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Research Article

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Deformability of non-prismatic prestressed concrete beams with multiple openings of different configurations

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Abstract: This work presents experimental research using draped prestressed steel strands to improve the load-carrying capacity of prestressed concrete non-prismatic beams with multiple openings of various designs. The short-term deflection of non-prismatic prestressed concrete beams (NPCBs) flexural members under static loading were used to evaluate this improvement. Six simply supported (NPCBs) beams, five beams with openings, and one solid specimen used as a reference beam were all tested as part of the experiment. All of the beams were subjected to a monotonic midpoint load test. The configuration of the opening (quadrilateral or circular), as well as the depth of the chords, were the variables studied in this study. In comparison to a solid beam, experimental results show that beams with openings have a lower load-carrying capacity not exceeding (2.3–10.6%) and higher mid-span deflection through all loading stages of elastic, service, and ultimate loads (14–73%), (19–44%), and (31–55%), respectively. Furthermore, specimens with circular openings had stiffer behaviour under load than those with quadrilateral openings. Beams with quadrilateral openings and inclined posts, on the other hand, were stiffer than beams with quadrilateral openings and vertical posts.

Keywords: Prestressed, non-prismatic, multiple openings, diagonal reinforcement

1 Introduction

Non-prismatic prestressed concrete beams (NPCBs) have been extensively preferred in industrial buildings, bridges, structural portal frames, and framed buildings due to their advantages [1]. Weight of structure can be reduced and larger spans can be achieved by the use of NPCBs instead of the prismatic beam without a clear decrease in loading capacity [2]. Insertion openings in NPCBs system have many benefits including, achieving arithmetic flexibility, easily shipment and erection that the mechanical equipment can pass through the webs and finally, the total weight would most significantly be reduced also. Additionally, concrete is generally inexpensive to produce and has strong fire resistance as well as is relatively low-cost maintenance, so instead of steel sections, it can be used as a good alternative to support warehouse roofs, industrial buildings and aircraft hangars [3–5].

By attaining suitable reinforcing details, many researchers attempted to restore the strength and rigidity of concrete beams having transverse openings to those of solid beams. The negative impacts of stress concentrations around the openings could be removed, load-carrying capabilities could be enhanced, and deflections could be reduced in this way. Mansur *et al.* [6] proved that the failure of continuous RC beams with a big rectangular opening is often connected to Vierendeel truss action in extensive experimental research. As the opening was moved to a more severely stressed region of the span, the deformations in the beam with the opening climbed and the collapse load dropped. Mansur *et al.* [6] discovered that as the opening length and/or depth expand, the Vierendeel action becomes more evident, and the collapse load decreases. The deflections of an RC beam with a wide rectangular opening can be approximated, according to Mansur *et al.* [7], by attributing lower flexural and shear rigidities to the sections containing the opening. Tan *et al.* [8] conducted tests on RC beams with circular openings and found that diagonal reinforcement is an applicable approach for crack reduction. The strength and behaviour of RC deep beams with web openings were examined by Yang *et al.* [9]. The collapse of a deep RC beam is caused by diagonal cracks extending from the corners of the opening, according to their findings. Others, such as Dundar [10], Egri-

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boz [11], Aykac, and Yilmaz [12], highlighted the influence of many openings. Multiple openings were intended to give a more efficient design by distributing stress concentrations around openings throughout the entire beam length and increasing the ductility of the beams. Based on experimental research that included 13 non-prismatic concrete beams (NCBs) with openings under monotonic static loads, Hassan and Izzet [4] presented an analysis of the serviceability of non-prismatic reinforced concrete beams with openings of various diameters. A developed unified calculation approach has been proposed for deflection and cracks widths under static loads at the service stage. The deflection was calculated using two methods: the first method used relevant equations to calculate the deflections, and the second method used the direct stiffness method to evaluate the deflection, in which the beam is treated as a structural member with several segments constituting solid sections and sections crossed by the opening. Abdulkareem and Izzet [13] investigated the serviceability of the post-fire behaviour of non-prismatic concrete beams (NCBs) of various shapes and sizes. It was discovered that fire had a negative impact on the strength and deformability of these types of beams throughout a wide range of conditions. Large openings in prestressed concrete members, on the other hand, can be accommodated without compromising strength or violating serviceability criteria. Warwaruk [15], Dinakaran and Sastry [14]. Beams with openings, whether prestressed or common reinforced concrete, behave similarly to Vierendeel trusses, with contra flexure points towards the chord length's centre. Depending on the extent of cracking of the upper and lower chord members, the shear stress in the middle of the opening can be distributed within the upper and lower chords relative to the cross-sectional area, chord stiffness, or a combination of these [16, 17]. The failure of the beam happens through the creation of a mechanism consisting of plastic hinges at the ends of the chord components, provided that the individual chord elements are stiff enough to resist direct compression, tension, and shear failures.

This study aims to enhance the load-carrying capacity of NPCBs with web openings by using draped prestressing steel strands in the lower tension zone (lower chord) and a wide flange at the upper chord. Also, to investigate the short-term deflection response of NPCBs flexural members with multiple openings of different shapes, the efficiency of beams under static loading up to failure, and find the acceptable geometric scheme of the openings.

2 Experimental program

Six simply supported NPCBs with different openings were manufactured and tested under the action of a single monotonic static loading at the mid-span section for the experimental program. Obviously, this type of structure loaded above the specific nodes (posts), herein to eliminate the difference in posts positions, mid-span loading was chosen. Whereas the openings of different configurations, (quadrilateral or circular), were used. All beams were fabricated with similar depths of their upper and lower chords.

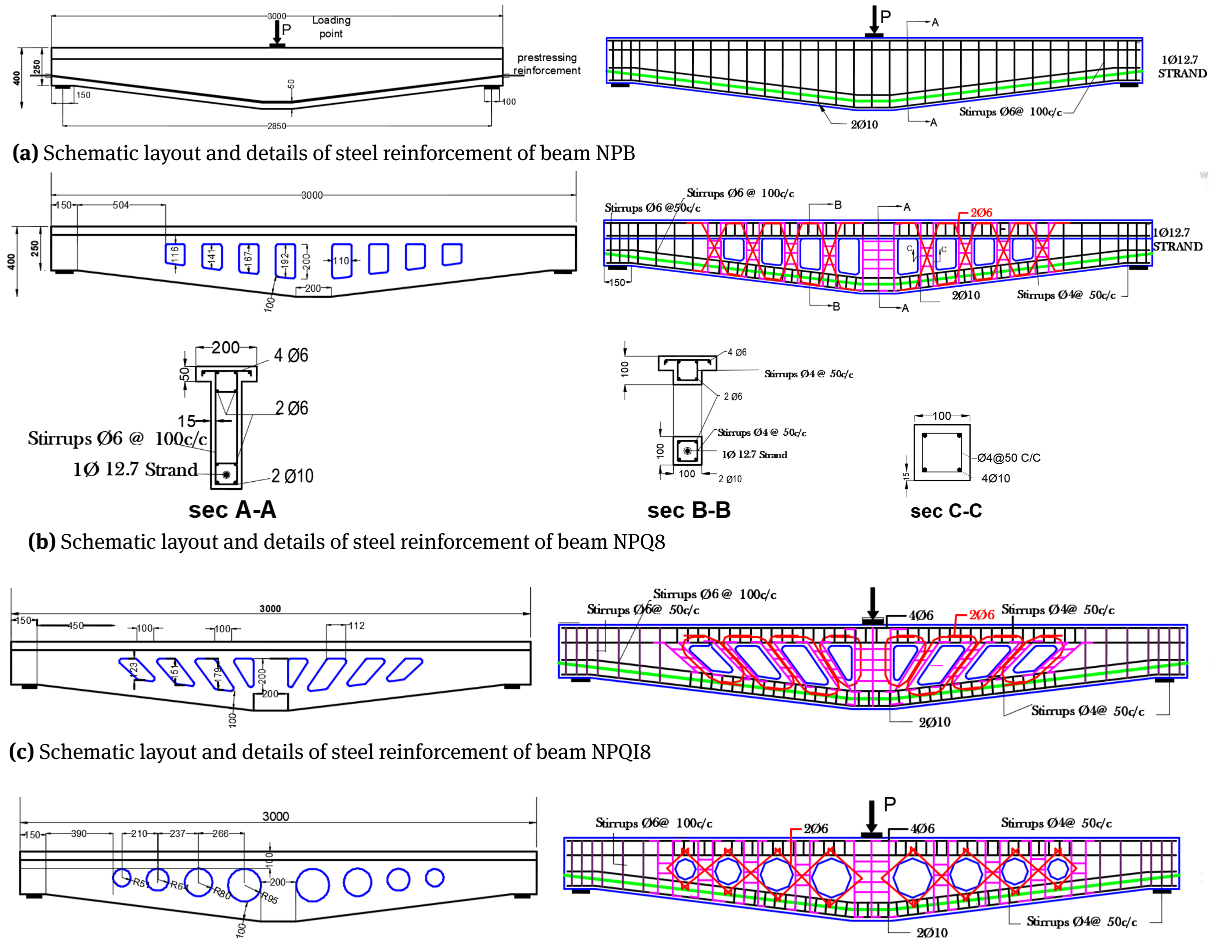
2.1 Details of the test matrix

The test matrix includes one beam specimen without openings (solid) and five perforated specimens with eight openings (quadrilateral or circular configurations). All beams had the same typical dimensions and geometry with an overall length of 3000 mm, and a clear span of 2850 mm. The overall beam depth is 400 mm at the mid-span and

Table 1: Details of the tested beams

Group	Beam ID*	Shape of openings	Number of openings	Total area of openings (mm^2)	Upper chord height (mm)	Lower chord height (mm)
solid beam	NPB	—	—		—	—
A	NPHQ8	Quadrilateral with vertical post	8	180000	75	75
	NPHC8	Circular	8	228000	75	75
B	NPQ8	Quadrilateral with vertical post	8	139000	100	100
	NPC8	Circular	8	139000	100	100
C	NPQI8	Quadrilateral with inclined posts	8	139000	100	100
	NPC8	Circular	8	139000	100	100

*N: Non-prismatic, P: Prestressed, B: Beam, H: Height of chord 75, C: Circular, Q: Quadrilateral openings with vertical post, QI: Quadrilateral openings with inclined posts, 8: Number of openings.



(a) Schematic layout and details of steel reinforcement of beam NPB

(b) Schematic layout and details of steel reinforcement of beam NPQ8

(c) Schematic layout and details of steel reinforcement of beam NPQI8

(d) Schematic layout and details of steel reinforcement of beam NPC8

Figure 1: Schematic layout and details of steel reinforcement for all specimens. (Note: All dimensions in mm)

250 mm at the end section, respectively. The depth of the beams decreased toward the support. The web width was 100 mm meanwhile the flange width was 200 mm, and the flange depth was 50 mm. The openings are identified by 100 mm posts width, the proper detailing for reinforcement included, the short stirrups in the chords, the diagonal reinforcement around the openings, the posts and full-depth stirrups next to openings and prestressing strand, as shown in Figure 1. According to the variable that has been examined in this study specimens were divided into three groups (A, B, and C), see Table 1.

2.2 Material properties

Table 2 lists the properties of the materials used in this experiment. Cement, coarse, and fine aggregates were all conducted to standard testing in accordance with Iraqi specifications (IQS), whilst the ASTM was used for reinforcing steel. Post-tensioning force of (110 kN) was applied from one end according to the limits of ACI-318M-19 [18] using a 7-wire strand of 12.7 mm diameter (Grade 270).

2.3 Setup and testing procedure

The test setup is depicted schematically in Figure 2. The beams were tested as simple supported members with a thick steel plate resting on steel rollers. To provide a load to the beams, an 800 kN hydraulic jack was used. A load cell with a digital load reader was used to control the applied load. A thick bearing steel plate with dimensions of 200×100×20 mm was used to apply the exterior concentrated load at the mid-span section.

The load was applied in steps of 2.5 kN increment. After the initiation of cracking, the load increment was increased to 5 kN. Strain in the main steel reinforcement (mild steel and strand) and the mid-span deflection were monitored during testing.

Table 2: Material properties

Material	Diameter, (mm)	Yield Stress, (MPa)	Average Compressive Strength (fc′), (MPa)	Average Ultimate Tensile Strength, (MPa)	Average Modulus of Elasticity, (GPa)
strand	12.7	1674	—	1860	197.5
rebar	10	600	—	678	200
	6	550	—	670	200
	4	410	—	516	200
Concrete	—	—	45	4.36	28.9

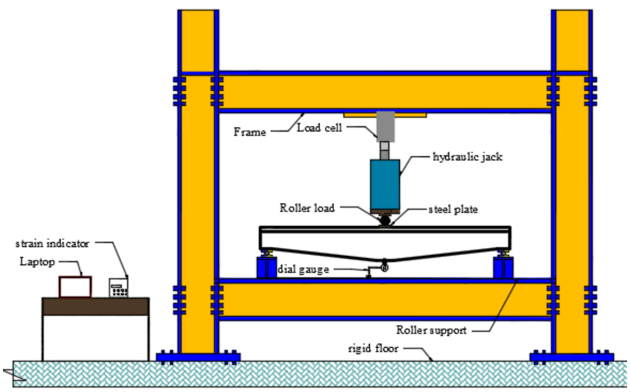


Figure 2: Test setup

3 Experimental results and discussion

3.1 Ultimate loads and failure modes

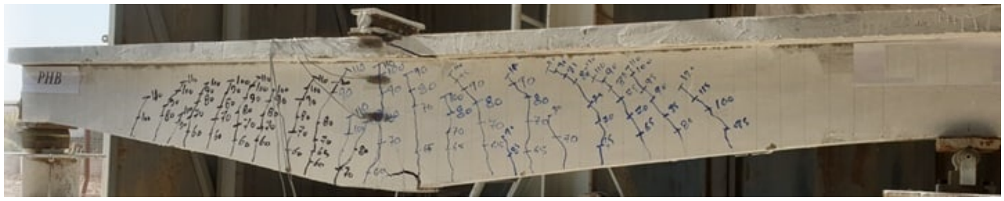
The failure load was defined as the load that corresponded to the maximum applied load beyond which the beam's strength significantly decreased. As implied in Table 3, beams with all additional enhancements involving tensile and compressive zones, insertion openings do not result in significant reductions in the load capacity compared to the solid beam, the decreasing ratio of ultimate strength capacity ranged between (2.3~10.6%) originated from two reasons. First, enlarging the compression chord area by using a beam flange to provide an adequate compression zone that accommodates the compressive stress that balances the tensile forces of the prestressing strand and the ordinary steel reinforcements. Second, the adequate amount of shear reinforcement achieved beside the additional diagonal bars provided around the corners of the opening.

Yielding of the bonded mild steel bars occurred in all tested beams. The solid beam (NPB), failed by crushing concrete at the upper compression zone after yielding the bonded bars and the unbonded strand. At this loading stage, the deflection increased progressively, and the beam failed soon after the applied load suddenly dropped, see Figure 3a.

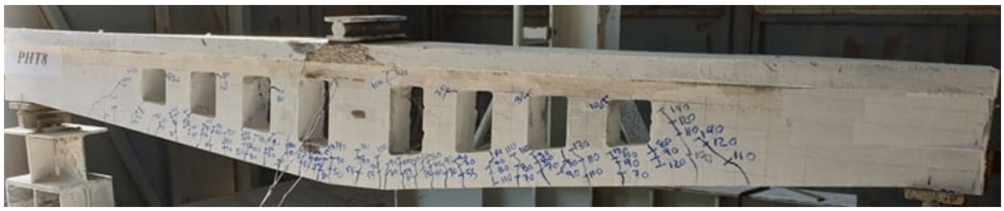
In beams with openings, various sets of failure were detected. First, the beams (NPQ8, NPHQ8, and NPI8) experienced tension-controlled flexural failure as a result of the formation of several flexural cracks in the tension zone due to the yielding of the bonded mild bars, followed by concrete crushing in the compression zone near the loading point and peeling off the concrete at the beam soffit, as shown in Figures 3b, 3c, and 3d. Second, frame-type shear failure was observed in beams with circular openings (NPCI and NPCII) by the formation of a diagonal crack crossing one of the nearest openings to the loading point, see Figures 3e, and 3f. Despite these beams failing by shear, they exhibited substantial ductile behavior because the diagonal reinforcements around the opening delay the widening and propagation of the diagonal crack. Also, using a significant intensity of transverse steel of closed stirrups offered confinement and played the role of the diagonal crack arrester.

3.2 Load-deflection response

Insertion of an opening in reinforced concrete beam results in a reduction in beam stiffness due to the sudden variation in the beam's cross-section. Furthermore, a non-prismatic beam affects approximately by the same variation through the change of the profile [3, 5]. Camber was measured at the midspan of the beam, the average measured upward deflection (camber) of the post-tensioned concrete beams was 0.88 mm for the solid specimen and 1.15 mm, with a deviation of 13.2% for those with openings, these values have been eliminated in measuring the load-deflection response. Figure 4 demonstrates that the prestressing force with draped profile has a noticeable effect on the behavior of such beams. That is reflected in the load-deflection performance of the tested member. Despite (NPCBs) beams with openings were offering less stiffness, they showed a slight decrease in the failure carrying capacity. The results

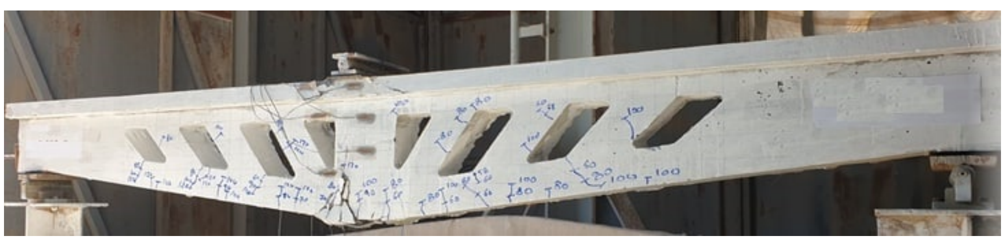


(a) Failure and crack patterns of NPB



(b) Failure and crack patterns of NPQ8

(c) Failure and crack patterns of NPHQ8

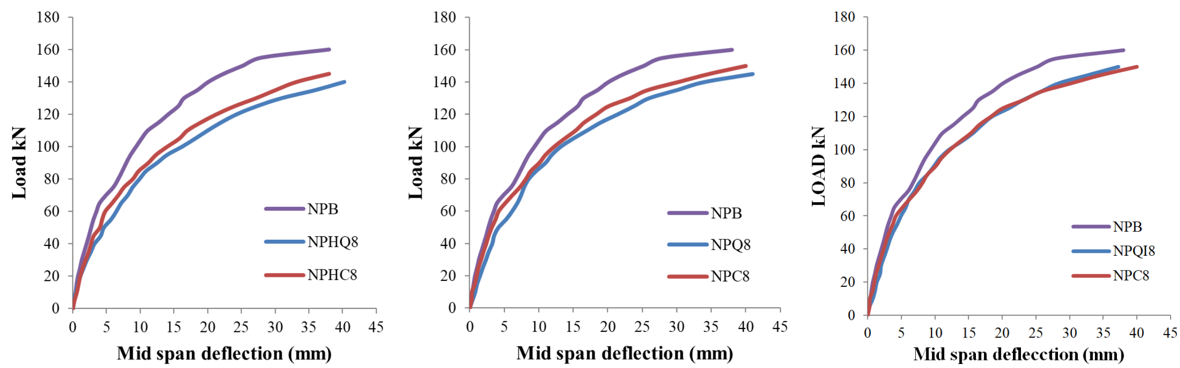


(d) Failure and crack patterns of NPQI8

(e) Failure and crack patterns of NPHC8

(f) Failure and crack patterns of NPC8

Figure 3: Failure mode and crack patterns of tested beams



(a) Group A **(b)** Group B **(c)** Group C

Figure 4: Load versus mid span deflection for non-prismatic beams

Table 3: Deflection at various loading stages of the tested beams

Group	Beam ID	@ 45(kN)		@ 90(kN)		@ P_{ult}, (kN)		Failure Load P_{ult}, (kN)	Decreasing ratio of P_{ult}, % (mm)**
		Deflection (mm)	% deflection increasing*	Deflection (mm)	% deflection increasing*	Deflection (mm)	% deflection increasing*		
solid beam	NPB	2.39	—	7.34	—	28.0	—	163.8	—
A	NPHQ8	4.15	73	10.57	44.0	36.8	31	146.3	10.6
	NPHC8	3.10	29	9.88	34.5	42.0	50	152.4	7.0
B	NPQ8	3.55	48	9.65	31.0	38.4	37	153.7	6.0
	NPC8	2.75	14.7	8.88	21.0	43.4	55	160.0	2.3
C	NPQI8	3.24	35	8.79	19.6	38.0	36	158.4	3.3
	NPC8	2.75	14.7	8.88	21.0	43.4	55	160.0	2.3

(*) = $\frac{\Delta Beam - \Delta Ref.beam}{\Delta Ref.beam} 100\%$ (**) = $\frac{\Delta Beam(At\ Pu) - \Delta Ref.beam(At\ Pu)}{\Delta Ref.beam(At\ Pu)} 100\%$

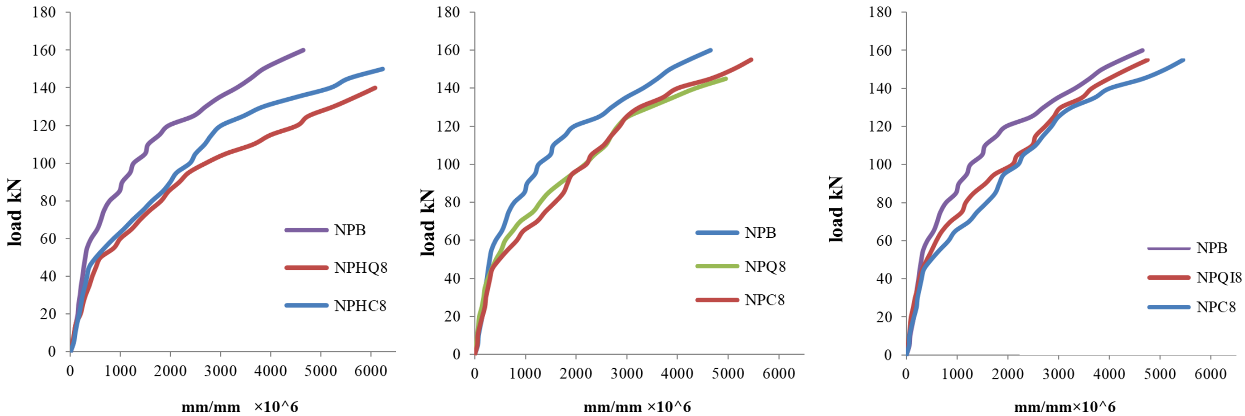
depicted in Figure 4 illustrate that the response of the solid and perforated beams was similar to the load that led to cracking, after which the load-deflection curves started to diverge. After the cracking formation and as far as the stiffness decreases, the divergence between the two performances begins to increase. It is worthy to mention that all tested beams with openings (NPCBs) displayed a detectable ductility before failure.

Table 3 reveals that at the earlier loading stage of (45 kN), concerning solid non-prismatic beam (NPB), the tested beams of Group (A) showed a higher reduction level of stiffness remarked by increasing the deflection by 73 and 29% for specimens NPHQ8 and NPCI, respectively, with upper and lower chords of 75 mm deep. Meanwhile, the increasing of deflection in beams of Groups (B) and (C) attained respectively the range (48–14.7%) and (35–14.7%). Also, it can be arranged beams stiffness reduction descendingly for those having circular, rectangular, and quadrilateral openings, respectively. Beams with circular openings allow transmitting the stresses smoothly from the loading point to the supports, whereas the stresses are transmitted turbulently and mostly concentrated at the sharp corners of the opening for those beams with polygonal openings. At the loading stage of 90 kN, this dissipation in beams stiffness was reduced for Groups (A) and (B), whereas it was less than that for beams of Group (C). The same observation was recorded at the ultimate loading stage.

3.3 Load versus mid-span strain of reinforcing steel

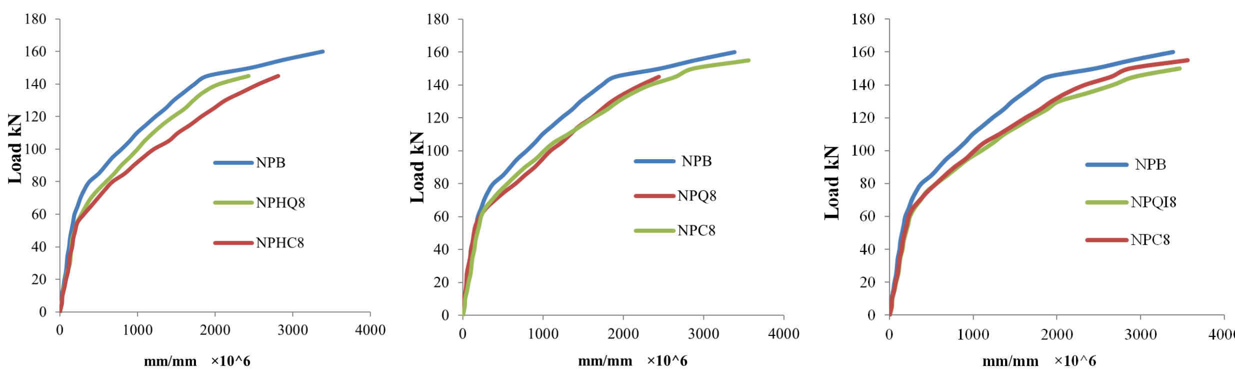
A strain gauge was positioned in the middle of the bottom bonded longitudinal steel reinforcement ⌀10 mm to detect the strain, and their results are plotted in Figure 5.

The presence of web openings increases the curvature due to the sudden change in the cross-sectional area and the moment of inertia. Before cracking, all beams showed an identical linear elastic behavior with different slopes. Whereas, after cracking, the slope of these curves gradually decreased with variant slope change which was affected by the variables that have been studied. The yielding strain for steel reinforcements was 3000×10^6 mm/mm, according to



(a) Group A **(b)** Group B **(c)** Group C

Figure 5: Load versus strain in lower steel reinforcement



(a) Group A **(b)** Group B **(c)** Group C

Figure 6: Load versus strain increment in unbounded reinforcement strand

tensile test findings done on a 10 mm diameter bar. Thus, all beams passed over this limit at the failure stage. The same observations were noticed in Figure 6. The strain increment in the unbonded prestressing strands of different tested beams almost exceeded 3000×10^6 mm/mm except for the strands of the specimens (NPHQ8), (NPCI), and (NPQ8).

The ability of the tested beam to resist inelastic deformation without the degradation of the load capacity before collapse is known as the member's ductility index μ the ductility index can be calculated as the ratio of ultimate deformation Δ_{ult} to deformation at yield Δ_{yield} [19]

$$\mu = \frac{\Delta_{ult}}{\Delta_{yield}} \tag{1}$$

Meanwhile, rigidity is defined as the resistance against deformations caused due to the bending effect of applied load on the tested beam. The member rigidity values can be calculated directly either from the load-deflection response which has been adopted hereien or the load-curvature response of the beam taking the slope of their initial linear portion. Meantime, due to the changeable flexural stiffness along the longitudinal axis of the non-prismatic beam with web openings, it is difficult to evaluate the rigidity of the investigated beams based on the load-curvature concept Therefore, the values of the slope of the initial linear portion of the load-deflection response were considered.

The ductility index μ and the initial stiffness (rigidity) are revealed in Table 4. It should be that the highest ductility index was calculated for the non-prismatic perforated specimens in comparison to the non-prismatic solid specimen. This fact is attributed to two main reasons; (1) the existing openings which led to a significant decrease in the member's flexural stiffness and, in turn, to increase the deflection at failure and (2) the use of steel ties along with the posts between openings and diagonal steel bars around the periphery of the openings led to strengthening the mentioned zones and the failure attained somewhere else through the upper and lower chords.

Table 4: Ductility and initial stiffness

Group	Beam ID	Δ_{ult} (mm)	Δ_{yield} (mm)	$(\mu) = \frac{\Delta_{ult}}{\Delta_{yield}}$	(%) increase	(kN/m)	(%) decrease
Control (solid)	NPB	28	18,3	1,53	—	18,2	—
A	NPHQ8	40,25	19,07	2,11	1,37	10,07	0,55
	NPHC8	38	20,76	1,83	1,19	14,03	0,77
B	NPQ8	41	23	1,78	1,16	12,7	0,7
	NPC8	40	19,23	2,08	1,35	16,6	0,91
C	NPQI8	37,5	23,3	1,61	1,05	13,43	0,74
	NPCII	40	19,23	2,08	1,35	16,6	0,91

Table 4 shows that in quadrilateral web openings (i.e., specimen NPHQ8), decreasing the depth of each of the top and lower chords by 25% resulted in a considerable increase in the ductility index when compared to the specimen (NPQ8). Furthermore, with the same upper and lower chords and opening area, beams with circular openings (NPCII) have higher values than beams with quadrilateral openings (NPQ8). The beam (NPHQ8), on the other hand, was more ductile than (NPCI). This could be due to the larger area of the opening formed for (NPCI) compared to (NPHQ 8), which had the same upper and lower chords. Non-prismatic beams perforated with circular configuration openings have higher rigidity than non-prismatic beams perforated with polygonal openings.

4 Conclusion

- Using draped tensile prestressing force to enlarge the upper concrete chord reduces the reduction that may happen with existing openings. The reduction in ultimate load-carrying capacity was between (2.3~10.6%).
- Also, using adequate steel reinforcement stirrups with diagonal reinforcement around the corners of the opening minimized the initiation threat of corners cracks leading to plastic hinges and may develop to a typical failure of such beams (Beam-type failure or Frame-type shear failure).
- Existing openings in a beam increase the deflection as compared to a solid beam. At three loading stages at elastic, service, and ultimate loads, the increasing ratio of mid-span deflection ranges between (14.7–73%), (19.6–44%), and (31–55%), respectively to the solid beam. Depending on the openings configurations and posts inclinations.
- Non-prismatic beams with circular openings behave stiffer than those with quadrilateral ones by about 25 and 22% at before the initiation of cracks for beams having similar upper chord thickness of 75 and 100 mm, respectively, whereas inclined posts reduce this difference to 15%. The same observation as that for the ultimate load-carrying capacity was noticed. Non-prismatic specimens with circular configuration openings showed an increase in the carrying capacity.
- For beams with circular or quadrilateral openings, it was observed that reducing the upper chord thickness by 25% has a slight effect on load carrying capacity (not more than 5%). As well inclined posts enhance load carrying capacity by 3% in comparison to vertical ones.

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