

FLEXURAL BEHAVIOUR OF SELF-COMPACTED CONCRETE PERFORATED LACED REINFORCED BEAMS UNDER MONOTONIC LOADS

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Abstract

Studying the flexural behaviour of self-compacted perforated beams reinforced by laced rebar instead of stirrups is the aim of this work. The research work focused on the effect of replacing stirrups in perforated beams with lacing reinforcement at 45° angles. The void ratio of the beams studied were (3.6, 8, and 14.2) %. Four beams have been cast for this purpose having the dimensions of (150×220×1500) mm, one solid beam without perforation was considered as a reference beam, the other three beams each has 6 voids of (50, 75 and 100) mm in diameter. Lacing bars were used as shear reinforcement instead of traditional stirrups in all specimens. All the beams were tested under two-point bending loads up to failure. The experimental results revealed that the ultimate strength of the 100 mm voided beams was reduced by about 24.3 %, while the ultimate deflection was decreased by about 34%, with respect to the reference solid beam. Furthermore, for the other perforated beams having 6 voids of (50 and 75) mm the reduction in ultimate loads was nonsignificant compared to the reference beam, but there was an increase in the ultimate deflections of about 12.5 % and 15.7 %, respectively.

Keywords

Self-compacting, Lacing reinforcement, Void ratio, Flexural behaviour, Circular perforations.

1. Introduction

To accommodate ductwork and various utilities, including air conditioning, plumbing, computer networks, and sewage systems, it is necessary to provide openings in some elements of concrete structures. Therefore, web perforations in beams had become a routine in recent modern practice (Arun & Arunalam, 2014).

Using perforated beams and slabs is economical and helps in maintaining the performance of structures by decreasing the overall volume of concrete (Quoc & Viet, 2024). However, the presence of these voids can disrupt loading paths and potentially compromise the structural integrity of the beams due to the weakened areas around the openings (Amiri, 2011). Reinforced concrete beams can be designed with voids in various shapes, with rounded and rectangular forms being the most popular (Omer & Wrya, 2025). The behaviour of beams having minor circular openings differs from that of beams with wide rectangular opening (Alsheikh, 2014). The size of perforations or voids in structural beams may be considered as large based on the shape of voids. A circular void is considered large if the diameter exceeds 40% of the effective depth (d) in beams; while the square voids are considered large if the side is larger than $\frac{1}{4}$ of the effective depth (d) (Ame, et al., 2020), moreover, the behaviour of the beams may be considered as a guide to state if the size of the opening selected is large or small, therefore, in beams designed according to the beam theory the voids are categorized as small (Tawfik et al, 2025).

Design standards, including the American Concrete Institute standards (ACI 318), the Architectural Institute of Japan (AIJ), and the plastic truss method, have provided theoretical equations for special cases concerning reinforced concrete beams with openings (AIJ, 1994 and ACI 318, 2008). Lacing Reinforced Concrete (LRC) structural elements use equal reinforcement on the compression and tension sides of the element. Lacing serves as a continuous form of shear reinforcement, in contrast to reinforcing by stirrups. It is positioned within the flat of main bending and secured in place using transverse bars (Mohammed, et al., 2025).

By linking the longitudinal bars at bottom and top of concrete beams within laced bars, these bars enhanced the ability of reinforcement of beams at area of extreme displacement. (Allawi & Jabir, 2016). Research has demonstrated that lacings increase the shear strength of beams, exposed to the explosion load, preventing concrete spalling, hardening of strain which follow yielding, and improve the performance of support rotation by significant ductility of reinforced concrete member (Sudharsan & Blessy, 2017). However, installing lacing bars can be challenging, as they are positioned alongside longitudinal bars (Anandavalli et al., 2012). The Unified Facilities Criteria document (UFC, 2008) was previously referenced for specifying lacing reinforcement in beams. The UFC suggests using conventional standards for components under static loads, while this guide addresses structural components exposed to dynamic loads. The strength of the four beams investigated in this research work was evaluated using the established (ACI 318 M, 2014). It allows for the calculation of nominal flexural and shear strengths using specific equations, with the minor contribution of the upper longitudinal bars to flexural strength often neglected to simplify computations. However, it is essential to highlight that no existing code acknowledges the significant of lacings rebar for improving the bending capacity of reinforced concrete. To the authors' knowledge, this research work is one of the new studies to investigate the performance of perforated beams to provide a clearer understanding of using lacing reinforcement.

2. Methodology

2.1. Research Design

Limited experimental and theoretical research works are available in literature dealing with using lacing reinforcement instead of vertical stirrups in perforated beams. The present research aimed to study the effect of this replacement on the load carrying capacity of perforated beams. Four perforated beams were cast for this purpose; each beam contained six equal sized voids. The voids ratio of the specimens has increased from zero to 14. The effect of this change in void ratio on the ultimate load is also studied, and a comparison was made between the results of the tested beams with respect to the solid beam cast with the same type of lacing reinforcement.

2.2. Characteristics of the Specimens

Four identical beam specimens, each with an a/d ratio of less than 2.5, were cast. The specimens have a depth of 220 mm, a width of 150 mm, and a length of 1500 mm. These dimensions align with those of several beams analysed in previous studies (Albidah et al., 2019) & (Al-Gasham et al., 2020). Additionally, the depth-to-length ratio was consistent with

findings from earlier research (Ibrahim & Ebead, 2020). However, the size effect acting a crucial influence on capability of reinforced concrete components which are vulnerable to shear failure, like flat plates, deep and moderately deep beams, (Al-Gasham Muttoni, 2019) & (Femandez & Muttoni, 2018). When effective depth is below 400 mm, this effect becomes negligible (Chen & Ma, 2019). Consequently, the findings of this study were not substantially influenced by the size factor. Most specimens demonstrated flexural failure when depth is less than 400 mm, along with the presence of shear reinforcement that helps alleviate the effect of size (Jin et al., 2019) Lacing reinforcement for the four specimens in this investigation was designed according to the Unified Facilities Criteria (UFC) handbook (UFC, 2008). Although this document is intended for reinforced concrete elements exposed to explosive loads, it recommends using standard codes for components subjected to static stresses. Therefore, all beams in this study were designed in accordance with the (ACI 318 M, 2014) specifications for flexural and shear strength.

Four beams were prepared for the study: three with perforations and one solid reference beam (Table 1). All beams had the same reinforcement details as well as an overall span of 1.5 m and 1.4 m centre to centre. Each beam has been reinforced by 3 deformed steel bars, 12 mm in diameter as flexural reinforcement on bottom side and 2 deformed steel bars, 8 mm in diameter on the top side. Reinforcement of shear was provided by 8 mm in diameter lacing bars bent at 45° angles, a common design choice for laced members (Anandavalli et al., 2012). Two lacing bars were placed oppositely on each side of the perforated beam, forming a series of continuous diamonds shapes that enclosed the corner longitudinal bars. As shown in Figures 2 and 3, these diamonds shapes made 45° angles with the horizon and are spaced at 170 mm centre to centre. This spacing corresponds to the lacing section's horizontal projection extends across two consecutive transverse rebars.

Figure 1 illustrates the details of the reinforcement in the cross section, Figure 2 refers to the solid reference beam, while Figure 3 shows all the perforated beams studied.

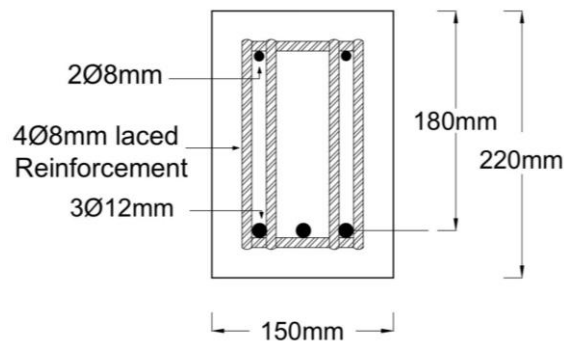


Figure 1: Cross section of beams

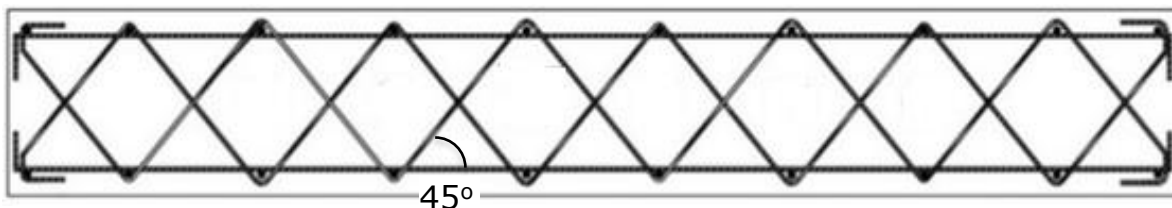


Figure 2: Solid beam

Three perforated beams reinforced by laced bar, labelled PB-100-L, PB-75-L, and PB-50-L, were created with six circular perforations each. The perforation diameters were 100 mm, 75 mm, and 50 mm respectively, spaced at 170 mm

intervals. The web width between the perforation of beams varied according to the diameter of voids: 70 mm for PB-100-L, 105 mm for PB-75-L, and 120 mm for PB-50-L.

The half of perforation size were not exceeded the designed width web of these beams as per (Egyptian Code, 2016), to ensure each perforation acted independently.

The solid section of perforation beams was extended at both ends, outside half beam depth to overcome shear failure close to supports. The resulting mass loss due to the perforations was approximately 3.6% for PB-100-L, 8% for PB-75-L, and 14.2% for PB-50-L, representing the six-perforated beams. These perforation sizes were chosen to evaluate the impact of lacing on beams with openings, encompassing a range of void ratios from 3.6% to 14.2%. The distance from main reinforcement to the top fibre of beam (effective depth) is 180 mm and the flexural reinforcement was positioned at 40mm from the bottom fibre of beam cross section.

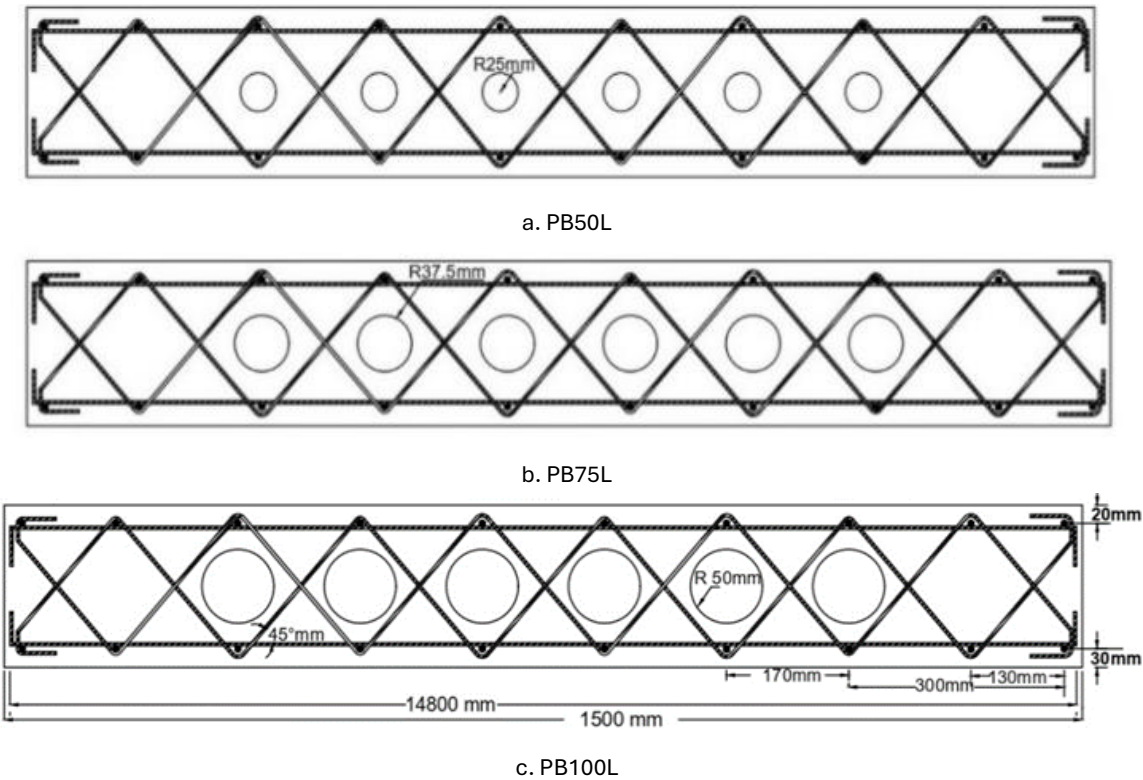


Figure 3: Perforated beams (a, b, c)

Table 1: Configuration of tested specimens

Tested beams	Weight of concrete [kg]	Void ratio [%]	Details of beams	
SBL	124	0.0	Solid beam	Control beam
PB50L	119.4	3.6	Beam has six voids 50mm diameter enhanced by laced rebars with 45o inclination angles.	Studying the effect of voids sizes on the structural behaviour of beams reinforced by laced bars
PB75L	113.8	8	Beam has six voids 75mm diameter enhanced by laced rebars with 45o inclination angles.	
PB100L	106	14.2	Beam has six voids 100mm diameter enhanced by laced rebars with 45o inclination angles.	

2.3. Experimental Procedure

2.3.1. Instrumentation

The flexural behaviour of the tested beams was performed by subjecting two-point loads, as shown in Figure 4. The clear span was 1400 mm, and the shear span was 400 mm, representing the distance from the supports to the points of applied loads. This test configuration effectively generates a concentrated bending zone within the beam; the flexural span will be (600 mm) long positioned in the internal region between the location of point loads, where the maximum moment will occur and remain constant. The load was applied to the specimen increasingly in increments of 5 kN until failure occurred. Three mechanical dial gauges were located beneath the specimen to record the deflection, one under the point load, the other at midspan and another gauge was installed at the centre of the shear span. The load was registered based on the 5 kN increment starting from zero up to failure, and the deformation was registered from the dial gauges with each increment of load.



Figure 4: Test setup

2.3.2. Material Properties

Self-Compacting Concrete (SCC) is a type of fresh concrete that can flow easily to fill forms with condensed steel without using vibration (Marewangeng et al., 2020).

This type of concrete fills all areas within the formwork under its self-weight (MARK et al, 2025), therefore, to enable the casting of concrete easily around voids, all beams were constructed using this type of concrete. This concrete consisted of 400 kg/m³ of Type I cement, (773 kg/m³) of natural sand and (859 kg/m³) of crushed aggregate. Additionally, (150 kg) of limestone powder has been utilized as a filling material, resulting in a water/cement ratio of (0.392). A superplasticizer, (7.5 litres for cubic meter), was also added. The SCC mix was formulated according to the guidelines set forth by EFNARC in 2002 (Ahmed et al., 2012).

Fresh SCC is distinguished by its ability to fill spaces, pass through obstacles, and resist segregation. Various testing methods have been employed to evaluate these properties, the L-box test to measure passing ability, the V-funnel test to evaluate segregation resistance, and the slump flow test to assess filling ability. The average diameter of the concrete circle in the slump test was approximately (670 mm) and the time to reach a diameter of 500 mm (T500) was about (3.5 seconds), aligning with the specifications for SCC. The ratio (H2/H1) from the L-box test, which represents the concrete level height at end over the total height, has equalled to 0.85. This result is consistent with various specifications for SCC (Aggarwal et al., 2008). Table 2 shows the actual mechanical properties of each specimen, derived from the average values of three control

samples, tested at the same date of respective beam specimen. The mechanical properties of the reinforcing bars used are detailed in Table 3.

Table 2: The mechanical properties of tested specimen

Tested beams	fc' [MPa]	fr [MPa]	ft [MPa]	E [GPa]
SBL	27.3	3.2	2.9	20.8
PB50L	29.2	3.5	3	22.8
PB75L	28	2.8	3.2	21.3
PB100L	30.5	3.1	2.7	19.6

Table 3: Steel bars physical properties

Diameter [mm]	Area [mm ²]	fy [MPa]	fu [MPa]
8	49	551	690
12	112	513	671

3. Discussions of Results

3.1. Crack Behaviour of Beams

During the study, cracks were monitored, and the loads associated with them were registered. The cracks on the tested beams are shown in Figure 5. The three specimens (PB50L, PB75L, and PB100L) experienced flexural failure. The initial flexural cracks in these beams occurred at loads ranging from 20 to 35 kN within the flexural span. As the load was increased, the flexural cracks widened and moved upward. When the load reached 50 kN, inclined cracks started to develop, independent fractures and extensions of cracks within the shear span existed because of flexural mode. Eventually, when the beams reached failure, some of the flexural cracks swiftly extended and nearly propagated to the upper face of the beam. This behaviour resulted into crushing of the top surface of concrete. However, these fractures did not extend to the compression side of the beam.

The PB100L specimen exhibited a combined flexural-shear failure mode. At loads between 18 and 28 kN, the first cracks started to appear at the tension face, where the bending moment was greatest, directly below the points of the subjected loads. Subsequently, when the load reached 40 to 46 kN, inclined fractures developed within the shear span. Both types of cracks grew, widened, and progressed higher as the load increased, resulting in the failure of the beam and the crushing of the concrete. Brittle shear failure was evident in beam PB100L. The flexural fractures were found to be limited and did not advance much beyond 2/3 of the beam depth. Refer to Table 4 for further details.

Table 4: Experimental results and details of specimen

Tested beams*	Failure mode	P _y (yield load) [kN]	Ultimate load [kN]	Deflection [mm]
SBL	Flexural	150	200	5.14
PB50L	Flexural	135	201	5.33
PB75L	Flexural	120	196	4.4
PB100L	Flexural + shear	80	140	Not applicable

* All beams were reinforced with (3 Ø 12) mm

3.2. Failure Mode of Beams

Based on the loading outline, the four beams initially exhibited flexural cracks in the midspan area. As loading continued, these flexural cracks became more distributed around the midspan, increasing in both length and width.

Subsequently, shear-flexural cracks developed, eventually leading to the formation of shear cracks. All beams exhibited failure predominantly through flexural mode, except for beam PB100L, which failed by shear mode frame-type, as illustrated in Figure 5.

Reference beam SBL began to show flexural cracking at the midspan under a vertical load of approximately 21 kN. With continued loading, the flexural cracks extended on the tension side until reaching a vertical load of around 50 kN, at which point shear cracks started to appear.

Crushing was observed in the PB50L and PB75L beams, as shown in Figure 5. Shortly thereafter, the primary flexural crack width exceeded one millimetre, and the beam could not be loaded further.



Figure 5: Experimental crack patterns in beams at failure

3.3. Load-deflection Relationships

For the tested perforated beams, it can be observed from the recoded applied loading values that beam BP75L exhibited the highest permanent deflections, while beam BP100 mm recoded the lowest permanent deflections. The solid beam BSL, along with all the perforated beams, displayed similar behaviour initially until the first flexural crack appeared, after which significant variations became evident. As loading continued, flexural cracks have started to progressive toward the tension side and through voids, with an increasing number of cracks forming beneath the perforations. Consequently, deflections increased due to a reduction in stiffness, as shown in Figure 5 and 6.

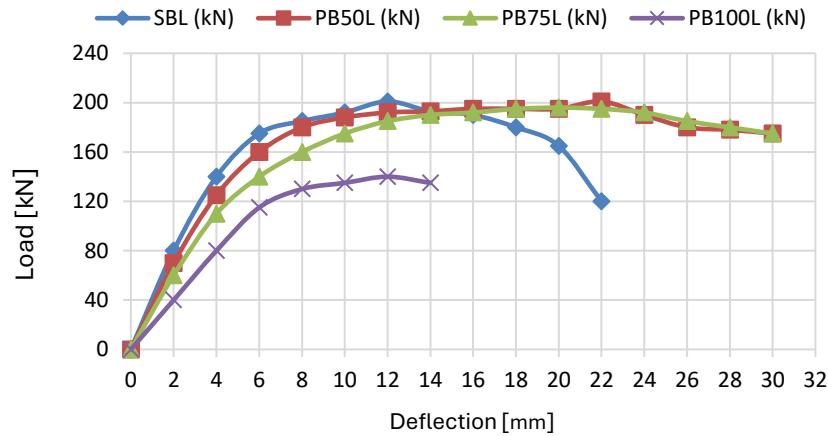


Figure 6: Load deflection curves for all tested beams

3.4. The Specimen's Ductility

According to many researchers' definitions, ductility is the ability of members to withstand plastic deformation prior to failure, or it represents a significant property for evaluating the behaviour of reinforced concrete members. (Al-Gasham et al., 2019) & (Abbass et al., 2019). The Ductility was calculated according to previous studies identifying various methods, one of them depended on ultimate load. It can be obtained by dividing measured ultimate deflection by yield load.

Most studies suggest that the ultimate load can be assessed in the post-peak region when the load ranges from 0.8 to 0.99 of the peak loads (Abbass et al., 2020).

The method most employed in this study calculates ductility as the ratio of D0.9 "deflection at 0.9 percent of the ultimate load from the curve of load versus deflection" to D_y "deflection at yielding load". However, the PB50L and PB75L beams exhibited deflections exceeding D0.9; all other beams failed before achieving 90 percent of their ultimate loads. Consequently, at the end of the tests, all recorded deflections were used to determine D0.9 for these beams. As shown in Table 4, the ductility values for the tested beams are presented, except for the PB100L, exhibited a brittle-shear collapse. As shown in Table 5, ductility of the PB75L beam decreased by approximately 14.4 % compared to the SBL control beam, whereas the ductility of the PB50L beam increased by about 3 %.

3.5. Performance of Perforation System in Laced Reinforced Concrete Beams

Applying perforations with varying void ratios in reinforced concrete beams, enhanced with laced bars instead of stirrups, has significantly affected both ductility and load capacity. Consequently, the ductility and load capacity of three perforated beams were compared to a solid reference beam to determine gains or losses. results are tabulated in Table 5.

Table 5: Developed ductility versus ultimate capacity

Tested beams	Concrete loses	Ultimate capacity gain	Ductility gain
SBL	-	-	-
PB50L	3.7 %	1 %	3 %
PB75L	8 %	-2 %	-14.4 %
PB100L	14.2 %	-30 %	Not applicable

Incorporating six 50 mm diameter perforations (PB50L) allowed the beam to achieve the highest ductility and ultimate load capacity as shown in Figure 7 Conversely, the perforations in the PB75L beam did not improve ultimate

capacity compared to the solid beam, and this came at the expense of ductility.

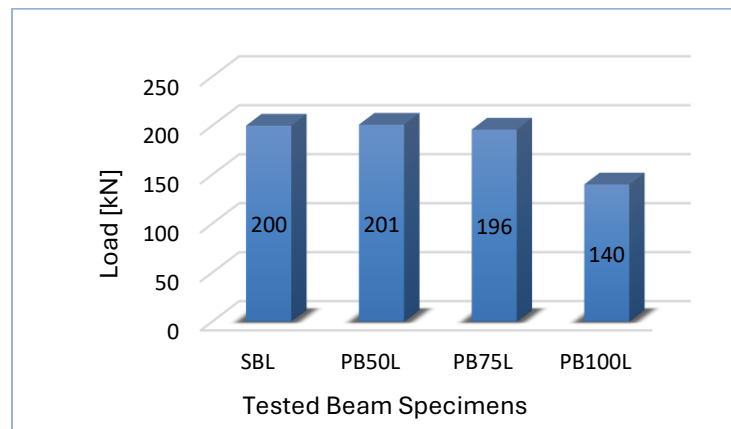


Figure 7: Ultimate loads of all beams

However, in terms of ultimate capacity and ductility, the PB50L beam outperforms the PB75L beam. Among all the perforated beams, the beam with 100 mm perforations (PB100L) demonstrated inferior performance compared to those with 50 mm and 75 mm perforations (PB50L and PB75L), despite maintaining the same reinforcement percentages and varying levels of concrete loss. Ultimately, it comes down to finding the right balance between these criteria.

4. Discussion

The presence of service voids can disrupt loading paths and potentially compromise the structural integrity of the beams due to the weakened areas around the openings (Amiri et al., 2011). Madheswaran et al., (2015) has proved that lacing reinforcement would increase the shear strength of the beams exposed to explosion loads and improve the performance of support rotation by significant ductility of reinforced concrete members.

However, installing lacing bars in beams having various voids ratio can be challenging. As a result, this procedure can control the weakened area around the perforations caused by generated shear force.

5. Conclusions

The beam PB75L with 75 mm diameter perforations exhibited the largest deflection. The maximum deflection at failure, was about 1.5 times greater than that of the solid reference beam. The ductility index was significantly influenced by the diameter of voids in the perforated beams. It increased by 3 % in specimen PB50L and decreased by 14.4 % in specimen PB75L, with respect to the reference solid beam SBL.

For the beam with six voids measuring 100 mm in diameter, the configuration of laced reinforcement around the perforations had a minimal impact on the ultimate capacity of the perforated beams. However, it significantly affected the exhibited ductility, compared with the solid beam.

Moreover, it was noted that specimen PB75L, which had an 8 % mass loss, experienced a 2 % decrease in ultimate load capacity and a 14.4 % decrease in ductility compared with the solid beam.

The beam PB50L which had 3.7 % mass loss showed the best performance. It achieved an ultimate capacity approximately equivalent to that of the solid beam, while ductility was enhanced by about 3 %.

The size of openings in a beam, whether large or small, influences the structural behaviour of that beam. Beams with openings of 50 mm, 75 mm, and 100 mm were observed to behave similarly to those with small openings, contrary to some researchers who categorize openings larger than half the beam's depth as 'large' and possibly outside the bounds of

standard beam theory. However, the behaviour observed suggests that beam theory is still valid.

Achieving the optimal balance between ultimate strength and ductility in a perforated beam, choosing the most favourable criteria to determine the appropriate reinforcement configuration of the perforations, as well as the size of the perforations, requires careful compromise.

6. Future Research Work

- Investigate the behaviour of perforated laced reinforced beams under other types of loading such as seismic or repeated loading.
- Numerical investigation on the behaviour of perforated laced reinforced beams under different types of loading (using finite element programmes).
- Studying different layouts of lacing reinforcement around openings to choose the most appropriate layout to balance strength and ductility.
- Studying the behaviour of perforated laced reinforced beams strengthened with fibres under different types of loading.

7. Abbreviations

ACI - American Concrete Institute

AIJ - Architectural Institute of Japan

SCC - Self-compacting concrete

LVDT - Linear Variable Differential Transformer

LRC - Lacing reinforced concrete.

d - effective length of beam

UFC - Unified Facilities Criteria

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Author Contributions

M.A. Experimental work and drafting the article. **A.M.** Experimental work, and analysis of all beams studied. **L.Y.** Experimental work and drafting the Article. **F.R.** Analysis, and interpretation of data. **M.H.** Conception design and analysis. All authors critically reviewed and approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

References

- Arun, M. & Arunalam, N. (2014). Experimental investigation on flexural strength of Reinforced Concrete Hollow beams, International Journal of Earth Sciences and Engineering 7(2):712-719.
- Quoc, A. V. & Viet, C. M. (2024). Estimating the Punching Shear Capacity of Voided Reinforced Concrete Slab. Geomate Journal 27 (124) P.P.:128-35. <https://doi.org/10.21660/2024.124.4697>.
- Amiri, S., Masoudnia, R. & Pabaria, A. A. (2011) The study of the effects of web openings on the concrete beams. Australian Journal of Basic and Applied Sciences, 5(7), P.P. 547-556.

- Omer, M. A. & Wrya A. (2025). Behaviour of Reinforced Concrete Beams with Openings: A Review, *Emerging Technologies, and Engineering Journal*, 2(1), 54-71. <https://doi.org/10.53898/etej2025215>.
- Alsheikh, S. A. (2014). Flexural behaviour of RC beams with opening. *Concrete Research Letters*, 5(2), 812-824.3. <https://doi.org/10.20528/cjrl>.
- El Ame, F., Mwero, J. N. & Kabubo, C. K. (2020). Openings Effect on the Performance of Reinforced Concrete Beams Loaded in Bending and Shear. *Engineering, Technology & Applied Science Research*, 10(2). Architectural Institute of Japan; AIJ structural design guidelines for reinforced concrete buildings, (1994). 113-18. <https://doi.org/10.48084/etasr.3317>
- ACI Committee, 3; (2008). Building code requirements for structural concrete (ACI 318-08) and commentary. American Concrete Institute.
- Mohammed, S. D., Salman, H. M., Ibrahim, T. H., Oukaili, N. K. & Allawi, A. A. (2025). On the Impact of Lacing Reinforcement Arrangement on Reinforced Concrete Deep Beams Performance. *Civil Engineering Journal*, 11(02). <https://doi.org/10.28991/CEJ-2025-011-02-019>.
- Allawi, A. A. & Jabir, H. A.; (2016). Experimental behaviour of laced reinforced concrete one way slab under static load. *Journal of Engineering*, 22(5), 42-59. <https://doi.org/10.31026/j.eng.2016.05.04>.
- Sudharsan, N. & Blessy Grant, C. J. (2017). Structural Behaviour of Laced Reinforced Concrete Elements-A Review. *International Journal of Current Engineering and scientific research*, 4(12), 36-41.
- Anandavalli, N., Lakshmanan, N., Knight, G. S., Iyer, N. R. & Rajasankar, J. (2012). Performance of laced steel-concrete composite (LSCC) beams under monotonic loading. *Engineering Structures*, 41, 177-185. <https://doi.org/10.1016/j.engstruct.2012.03.033>.
- Unified Facilities Criteria (UFC). (2008). Structures to resist the effects of accidental explosions, Department of defence, Washington, DC, USA.
- ACI 318 committee. (2014) Building code requirements for structural concrete (ACI 318-14): commentary on building code requirements for structural concrete (ACI 318R-14), American Concrete Institute. ACI, Farmington Hills, MI, USA.
- Albidah, A., Abadel, A., Abbas, H., Almusallam, T. & Al-Salloum, Y. (2019). Experimental and analytical study of strengthening schemes for shear deficient RC deep beams. *Construction and building materials*, 216, 673-686., <http://dx.doi.org/10.1016/j.conbuildmat.2019.05.024>.
- Al-Gasham, T. S., Mhalhal, J. M. & Abid, S. R. (2020). Flexural behavior of laced reinforced concrete moderately deep beams. *Case Studies in Construction Materials*, 13, e00363, <https://doi.org/10.1016/j.cscm.2020.e00363>.
- Ibrahim, M., Wakjira, T. & Ebead, U. (2020). Shear strengthening of reinforced concrete deep beams using near-surface mounted hybrid carbon/glass fibre reinforced polymer strips. *Engineering Structures*, 210, 110412. <http://dx.doi.org/10.1016/j.engstruct.2020.110412>.
- Al-Gasham, T. S., Mhalhal, J. M. & Jabir, H. A. (2019). Improving punching behavior of interior voided slab-column connections using steel sheets. *Engineering Structures*, 199, 109614. <http://dx.doi.org/10.1016/j.engstruct.2019.109614>.
- Fernández Ruiz, M. & Muttoni, A. (2018). Size effect in shear and punching shear failures of concrete members without transverse reinforcement: Differences between statically determinate members and redundant structures. *Structural concrete*, 19(1), 65-75. <https://doi.org/10.1002/suco.201700059>.
- Chen, H., Yi, W. J. & Ma, Z. J.; (2019). Sheer size effect in simply supported RC deep beams. *Engineering Structures*. 182, 268-278. <https://doi.org/10.1016/j.engstruct.2018.12.062>.
- Jin, L., Wang, T., Jiang, X. A. & Du, X. (2019). Size effect in shear failure of RC beams with stirrups: Simulation and formulation. *Engineering Structures*, 199, 109573. <http://dx.doi.org/10.1016/j.engstruct.2019.109573>.
- Anandavalli, N., Lakshmanan, N., Iyer, N. R., Prakash, A., Ramanjaneyulu, K., Rajasankar, J. & Rajagopal, C. (2012). Behaviour of a blast loaded laced reinforced concrete structure. *Defence Science Journal*, 62(5), 284-289. <https://doi.org/10.14429/DSJ.62.820>.
- Egyptain Code (2016). Design and Construction of Reinforced Concrete Structures, (ECP 203-2016), Ministry of Development, New Communities, Housing and Utilities, Housing and Building Research Center; 2016.
- Marewangeng, A., Tjaronge, M. W., Djamaluddin, A. R. & Aly, S. H. (2020). Mechanical Characteristics of self-compacting concrete using laterite stone as coarse aggregate. *GEOMATE Journal*, 19(71), 250-255. <https://doi.org/10.21660/2020.71.357214>.
- Ahmed, A., Fayyadh, M. M., Naganathan, S. & Nasharuddin, K. (2012). Reinforced concrete beams with web openings: A state of the art review. *Materials & Design*, 40, 90-102. <https://doi.org/10.1016/j.matdes.2012.03.001>.
- Aggarwal, P., Siddique, R., Aggarwal, Y. & Gupta, S. M. (2008). Self-compacting concrete-procedure for mix design. *Leonardo electronic journal of practices and technologies*, 12, 15-24.

- Al-Gasham, T. S., Mhalhal, J. M. & Jabir, H. A. (2019, December). Influence of post-heating on the behavior of reinforced self-compacting concrete hollow columns. In Structures (Vol. 22, pp. 266-277). Elsevier. <http://dx.doi.org/10.1016/j.istruc.2019.08.013>.
- Abbass, A., Abid, S. & Özakça, M. (2019). Experimental investigation on the effect of steel fibers on the flexural behavior and ductility of high - Strength concrete hollow beams. Advances in Civil Engineering, 2019(1), 8390345. <https://doi.org/10.1155/2019/8390345>.
- Abbass, A. A., Abid, S. R., Arna'ot, F. H., Al-Ameri, R. A. & Özakça, M. (2020, February). Flexural response of hollow high strength concrete beams considering different size reductions. In Structures (Vol. 23, pp. 69-86). Elsevier. <http://dx.doi.org/10.1016/j.istruc.2019.10.001>.
- Madheswaran, C. K., Gnanasundar, G. & Gopalakrishnan, N. (2014). Performance of laced reinforced geopolymer concrete (LRGPC) beams under monotonic loading. In Advances in Structural Engineering: Mechanics, Volume One (pp. 355-367). New Delhi: Springer India. <http://dx.doi.org/10.1007/978-81-322-2190-6>.
- Mark, O., Ede, A., Arum, C. & Oyeibisi, S. (2021). Effects of induction-furnace slag on strength properties of self-compacting concrete. Civil and Environmental Engineering, 17(2), 513-527. <https://doi.org/10.2478/cee-2021-0053>.
- Taufik, Thamrin, R., Haris, S., Kurniawan, R., Yastari, F. P., Ali, N. & Sandra, N. (2025). Shear Capacity of Reinforced Concrete Beams with Multiple Openings. Civil and Environmental Engineering, 21(2), 1028-1046. <https://doi.org/10.2478/cee-2025-0078>.

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