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Flexural Behavior of Prestressed Self-Compacting Concrete Beams with Openings

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ABSTRACT

It is necessary for reinforced concrete beams to have apertures in many buildings, especially those with service levels. Apertures are necessary for a range of utility services, such as air conditioning units, electrical cables, water pipes, and network connections, in order to enable bypassing. This saves a great deal of money by enabling buildings to have lower-story heights. In this study, the flexural behavior of simply supported post-tensioned self-compacting concrete beams with rectangular openings is evaluated through an experimental test program. The use of self-compacting concrete (SCC) was adopted because of its efficiency in filling the forms in the tight portions around the openings. The tested beams included one control beam without openings, one post-tensioned control beam without openings, and three post-tensioned beams with different opening configurations. While the first beam was provided with a small opening in the middle third of the span, the second had a relatively larger opening and the third beam had two small openings in the shear span. The test results showed that post-tensioning effectively increased the cracking and ultimate loads as the ultimate load was almost twice as that of the control beam without openings. The deflection values during the whole loading course were reduced, while the ductility index values indicated a convenient structural behavior. Within the current test limits, it was found that the one opening around the middle of the span or two openings within the shear spans had a slight influence on the structural behavior as long the opening height is no more than one-third of the beam height and the opening length is about 7 percent of the clear span.

Keywords: *Flexural behavior, rectangular opening, SCC, and post-tensioned beams.*

1. Introduction

The clear floor height restrictions often affect the designs of architectural and mechanical engineers. Openings are commonly planned in the web of concrete beams to account for utility needs and thus, story height can be effectively decreased. This arrangement can positively influence the overall cost of construction (Ali S, Saeed J, 2022). On the other hand, the strength and stiffness of structural beam elements can be significantly affected due to the intrusion of the openings depending on their location and relative dimensions (Jebasingh D, 2022). Proper positioning, comprehensive design and reinforcement detailing around the openings are therefore necessary. Beams with openings usually demonstrate more complex behavior with regard to stress concentration and deformations about the openings (Park SY, Grace NF, et al., 2022). During the design phase, it is necessary to take notice of how openings can affect strength and serviceability. The primary issue with openings in reinforced concrete beams is the sudden change in geometry, which has a major impact on the element's structural behavior (Mansur MA, Kiang Ht,1999)(Clark G, 2013).

Reinforced concrete beams with openings have been the subject of several studies. Comparatively little thought has gone into how prestressed beams with apertures behave (Mohammedali TK, 2021). Post-tensioning is a relatively new technique when compared to reinforced concrete; it was developed in the middle of the 20th century as a result of steel shortages during and after World War II. By carefully adjusting the profile or alignment of the tendons to meet and balance the anticipated stresses in service, the developers of post-tensioned buildings may precisely give the tensile strength where it is needed (Kramer KW, 2005) Nonetheless, when it comes to prestressed concrete, the potential for cracking around the entrance during the transfer of prestress must be carefully considered (Alan H, et al., 2005) (Hassanin AI, Elsheikh AI, 2021). In order to manage these cracks, stirrups should be positioned sufficiently on each side of an opening. Basically, web openings in pretensioned beams should be positioned away from the areas necessary for the emission of full tendon force. Further, beams with openings positioned in high shear zones perform worse than those with openings situated in areas with a predominance of flexural stresses (Elkhouly AF, 2024) (Elsayed M, et al., 2022). The bottom and top chords of an opening in pre-tensioned prestressed beams should receive the shear force at that location in proportion to their uncracked moments of inertia until cracking occurs (Tran DT, 2021) (Taha K, et al.,).

The degree of cracking in the tension chord determined the shear distribution between the opening chords after it had cracked. Beyond cracking, the tension chord's level of cracking determined the shear distribution between the opening chords (Fu L, et al., 2022) (Hekal GM, et al, 2020) According to a cautious design, the shear allocated to the tension chord should be based on the ratio of the uncracked moments of inertia, and the shear assigned to the compression chord should be based on the ratio of the cracked moments of inertia (Mihaylov BI, et al.,2019)(Lu, ZH, et al., 2021).

In the current work, a Self-compacting Concrete (SCC) mix was used with regard to the merits of this special type of concrete. Okamura originally presented the idea for self-compacting concrete in 1986, and Ozawa constructed the first prototype in 1988. Because of its superior seclusion resistance and deformability, SCC is recognized as a high-performance concrete with many applications in large bridges and undersea projects, as well as lighter and thinner structural components (Ahmad W, et al., 2022) (Shi C, et al., 2020). SCC has a high ability to flow in tight forms or forms with congested reinforcement (Nasir M, 2020). Knowing that the chords under the openings are difficult to reach and compact, the use of SCC would be a suitable alternative to conventional concrete (Rajakarunakarana SA, et al., 2022)(Prakash R, et al., 2022). SCC mixes are typically proportioned using highly efficient water reducers and viscosity chemical additions to control the segregation of coarse particles while a high flowability is achieved. Also, finally, divided mineral materials are incorporated to increase the quantity of fine materials, while the cement content is maintained within reasonable values in the range of 350 – 450 kg/m^3. This mix design approach enables efficient concrete mixes with regard to strength, durability and cost.

The work described in this paper is part of an ongoing comprehensive research work to evaluate the structural performance of post-tensioned RC beams with openings with different configurations with respect to the size and location along the span. The presented results belong to the testing program aiming at describing the structural performance as the openings are introduced compared to that of control beams without openings.

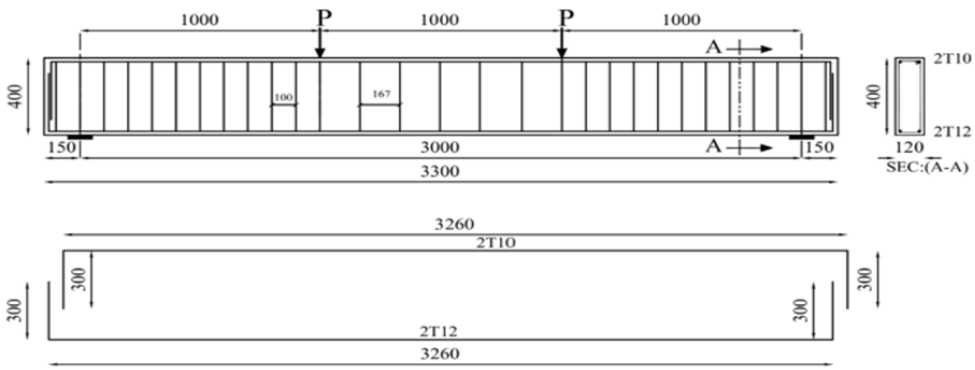
2. EXPERIMENTAL WORK

2.1 TEST SPECIMENS

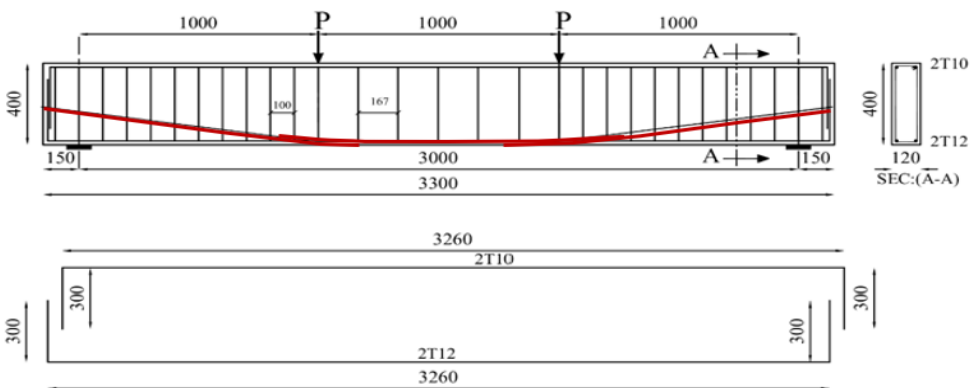
The experimental program involved the testing of five full-scale RC beams. The beams included two control beams without openings, beam (C) was a conventional beam and beam (P) was post-tensioned. The other three beams were post-tensioned and provided with either a large opening, beam (P1-LM), or one smaller opening, beam (P1- SM), located at the middle of the span or one small opening in each shear span, beam (P2-SS). All test specimens had the same cross-section of 120 mm width and 400 mm height. The total beam length was 3300 mm with a clear span of 3000 mm with an overhang length of 150 mm, as shown in Fig. (1). The beams were designed according to ACI 318M-19. Each beam was reinforced with two 12mm bars as tension reinforcement and two

10mm bars as compression reinforcement and with 8 mm stirrups distributed uniformly at a spacing of 150 mm to ensure tension failure collapse and to prevent shear failure.

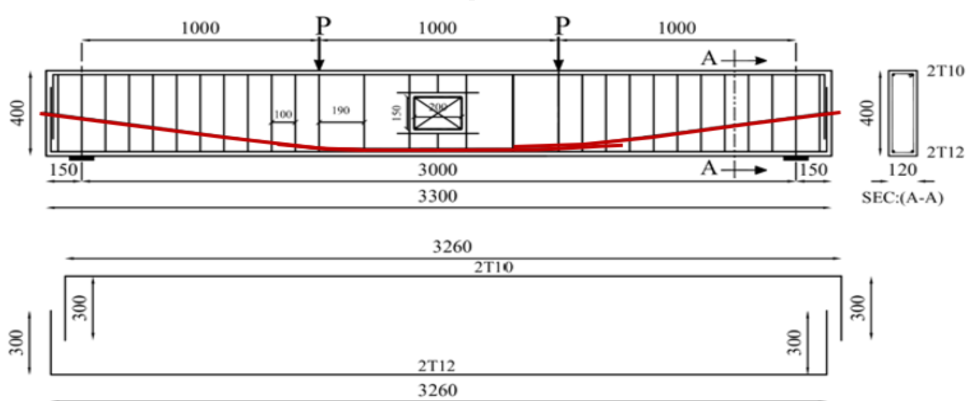
All openings had a fixed height of 150 mm allowing for 100 mm upper and lower chords. A small opening had a height of 150 mm and a length of 200 mm and the larger opening had a height of 150 mm and a length of 400 mm which is 13.3 percent of the clear span. Two 8mm rebars were laid directly under and above the opening. These bars extended 150 mm beyond the opening sides. Fig. (1) shows test beam configuration and reinforcement.



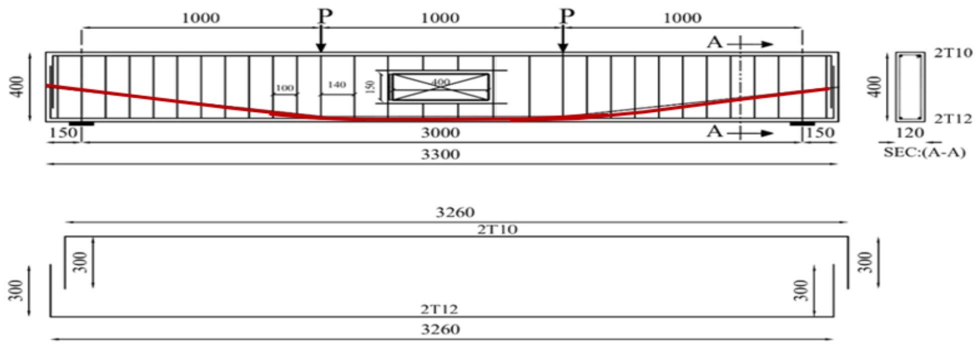
(a) Specimen (c)



(b) Specimen (P)



(c) Specimen (P1-SM)



(d) Specimen (P1-LM)

Fig. 1: Configuration and reinforcement of the tested beams (dimensions in mm)

2.2 MATERIAL PROPERTIES

2.2.1 Self Compacted Concrete

Ready-mix concrete was used in casting the test specimens. Samples of the materials were supplied by the concrete mix plant to evaluate their properties and to design trial mixes. Ordinary Portland cement (CEM I- 42.5N) conformed to the requirements of E.S.S. 4765-1/2009 with a specific gravity of 3.15 and Blaine fineness of 3994 cm^2/gm. The coarse aggregate was crushed dolomite with a maximum nominal size of 12 mm, a specific gravity of 2.75, and a crushing modulus of 18.5%. The fine aggregate was well-graded siliceous sand with a specific gravity of 2.60, and a fineness modulus of 2.4. Class (F) fly ash meets the requirements of ASTM C618 with a specific gravity of 2.1. A high-range water reducer (HRWR) meeting the requirements of ASTM C494 (Type A and F) was used. The admixture is a brown liquid having a density of 1.18 kg/liter at room temperature.

Trial mixes were proportioned and tested to evaluate the rheological and mechanical properties given that the characteristic strength is no less than 50 MPa. The proportions of the selected mix achieving SCC requirements is shown in Table (1). The properties of fresh and hardened concrete are given in Table (2).

Table 1. SCC constituents and mix proportions (Kg/m^3)

Cement	Fly ash	water	Fine Agg.	Coarse Agg.	HRWR
450	40	160	980	850	9

Table 2. Fresh and hardened SCC mix properties

Mix Properties	
Slump flow diameter, mm	780
J- ring (average diameter), mm	730
V-funnel time, sec.	6.5

28-day compressive strength (cubes), MPa	52
Modulus of elasticity, GPa	27.5
Modulus od rupture, MPa	8.0

2.2.2 Reinforcement Steel Bars

The steel reinforcements included 10 mm and 12 mm diameter high tensile ripped steel bars with a yield strength of 530 MPa and 520 MPa, respectively, satisfying the requirements of grade B500DWR according to the standard specification ISO 6935 – 2. The 8 mm mild steel plain rebars had a yield strength of 280 MPa satisfying the requirements of grade B240D-P according to the standard specification ISO 6935 – 1. For beam prestressing, 7- wire low relaxation stand was used. According to the manufacturer data sheet, the strands had a diameter of 12.7 mm with an ultimate tensile strength of 1860 MPa and a modulus of elasticity is 200 GPa, conforming with the specification ASTM (A 416 - Grade 270).

2.3 MANUFACTURING OF TEST BEAMS

Wooden forms were manufactured and laid on a flat horizontal surface. Wooden boxes were fixed in place to create the intended openings. The steel rebars were assembled and the cages were then laid in their proper positions in the forms. A 20 mm diameter smooth polyethylene conduit was cut to the desired length and fixed to shape the path of the prestressing tendon in a plane at the middle of the beam width. The prestressing tendon was then inserted through the conduit via two holes in the wooden form. A 200 mm long spiral strips made of 6 mm mild steel were inserted to confine the two ends of the conduit to prevent concrete form crushing while and after applying the post-tensioning force.

One cubic meter of ready-mix concrete was delivered to the casting yard and once the beams were casted, the specimens were marked to indicate the position of the main steel. Fig. (2) shows the laid forms and the casting process. The beams remained in the forms and cured using wet burlap for 28 days. After concrete had acquired its full strength, the prestressing force was applied using a hydraulic jack, Fig. (3). Wedge grips mounted in a 40 mm cubic steel block were used to grip the strand during stressing and to hold the strand permanently anchored. The applied tensile stress in the strand was 550 MPa which is about 30 percent of its tensile strength.

Fig. 2: Reinforcement details and casting of test beams using ready-mix concrete

Fig. 3: Applying the post-tensioning force using a hydraulic jack

2.4 TEST SETUP AND INSTRUMENTS

Once the forms were stripped, the test beam sides were painted in white using a water-based painting to facilitate detecting and marking the cracks. The test beams were loaded in flexure under two-point loading so that the shear span was one-third of the clear span. The load was applied through a rigid steel beam and roller loading axis. An electrical driven hydraulic pump connected to a double-acting cylinder enabled a testing load capacity of 150 KN through a rigid steel frame, Fig. (4). The deflection at mid-clear span was measured using 100 mm stroke linear variables differential transformer (LVDT) sensors. A data logger system was connected to record the relationship between the acting load and the instantaneous corresponding deflections. Fig. (5) shows a schematic drawing of the setup.

Fig. 4: Applying test load using double action hydraulic cylinder and loading frame

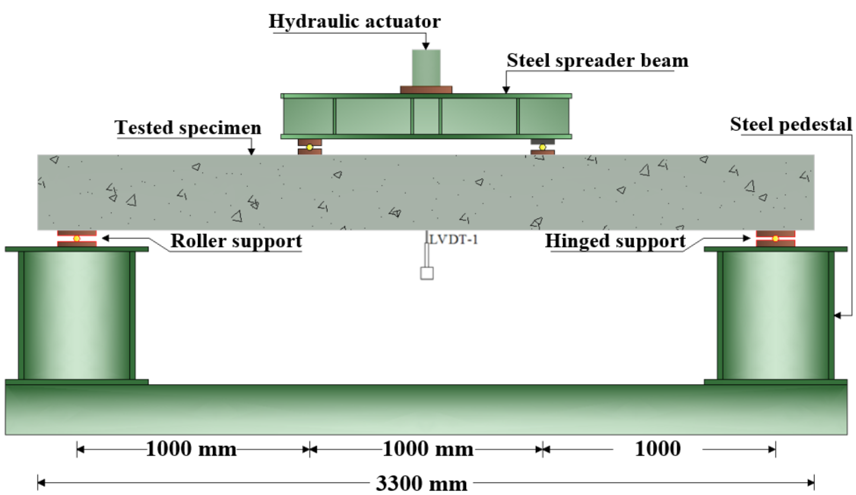


Fig. 5: Test setup and instrumentations

3. EXPERIMENT TEST RESULTS

The specimens were tested under four-point loading till failure indicated by a drop in the applied load or excessive concrete crushing.

3.1 Load-deflection response

All beams showed a typical three-stages behavior associated with pre-cracking, post-cracking and yield of steel rebars, Fig. (6). In the pre-cracking stage, the beams showed the highest stiffness that was decreased upon cracking in the second stage, while the load-deflection curves kept linear until the tension steel yielded. Once the bottom steel yielded, a load-deflection plateau was observed in the conventional control beam (C) as the beam continued to deflect while the acting load slightly increased until the beam finally failed due to concrete crushing within the middle third of the span. On the other hand, such a plateau was not observed in the prestressed beams as the applied load continuously increased after steel yield. This behavior is attributed to the initial stress state induced in the concrete section due to prestressing and subsequent limited tendency of the beam to crack. The load-deflection curves for all prestressed beams were quite identical with only slight increase in pre-yielding flexure stiffness in beam P2-SS. Table (3) reports the deflection values (Δ) at cracking, yield and ultimate loads. It can be observed that the deflection was effectively reduced due to prestressing during the whole loading course. Although the prestressed beams ductility index (μ), which measures the ratio of deflection at ultimate load to the deflection at steel yielding ((Δu / Δy)), was lower than that of beam C, the readings nevertheless suggested a reasonable deflection capacity before failure. Strand is regarded as the main tension reinforcement in post-tensioned specimens. A numerical representation of safety against abrupt failure is the ductility index. Showing how much bending the flexure parts can withstand before failure.

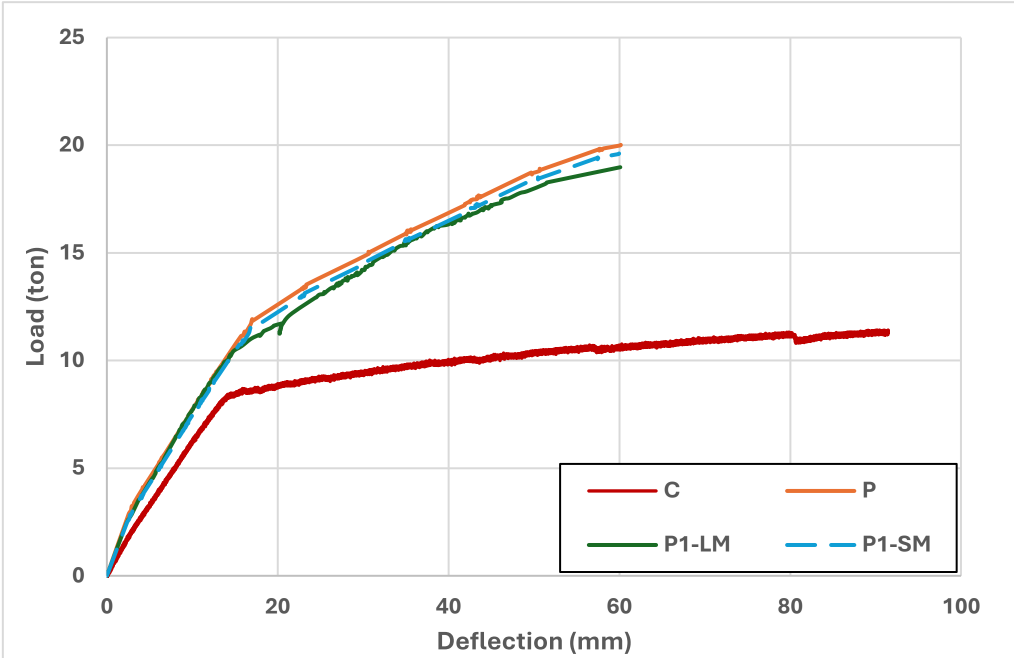


Fig. 6: Load–deflection curves of test beams under two-point loading

Table 3. Results describing the flexure behavior of test beams

Test Specimen	P_{cr} (ton)	Δ_{cr} (mm)	K_{pc} (ton/mm)	P_y (ton)	Δy (mm)	K_{py} (ton/mm)	P_u (ton)	Δ_u (mm)	K_{pf} (ton/mm)	μ
C	2.0	3.0	0.66	8.0	13.5	0.57	11.0	91.0	0.038	6.74
P	3.2	2.9	1.10	12.0	17.0	0.62	20.0	60.0	0.186	3.53
P1-SM	3.0	3.1	0.96	11.5	16.8	0.62	19.6	59.9	0.187	3.56
P1-LM	3.0	3.2	0.93	10.6	14.0	0.70	19.0	60.0	0.182	4.28

P_{cr}, P_y, P_u: first crack, yield, and ultimate loads
Δ_{cr} , Δ_y , Δ_u: deflection at P_{cr} , P_y *and* P_u
K_{pc}, K_{py}, K_{pf}: pre-cracking, pre-yield and pre-failure flexure stiffness
μ = ductility factor (Δ_u / Δ_y)

The degradation of stiffness within the three stages is expressed in terms of the flexure stiffness (K), which is numerically equal to the slope of the load-deflection curve during the different stages. The pre-cracking, pre-yield, and pre-failure flexural stiffness values are calculated computed according to the following equations (Borcher A, 2010):

$$K_{pc} = P_{cr} / \Delta_{cr} \qquad K_{py} = (P_y - P_{cr}) / (\Delta_y - \Delta c_r) \qquad K_{pf} = (P_u - P_y) / (\Delta_u - \Delta_y)$$

The K_{pc}, $K_{py,}$ and K_{pf} values reported in Table (3) indicated the improved stiffness due to prestressing.

3.2. MODE OF FAILURE AND ULTIMATE LOADS

The cracking patterns of the test beams at failure are shown in Fig. (7). In the control beam (C), the initial cracks developed in the middle third within the maximum moment region and continued to increase in number and to extend upwards with loading. At higher loads, the cracks developed in shear spans and at higher loads diagonal shear cracks were observed. Finally, ductile failure occurred as the flexural cracks extended to the upper compression zone and the beam failed due to concrete crushing. The cracking pattern shows that the cracks were fine and evenly distributed along 80 percent of the clear span. In beam (P), the stresses induced due to prestressing along the span limited the extension of cracks outside the middle third. While beam (P) failed in flexure, the associated cracks were wider and limited in number.

As a small opening (P1-SM) was introduced in the maximum moment region, the cracks were shifted away from the opening location. While limited short cracks were observed in the shear span, failure occurred due to crushing of concrete under the loading points upon the extension of flexure cracks. As the opening width increased to 40 percent of the middle span length in the beam (P1-LM), the reinforced portion about the opening was free from cracks. Failure was associated with the formation of two plastic hinges through two wide cracks that extended upwards until concrete was crushed under the points of loading. The curvature profile shows that the middle third of the span was flat at failure due to the formation of plastic hinges

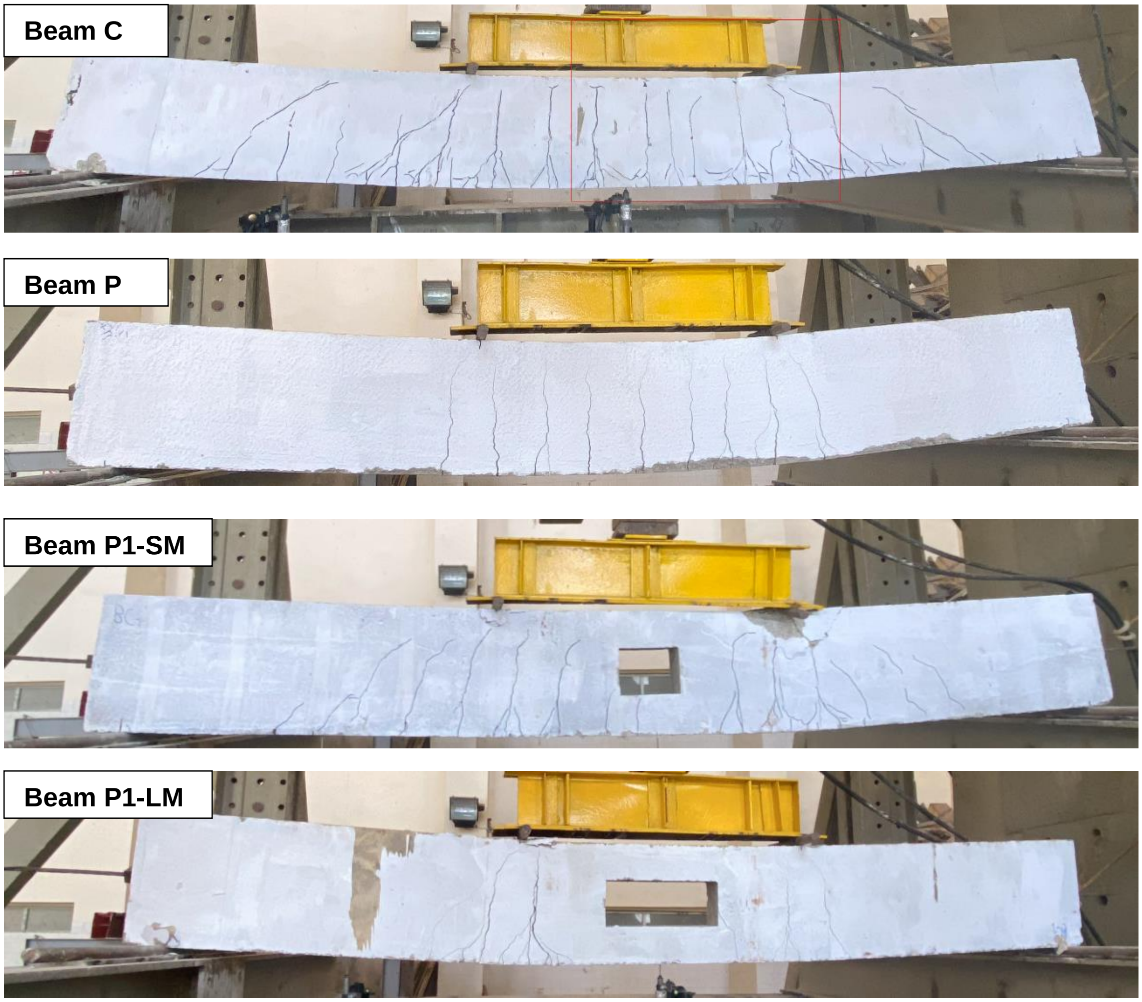


Fig. 7: Cracking patterns at ultimate load

4. Conclusions

Based on the results obtained in this research, the following conclusions could be drawn:

1. Post-tensioning using curved unbonded strands offers a reliable design alternative to increase the loading capacity and control the deformations and cracking in reinforced concrete beams.
2. The increase in the failure load due to using the Post-tensioning technique was about 49%.
3. The ductility index was lower for the prestressed beams than for beam (C).
4. The mid-span opening had no impact on the failure mechanism because of its ductility as beam (P).
5. Well designed and planed openings in post-tensioned RC beams should not significantly influence their structural behavior in terms of stiffness, ductility and loading capacity.
6. Depending on their size and location, openings in RC beams can significantly alter the cracking patterns of RC beams.

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