintaining the number and overall area of openings): Beams (Figure 10): 1.6% and 7.8% for beams GI45-8, relative to beam GI60-8 and GI90-8, respectively.
The decreasing percentage of deflection at different loading stages is as follows:

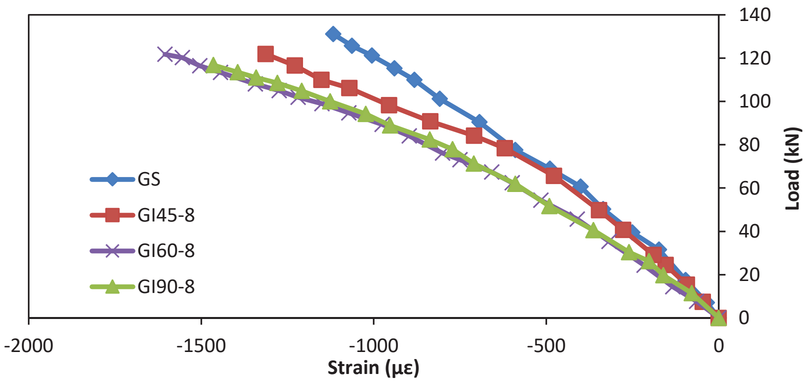
- At 30 kN load: 7.8% and 20.9% for beams GI45-8, relative to beam GI90-8 and GI60-8, respectively.
- At 80 kN load: 12.6% and 18.2% for beams GI45-8, relative to beam GI90-8 and GI60-8, respectively.
- At ultimate load: 25.9% and 11.6% for beams GI45-8, relative to beam GI90-8 and GI60-8, respectively.

These results reflect the enhancement in beam stiffness and rigidity.

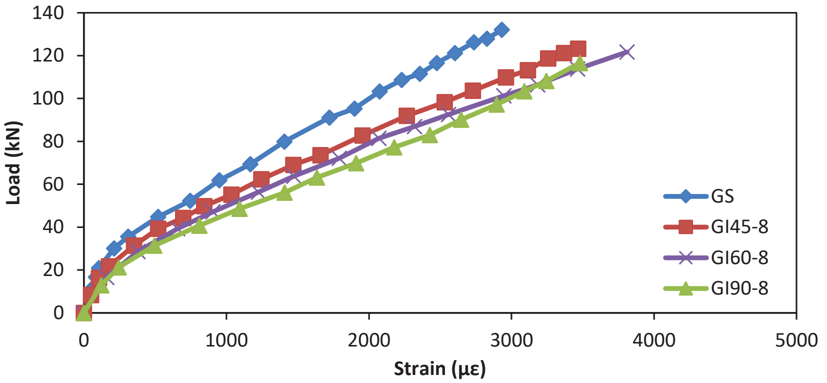
3.3 Load Versus Strain

Load versus top concrete compressive and bottom reinforcement tensile strains at beam mid-span are presented in Figure 11. This figure exhibits a marginal difference in behavior and approximately linear relation between loading and concrete compressive and steel tensile strains with a little descending near the ultimate loading stage. The top measured strain was modified by using the compatibility relation of upper and lower beam mid-span strains. Tables 4, 5, and 6 list values of compressive strains, as well as the tensile strain of steel reinforcement at 30 kN and 80 kN and ultimate stages, respectively. The following comparison demonstrates the decreasing percentage in the concrete compression strain (top concrete fiber) with a change in the inclination of posts between openings (Maintaining the number and overall area of openings):

- At 30 kN load: 23.1% and 28.6% for beams GI45-8, relative to beam GI60-8 and GI90-8, respectively.
- At 80 kN load: 16.7% and 18.8% for beams GI45-8, relative to beam GI60-8 and GI90-8, respectively.
- At ultimate load**:** 18.1% and 10.3% for beams GI45-8, relative to beam GI60-8 and GI90-8, respectively.
- The following comparison demonstrates the decreasing percentage in the tensile strain (lower main steel reinforcement) with a change in the inclination of posts between openings (Maintaining the number and overall area of openings):
- At 30 kN load: 13.1% and 19.8% for beams GI45-8, relative to beam GI60-8 and GI90-8, respectively.
- At 80 kN load: 8.5% and 18.7% for beams GI45-8, relative to beam GI60-8 and GI90-8, respectively.
- At ultimate load**:** 9.4% and 2% for beams GI45-8, relative to beam GI60-8 and GI90-8, respectively.



(a) Concrete compressive strain (top concrete fiber)



(b) Tensile strain (lower main steel reinforcement)
Figure 11: Load versus strain.

Table 4: Top concrete fiber and lower steel reinforcement mid-span strains at 30 kN load.

Group	Beam	inclination of posts	Compressive strain *ε (με)*	Relative to GS (%)	Tensile strain *ε (με)*	Relative to GS (%)
Solid beam (Ctrl)	GS	--------	170	------	225	----
Beams with openings	GI90-8	90°	280	1.65	455	2.02
	GI60-8	60°	260	1.53	420	1.87
	GI45-8	45°	200	1.18	365	1.62

Table 5: Top concrete fiber and lower steel reinforcement mid-span strains at 80 kN load.

Group	Beam	Inclination of posts	Compressive strain *ε (με)*	Relative to GS (%)	Tensile strain *ε (με)*	Relative to GS (%)
Solid beam (Ctrl)	GS	--------	590	-------	1430	------
Beams with openings	GI90-8	90°	800	1.36	2250	1.57
	GI60-8	60°	780	1.32	2000	1.40
	GI45-8	45°	650	1.10	1830	1.28

Table 6: Top concrete fiber and lower steel reinforcement mid-span strains at ultimate load.

Group	Beam	Inclination of posts	Compressive strain, *ε (με)*	Relative to GS (%)	Tensile strain, *ε (με)*	Relative to GS (%)
Solid beam (Ctrl)	GS	--------	1100	-----	2930	-----
Beams with openings	GI90-8	90°	1460	1.33	3500	1.19
	GI60-8	60°	1600	1.45	3820	1.30
	GI45-8	45°	1310	1.19	3460	1.18

4. CONCLUSIONS

- The ultimate load-carrying capacity of a solid gable beam was reduced by 6.1 to 12.9% due to the presence of openings.
- Presence openings in a reference gable beam (solid beam) led to an increase in the mid-span deflection between (22-54%), (22-52%), and (13-52%) when a static load is applied of 30 kN and 80 kN and the ultimate loads, respectively.
- The compression strain that occurred in the concrete fibers at the bottom and top of the higher chord was opposite to the tension strain that developed in the fibers at the top and bottom of the lower chord. This note provided further evidence that the solid gable beam exhibited the same structural behavior.
- According to the data of the experiments, it was found that the model with posts that were inclined at a 45-degree angle between openings was the best one to use for these kinds of beams. This was due to an improvement in the flexural performance, which was demonstrated by an increase in the ultimate load capacity and a decrease in deflection at the service limit.

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