

Effect of Large Openings on the Behavior of Reinforced Concrete Continuous Deep Beams under Static and Repeated Load

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Abstract. This paper aims to investigate the behavior of the existence of large openings on reinforced concrete continuous deep beams (RCCDBs) under static and limited cycles of repeated load. The experimental work included testing seven RCCDBs. One of these beams was solid subjected to static load, while the other beams having external shear spans, internal shear spans, and mid-span openings subjected to static and fifteen cycles of repeated loading. The range of the repeated loading was varied between a lower level and an upper level, equal to 30 and 70 percent, respectively, of the ultimate load of the beam subjected to static load. All test specimens were tested under five-point bending. For beams with large openings, 160×160 mm (which represents 40% of the overall depth of the section) openings were created symmetrically at various locations. Experimental results showed that the maximum ultimate loads of beams with large openings were decreased by about 36% for beams with large openings locating at interior shear spans compared to a solid beam. However, the maximum reduction in ultimate load of the beam with a large opening subjected to repeated load was about 6%.

Keywords: Continuous deep beams; large openings; static load; repeated load.

Introduction

In structural engineering experience, reinforced concrete continuous deep beam (RCCDB) is a subject of great interest [1-3]. The deep beam is one with a clear span (l_c) to overall depth (H) ratio that is less than or equal to four [4]. Figure 1 shows an example of continuous deep beams. Openings in the web of continuous deep beams are commonly required to facilitate important services like water supply, electricity cables, telephone, and computer network and provide functionality such as doors and windows. The presence of openings such as in tubes and cables reduces the total shear strength of such beams, resulting in an increased deformation at ultimate strength. [2,3,6,7]. Mansur and Tan [6] classified the openings in reinforced concrete (RC) beams as small or large. They recommended that an opening is considered large if the opening depth (h_o) is greater than 25% of the overall depth of the section (H). Apart from that, the opening may be described as small.

Openings in RCCDBs were never specified in the American Concrete Institute AC1318M-19. As a result, there is a great requirement for a safe, precise, and consistent design technique. Additionally, the existence of openings produces interruptions or disruptions in the normal flow of stresses. Loading on offshore structures, highways, and many other structures is often repeated in nature. Extensive theoretical and experimental studies of simply supported deep beams with or without openings over the years, well-established approaches for serviceability design under static loads have developed. [2, 3, 7-15]. However, the effects of repeated loading on RCCDBs are still rare and scarcely understood. Concrete structures subjected to repeated loading experience higher deflection comparing to those exposed to static loading. In this study, experimental investigations on the behavior of RCCDBs with large openings under five-point load have been carried out on continuous deep beams having large symmetrical openings subjected to static and limited cycles of repeated load.



Figure 1. Photo picture of RCCDB [5].

Experimental Program

Descriptions of tested beams. The experimental work included testing seven RCCDBs under five-point bending. The tested specimens were 2500 mm overall length (clear span of 1190 mm), 400 mm overall depth of beam, 160 mm width of the beam, and a shear span of 595 mm as shown in Figure 2. The first specimen (CDB-Solid) was prepared without opening (as a reference specimen). Openings of dimensions 160×160 mm (representing 40% of the overall beam depth) were created in the remaining specimens. These openings were created symmetrically at the external shear spans, internal shear spans, and center of spans of the other specimens. The RCCDBs with openings were tested under static and repeated load. At the same time, beam CDB-Solid was tested under static load only. Table 1 summarizes the description of the tested beams.

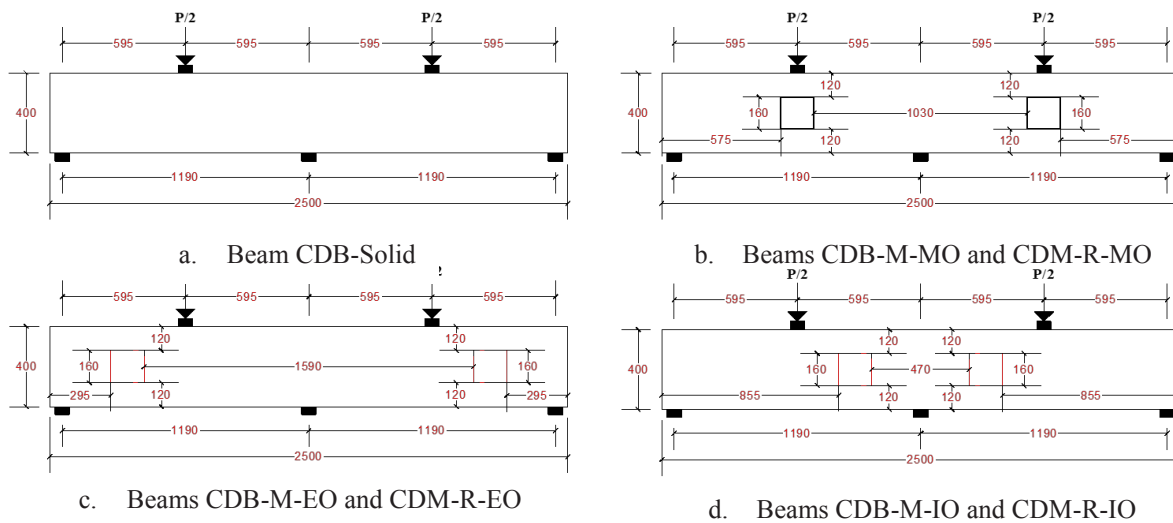


Figure 2. Layout of typical experimental specimens (all dimensions are in mm).

Table 1. Details of the tested specimens.

Specimen nomenclature *	Opening size (mm)	Location	Type of application load
CDB-Solid	---	Solid	Static load
CDB-M-EO	160×160	External shear span	Static load
CDB-M-IO	160×160	Internal shear span	Static load
CDB-M-MO	160×160	Mid-span	Static load
CDB-R-EO	160×160	External shear span	Repeated load
CDB-R-IO	160×160	Internal shear span	Repeated load
CDB-R-MO	160×160	Mid-span	Repeated load

* CDB: Continuous Deep Beam, M: Monotonic (static load), R: Repeated load, EO: External opening, IO: Internal opening, and MO: Mid-span openings (under load).

Details and preparation of the test specimens. Details of test specimens are given in Figure 3 for continuous deep beams with 5-point bending. The arrangement of reinforcements consists of 3 ϕ 12 mm rebars as longitudinal bottom reinforcement and 2 ϕ 12 mm rebars as top reinforcement. In addition, 2 ϕ 12 mm ($L = 0.7$ m) were provided at the negative region over the mid-span support. Furthermore, stirrups of ϕ 6 mm spaced each 70 mm c/c were used as shear reinforcement. In addition, 10 ϕ 6 mm rebars were used as nominal skin reinforcement. Normal weight concrete with cylindrical compressive strength of about 23 MPa was produced for casting the test specimens. The yield stress and ultimate strength for steel reinforcement were 510 MPa and 625 MPa, respectively, for bar diameter of 6 mm and 650 MPa and 730 MPa, respectively, for a bar diameter of 12 mm.

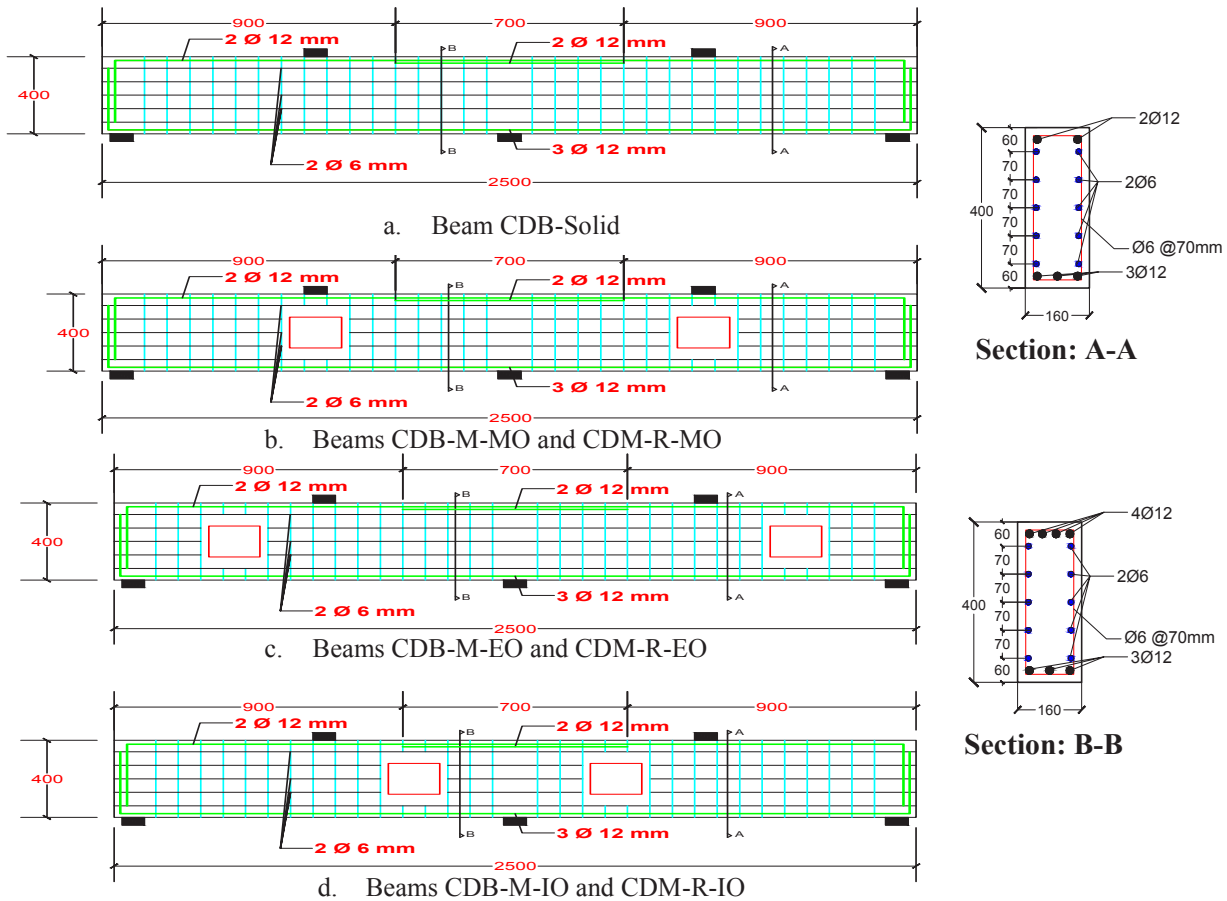


Figure 3. Details of steel reinforcement for typically tested beam (all dimensions are in mm).

Instrumentation and test setup. The test setup for beams with five-point bending and a shear span of 595 mm is shown in Figure 4. The load was applied with a 1000 kN hydraulic jack and measured using a load cell (2000 kN). Vertical deflections were measured using linear variable displacement transducers (LVDTs) for each span of beams. Three stages were involved in the application of repeated load. The minimum and maximum cyclic loads in the first stage were 30 percent and 70 percent, respectively, of the ultimate load of the similar beams under static load. The cyclic static load was applied until it reached 70% of the ultimate load, then it was unloaded to 30%. A total of fifteen loading and unloading cycles were completed. In the second step, the load was released to zero after fifteen cycles of loading. Static loading was applied to the beams until they failed in the final step.

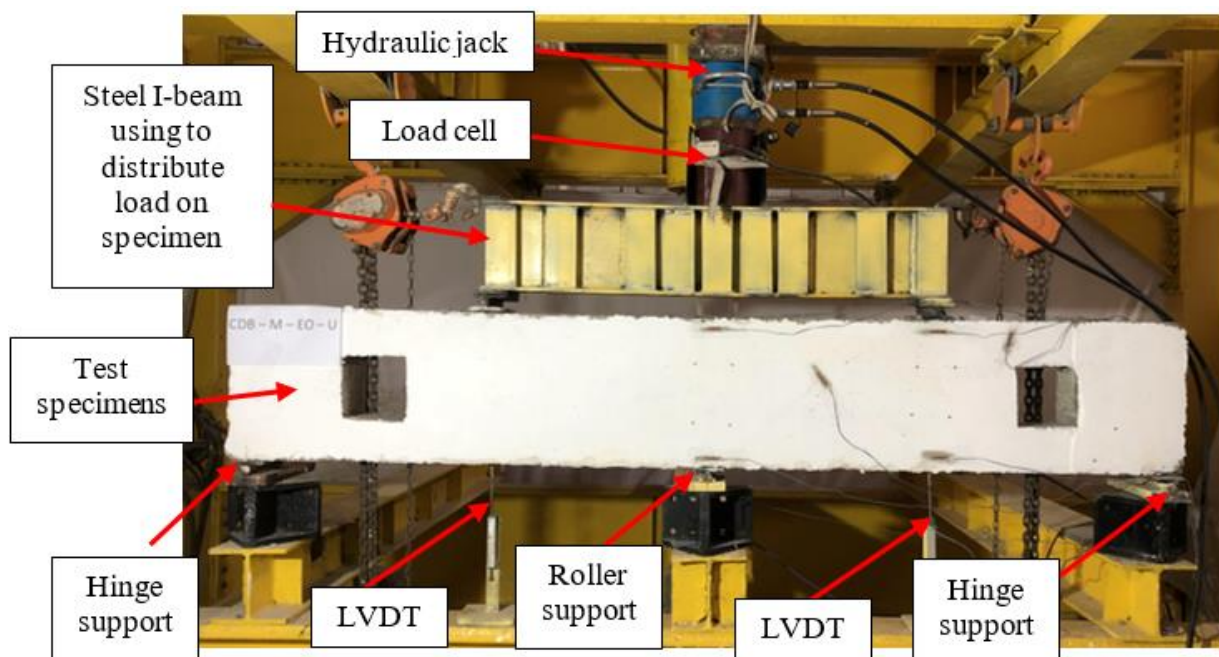


Figure 4. Test setup for typically tested beam.

Description of Experimental Test Results

Initial crack and mode of failure. The initial crack load was seen in the mid-span of each span of the continuous deep beam (i.e., flexural crack) for beam CDB-Solid during the experimental test. In the case of beams with large openings, the initial crack load was noticed at the opening corners and spread towards the loading and supporting points. Table 2 summarizes the cracking loads for tested beams. This table shows that the presence of large openings affects the behavior of continuous deep beams by decreasing the initial crack load compared to RCCDBs without opening (beam CDB-Solid). The percentages decrease in initial crack load were about 45, 58, and 30% for beams CDB-M-EO, CDB-M-IO, and CDB-M-MO, respectively, compared to beam CDB-Solid. These percentages were the same for beams subjected to limited cycles of repeated load.

Table 2. Cracking loads and mode of failure of tested beams.

Specimen nomenclature	Location	Initial (first) crack load (kN)	Mode of failure
CDB-Solid	Solid	200	Shear failure
CDB-M-EO	External shear spans	110	Opening shear failure
CDB-M-IO	Internal shear spans	85	Opening shear failure
CDB-M-MO	Mid-spans	140	Bearing failure
CDB-R-EO	External shear spans	110	Opening shear failure
CDB-R-IO	Internal shear spans	85	Opening shear failure
CDB-R-MO	Mid-spans	140	Bearing failure

Figure 5 shows the crack pattern for all tested beams. It was observed from this figure that the mode of failure was a shear failure for beam CDB-Solid. While for beams CDB-M-MO and CDB-R-MO the mode of failure was bearing failure at the top cord of openings. However, for beams with openings locating at external and internal shear spans (i.e., beams CDB-M-EO, CDB-M-IO, CDB-R-EO, and CDB-R-IO), the mode of failure was observed opening shear failure.

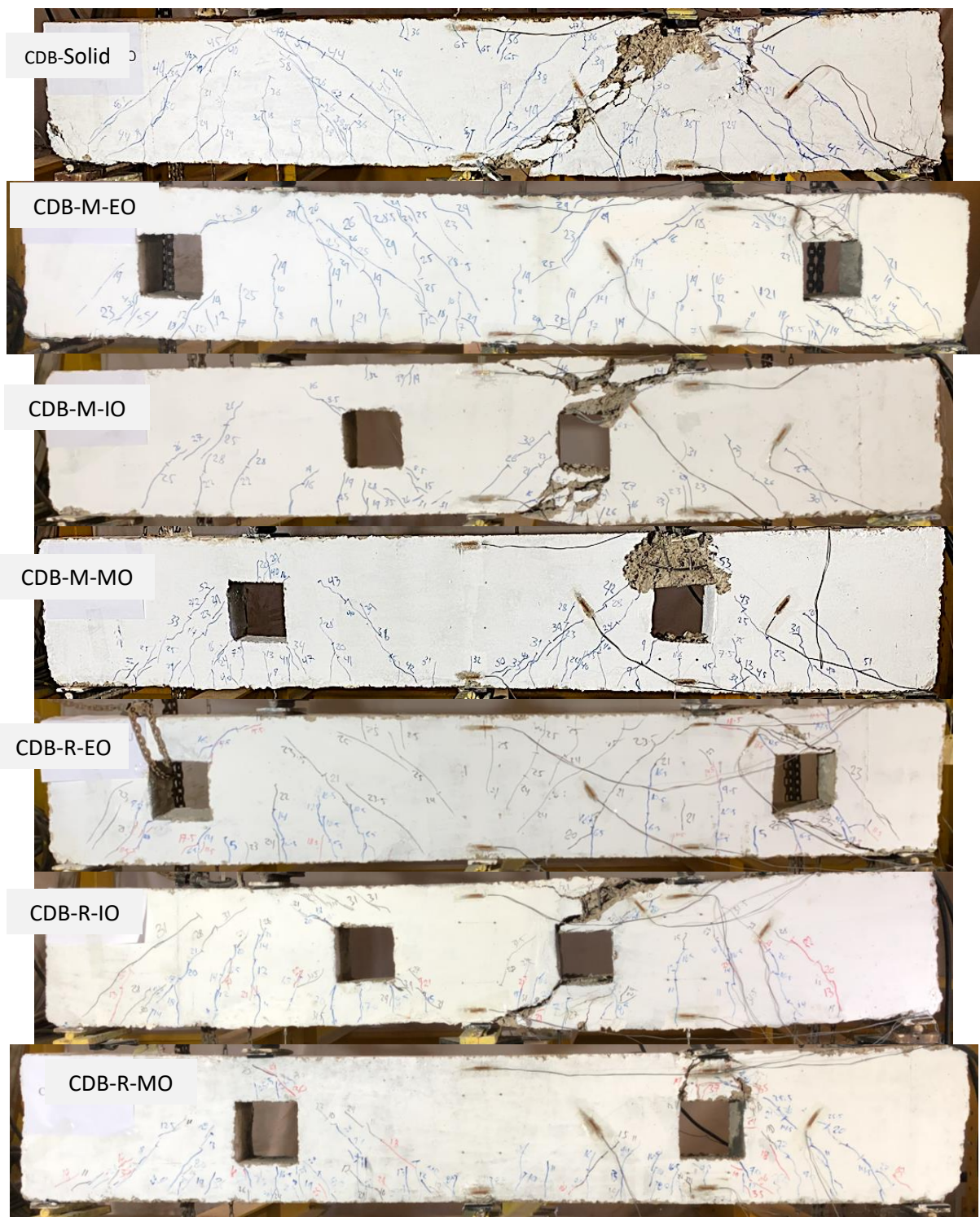


Figure 5. Crack pattern of tested beams at ultimate loads.

Load mid-span deflection response. Figure 6 shows the total applied load (P) with mid-span deflection of all test beams under static load. From this figure, it can be noticed that large openings reduce the stiffness and ultimate load and increase the deflections within the entire range of loading compared to beam CDB-Solid. In addition, Figure 7 to 9 shows the total applied load with mid-span deflection for a beam with various locations of large openings under static and limited cycles repeated load. From this figure, it can be noticed that the application of limited cycles of repeated load leads to a decrease in the ultimate load compared with beams under static load. Table 3 summarizes the test results of the seven specimens in terms of key parameters of load-deflection curves.

From this table, it was observed that the percentage decrease in ultimate loads for beams CDB-M-EO, CDB-M-IO, and CDB-M-MO was about 26, 36, and 23%, respectively, compared to beam CDB-Solid. While, these percentages became about 30, 40, and 26% for beams CDB-R-EO, CDB-R-IO, and CDB-R-MO, respectively. However, when beams CDB-R-EO, CDB-R-IO, and CDB-R-MO compared to beams CDB-M-EO, CDB-M-IO, and CDB-M-MO, the percentages decrease in ultimate loads were about 5, 6, and 4%, respectively. On the other hand, the presence of large openings leads to an increase in mid-span deflection by about 186, 238, and 27% for beams CDB-M-EO, CDB-M-IO, and CDB-M-MO, respectively, compared to beam CDB-Solid. While, in the case of repeated load, the percentage increase in mid-span deflection was about 191, 243, and 19% for beams CDB-R-EO, CDB-R-IO, and CDB-R-MO, respectively, compared to beam CDB-Solid. It is worthwhile to mention that these percentages were calculated corresponding to the ultimate load of beam CDB-M-IO and CDB-R-IO. However, when beams CDB-R-EO, CDB-R-IO, and CDB-R-MO compared to beams CDB-M-EO, CDB-M-IO, and CDB-M-MO, the percentages increase in mid-span deflection were about 18, 5, and 18%, respectively at the same load level of ultimate load of beams under repeated load.

Table 3. Ultimate loads and mid-span deflections of tested beams.

Specimen nomenclature	Location	Ultimate load (kN)	Ultimate mid-span deflection (Δ_u) (mm)
CDB-Solid	Solid	770	3.864
CDB-M-EO	External shear spans	570	4.142
CDB-M-IO	Internal shear spans	490	3.067
CDB-M-MO	Mid-spans	595	2.207
CDB-R-EO	External shear spans	540	4.067
CDB-R-IO	Internal shear spans	460	2.399
CDB-R-MO	Mid-spans	570	1.536

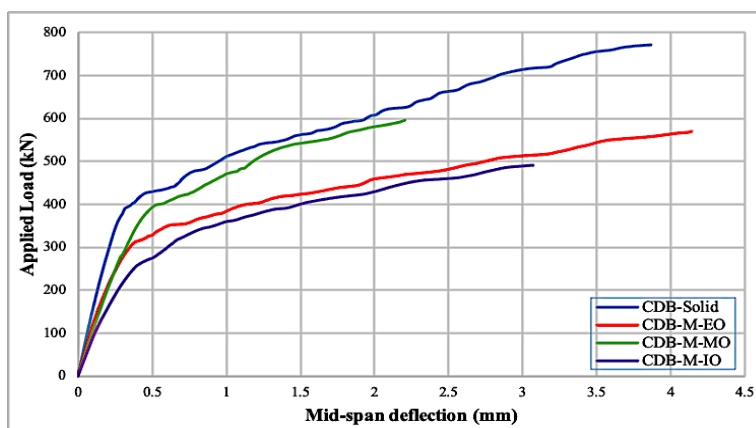


Figure 6. Load mid-span deflection for tested RCCDBs with openings under static load.

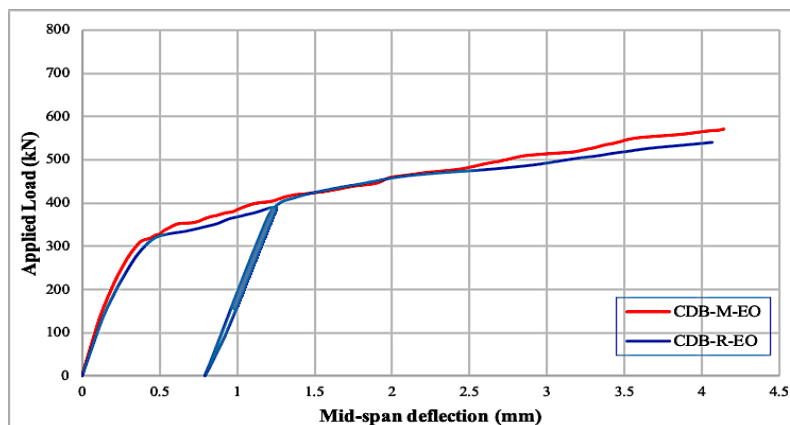


Figure 7. Load mid-span deflection for tested RCCDBs with openings located at external shear spans.

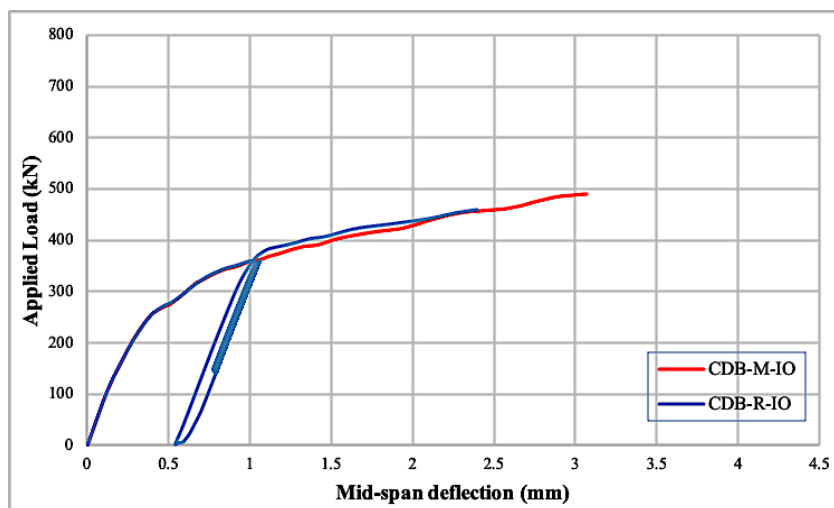


Figure 8. Load mid-span deflection for tested RCCDBs with openings located at internal shear spans.

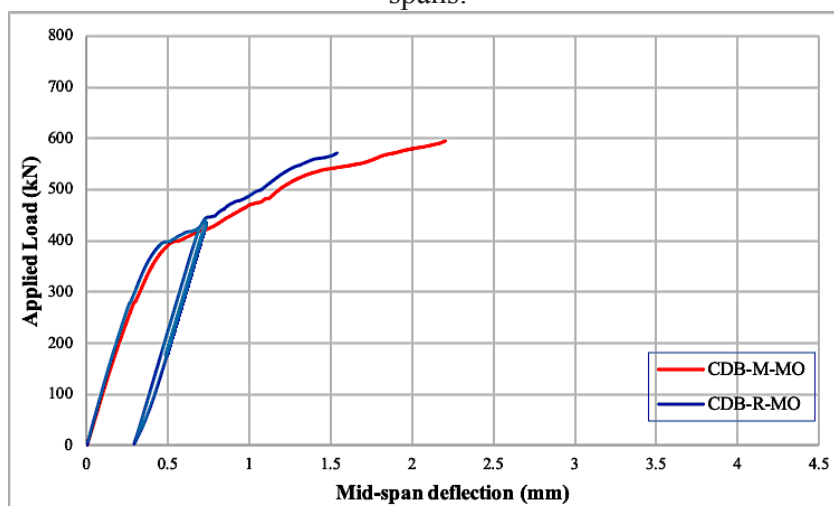


Figure 9. Load mid-span deflection for tested RCCDBs with openings located at mid-spans.

Conclusions

The following conclusions can be drawn from this research work.

- Large openings in RCCBD lead to a decrease in the ultimate load and an increase in mid-span deflection.
- From the experimental test, the existence of large openings within exterior or interior shear spans caused a reduction in ultimate load by about 26% and 36% compared with beam without openings. However, when opening located within mid-span region, the percentage decrease in ultimate load became about 23%.
- For beams under limited cycles of repeated load, it was observed that the reduction in ultimate load was about 5, 6, and 4% for beams with opening locating at the exterior, interior, and mid-span, respectively, compared to beam under static load.

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