Shear Failure Control of RC Box Beams Using Internal Transverse Diaphragms

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Abstract
The rapid development in construction and material technology arising the needs for simple techniques to increase the shear strength of RC box beams. This paper is devoted to investigating experimentally the structural behavior of RC box beams which have internal in-plane solid diaphragms under the effect of shear stresses. For this purpose, four beam specimens with (200x300x1200mm) dimensions are poured using normal strength concrete of class (f'_c=22MPa) and longitudinal flexural steel of class (f_y=410MPa) without transverse reinforcement (stirrups). Three of these specimens were a box with or without different locations of internal diaphragms and one of them was a solid. The number of the internal diaphragms is the major variable adopted in this study, while, the other variables are kept constant for all tested specimens. The experimental results indicated that the shear strength is increased for about (35%) to (47%) for beams containing internal in-plane diaphragms in comparison with the reference beam. Also, the change of beam section from box section to solid section led to increasing the capacity for about (100%).
Keywords: Shear Failure, Box Beam, Reinforced Concrete, Diaphragms, ACI-318 Code
DOI: 10.7176/CER/12-8-06
Publication date: August 31st 2020

1. Introduction
A thin walled box beam is characterized by a relative magnitude of its dimensions; the wall thickness is small compared to the other linear dimensions of the cross section (Abbas, H. E, 2007). A box beam structure consists of top and bottom flanges connected by vertical (or inclined) webs to form a cellular section. Presence of these hollow through a solid beam eliminates a significant amount of dead space, and as a result, the beam stiffness reduced and this lead to altering the simple beam behavior to a more complex one. The reduction of beam stiffness may also give rise to excessive deflection under service load and lead to a redistribution of internal forces and moments. Several researches are interested in box beams under the effect of flexural, shear and torsion loads (Chiad, S. S; 2013). Shear behavior of reinforced self-compacting concrete deep box beams strengthened internally by transverse ribs is studied (Aziz, A. et al; 2015, Aziz, A. 2016). From the other hand, the effect of cellular concrete blocks and transverse internal ribs on the shear strength of hollow reinforced concrete beams is studied (Aziz, A. H, 2015). Shear strength of continuous self-compacting concrete hollow beams containing internal concrete ribs is also studied (Aziz, A. et al., 2016). Reinforced concrete beams with lightweight concrete infill is also studied (Vanissorn, V. et al., 2012). Moreover, the torsional behavior of pre-stressed and non-pre-stressed self-compacting concrete box beams containing internal diaphragms, in the transverse direction, was investigated (Aziz, A. et al., 2017, Aziz, A. et al., 2018). In the present research, shear failure control of reinforced concrete box beam containing internal transverse diaphragms is experimentally studied.

2. Experimental Work
2.1 Experimental Program
Tests were carried out on four, rectangular section, simply supported beam specimens under monotonically concentrated load. The tested beams are reinforced in the longitudinal direction (flexural reinforcement at the bottom) without transverse reinforcement (shear reinforcement) and have been designed to ensure failed in a shear mode of failure. The number of internal hollows, which were separated from each other by transverse concrete diaphragms, is the major adopted variable. The beam length, the shear span-depth ratio (a/d), and longitudinal reinforcement are kept constant for all tested beams. To evaluate the compressive strength of concrete, the experimental program consists, also, cast and test of a series of control specimens (cubes).

2.2 Beam Specimens Details
The nominal dimensions and the details of tested beams are shown in Figure (1) and Table (1). The overall length was (1200 mm), while, the overall depth and width are (300mm) and (200 mm) respectively. All beam specimens were reinforced with (3 12 mm) deformed bars as tension (flexural) at the bottom (with clear cover of 25mm). To hold the polystyrene blocks in place, (2ϕ6 mm) smooth bars at the top are used, Figure (2). Two steel molds were used to cast all beam specimens. Each mold consists of a bed and two movable sides, these sides have been fixed together by screws to form the required shape. Polystyrene blocks are used to form the hollows

inside the beams because it's lightweight and its facility to configure with the required dimensions. For all tested beams, beyond the cells (at the ends), the whole beam section was solid concrete.

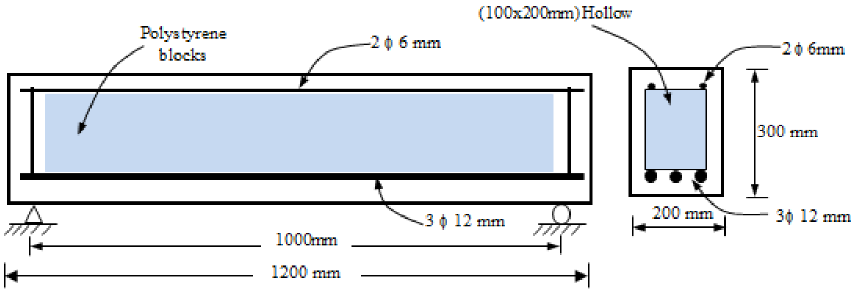

Figure 1. Details of the Tested Beams

Table 1. Beams Designation and Details

Beam Designation	Dimensions (mm)			Reinforcement	Transverse Diaphragms
	b_w	h	l	Flexural	
(B-1)*	200	300	1200	3ϕ12 mm (Bottom)	None
B-2					One**
B-3					Two**
B-4					None (Solid)

*Reference Beam **(50mm) Thickness

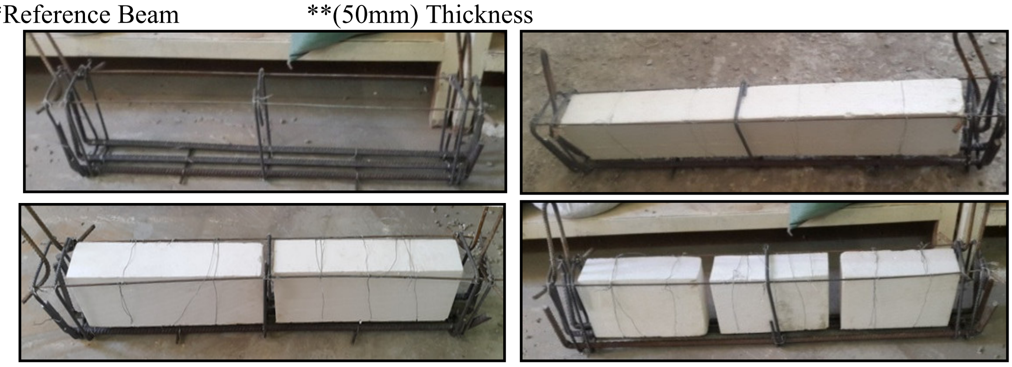

Figure 2. Details of Steel Reinforcement and Polystyrene Blocks

2.3 Materials

In manufacturing the tested and control specimens, local construction materials are used (except steel bars), description of materials properties are reported and presented in Table (2). Tensile test of steel reinforcement (manufactured in Ukraine) is carried out on (ϕ12mm) hot rolled, deformed, high tensile steel bar used as flexural reinforcement. Also, the test included testing of (ϕ6mm) plain mild steel bar which was used to hold polystyrene blocks in place. Table (3) shows the results of the tensile test for steel bars.

Table 2. Construction Materials Description

Material	Descriptions
Cement*	Ordinary Portland Cement (Type I)
Sand**	Natural sand with maximum size of (4.75mm)
Gravel**	Crushed gravel with maximum size of (10mm)
Water	Clean tap water (used for both mixing and curing)

* Conform to (IQS No. 5/1984). ** Conform to (IQS No. 45/1984).

Table 3. Steel Bars Properties

Nominal Diameter (mm)	Bar Type	f_y* (MPa)	f_u (MPa)	Elongation (%)
6	Plain	383	545	11
12	Deformed	410	625	16

* According to (ASTM 615- (A615M-16)).

2.4 Concrete mixing, cast and curing

One concrete mix is used in this work; the concrete mix proportions are reported in Table (4). It was found that the used mix produces good workability and uniform mixing of concrete without segregation. The concrete was mixed by using a horizontal rotary mixer with ($0.19m^3$) capacity. When the mixing process was completed, the samples were then cast in layers and compacted by a table vibrator to shake the concrete and consolidate it into the molds. Then, the top face of samples (top surface) was finished and leveled off by using steel trowel; and finally, the samples were covered by nylon sheets to impede water evaporation.

After (24) hours, the beam specimens and control specimens were stripped from the molds and cured in a water bath for (28) days with almost constant laboratory temperature, Figure (3). Before (24) hours from the date of testing, they were taken out of the water bath and tested in accordance with the standard specifications. It may be noted that to ensure that it would be easy to remove the samples when the concrete hardened, the inner faces of molds was oiled.

Table 4. Proportions of Concrete Mix*

Parameter	Quantity
Water/cement ratio	0.4
Water (Liter)	168
Cement (kg/m^3)	420
Fine Aggregate(kg/m^3)	600
Coarse Aggregate (kg/m^3)	1200

*Trial mix.

Figure 3. Beam specimen molds preparation

2.5 Test apparatus

A hydraulic machine with (300ton) capacity was used to test the control specimens and beam specimens. Deflection at the mid-span (center) has been measured by using ELE type dial gauge of (30mm) capacity and (0.01mm) accuracy. The ELE gauge was put below the bottom face of each span at the mid. Beam profile and loading arrangement are shown in Figure (4).

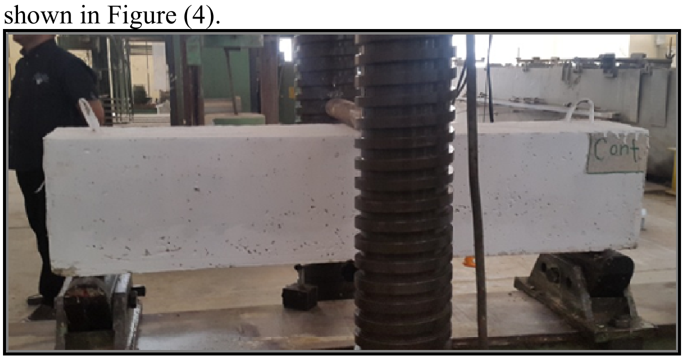

Figure 4. Beam specimen setup

2.6 Results of control specimens tests

Mechanical properties tested results of control specimens (compressive strength) are reported and provided in Table (5). Cubes compressive strength (f_{cu}) was carried out on concrete based on British standards (BSI 881-116) with standard cubes (150mm). The cubes were loaded uniaxially by the universal compressive machine up to the failure.

Table 5. Mechanical properties of concrete

Property	Value (MPa)
(f_{cu}) *	27
(f'_c)**	22

*Average of three samples. ** $f'_c = 0.82 f_{cu}$

2.7 Test methodology

The beam specimens were tested at (28days) age, where they were prepared by cleaning them and paint with white color, in order to detect the propagation of cracks. The beam specimens have been placed on the testing machine with a clear span of (1000mm), then adjusted to fit the supports, beam centerline, dial gauge and finally tested under a monotonic single-point loading up to failure; Figure (4) shows the setup of beam specimens. Initially, each beam is loaded with a small load to ensure that the dial a gauge is in touch with the bottom faces of beams and working correctly. After that, the load increased regularly at (1.0 kN/sec) and the readings taken every (5kN). When the beams reached advanced stage of loading, smaller increments of load were applied until failure, as the load indicator stopped in recording or returned back and the deflection increased very fast without any increase in applied load. Throughout the test, all necessary measurements and notices were recorded.

3. Results and discussions

As indicated before, the aims of this paper are to evaluate the effect and contribution of internal diaphragms (at different locations) on a shear failure of box reinforced concrete beams. The ultimate load capacities, load versus deflection at the center of the bottom face of each tested beam were recorded throughout the experimental work. To appear the cracks pattern and imported details, photographs for the tested specimens are taken. Tests observations, general behavior and recorded data are reported to recognize and understand the effects of adopted parameters on the behavior of the tested specimens.

3.1 Beam specimen behavior

Photographs of the tested beams after testing are shown in Figure (5) and tests results are given in Table (6). It may be noted that all beam specimens were designed to be failed in shear, which was distinguished by sudden failure and diagonally wide cracks which extend from supports towards the applied load locations. The general behavior of the tested beams can be described as follows; at early stages of loading, small vertical deflection initiated in the mid-span of tested beams, with further loading, diagonal cracks extended upwards and became wider in the shear span. One or more cracks propagated faster than the others and extend through weak locations in the beam (hollow zones) and reached the compression face (near applied load), where crushing of the concrete near the positions of applied loads had occurred due to highly concentrated stresses under load.

3.2 Failure mode

The appearance of the cracks reflects the failure mode for the tested beams. The experimental evidence shows that the diagonal cracks extended horizontally along the tension reinforcement and eventually, the failure takes place due to diagonal tension cracks were formed diagonally and moved up and towards the position of load, this crack is associated with crushing of the concrete near the positions of applied loads, this mode of failure is called "Shear-Compression" failure, as shown in Figure (5).

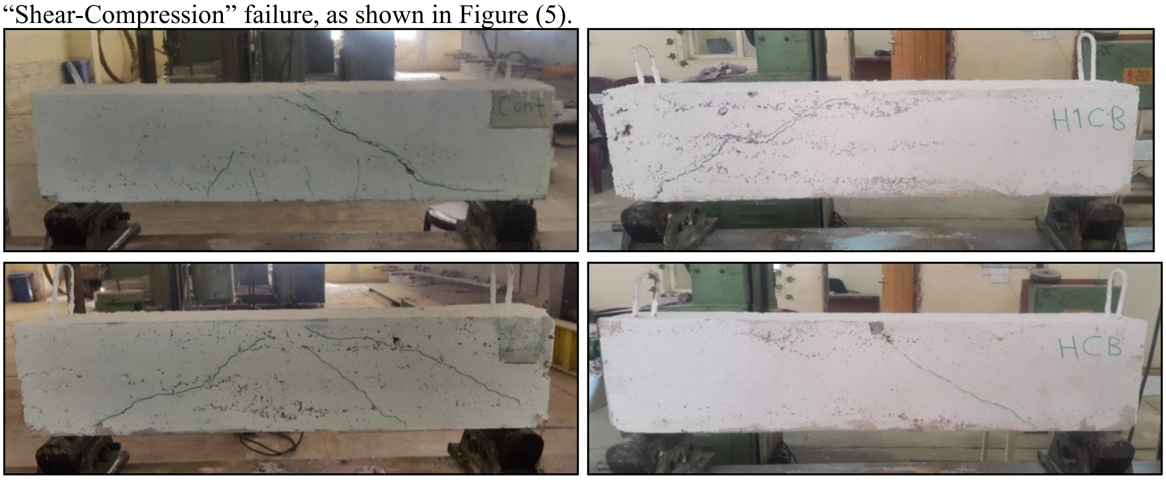

Figure 5. Crack patterns of tested beams

3.3 Ultimate shear strength (Vu)

The recorded ultimate loads of the tested beams are presented in Table (6). As expected, test results show that the reference beam (B-1) has the minimum ultimate strength in comparison with the other beams. This may be due to the absence of any internal diaphragm (concrete) in the section (in shear span). As shown in Table 6, the ultimate shear strength increased when the number of diaphragms increased (in shear span) and when we moved toward and closes up to the support. For the tested beam (B-4), which have made as solid without hollows, the ultimate shear strength increased by (100%) in comparison with the reference beam, this clearly due to concrete contribution to resisting shear stress. The ultimate shear strength increased about (35%) to (47%) for the tested beams (B-2) and (B-3) respectively, the presence of internal diaphragms led to increasing resistant area of concrete and as a result, the shear strength increased significantly.

Table 6. Ultimate and cracking load

Beam Designation	(B-1)*	B-2	B-3	B-4
Pu (kN)	85	115	135	170
Pu (kN)	15	20	24	35
Vu (kN) **	42.5	57.5	62.5	85
(Vu)i/(Vu)R (%)	1.0	1.35	1.47	2.0
Failure Mode	Shear-Compression			

*Reference Beam **$V_u = P_u/2$

3.4. Effect of number of diaphragms

As shown in Table (6), the presence of internal diaphragms in the box section leads to increases the stiffness of tested beams due to concrete contribution, and this leads to an increase in carrying capacity. In other words, due to abrupt changes in the sectional configuration (from solid to box section), the box beam corners, closed thin webs and flanges are subject to high stress concentration that may lead to a reduction in stiffness of the tested beam and produced cracking and excessive deflection, Figure (5). As shown in Table (6), the presence of internal diaphragms (see B-2 and B-3), led to increasing the ultimate shear strength from (35%) to (47%). The increasing in ultimate load was (100%) for the tested beam (B-4) when the section made fully without hollows. This means that the presence of internal diaphragms affected significantly on ultimate capacity of tested beams.

3.5 Load versus deflection curves

Load versus deflection curves of the tested beam specimens at the center of the bottom face at all loading increments up to failure are shown in Figure (6). In the beginning, the curves are identical and the tested beams exhibited linear behavior and the initial change of slope of the load-deflection curves occurred between (12kN to 35kN), which may be indicated the first crack loads. Beyond the first crack loading, each beam behaved in a certain manner. The behavior of beam specimen (B-4) exhibited greater loads and smaller deflections in comparison with the other beams; this beam had the greatest stiffness due to absence of any hollows.

Load-deflection curves for the tested beam specimens (B-1, B-2, and B-3) show a smooth increase, in both, applied loads and deflection. Presences of hollows lead to decreasing in carrying capacity of load beyond the first cracking, this associated with a reduction in beams stiffness and this is reflected on the associated deflection (excessive deflection). For tested beams (B-1 and B-2), a slight increase in the ultimate deflection of the beam (B-1) is observed by comparing with (B-2). This is may be due to the absence of any interior diaphragm inside the beam (B-1) which leads to decreasing of beam rigidity (stiffness) and as a result, slight increases in deflection is has occurred.

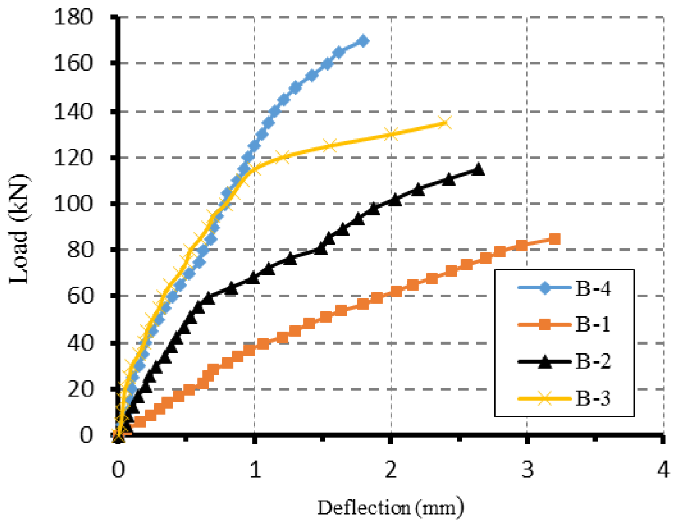

Figure 6. Load-Deflection Relationship of Tested Beams

4. Conclusions

In this paper, an experimental program has been performed, and the adopted variables seem to be a simple and more effective technique. The ultimate load carrying capacity found to be increasing with increasing the number of the internal diaphragms, and the deflection at the ultimate load is found to be decreasing. The diaphragms work as internal stiffeners which contributed to increase the shear strength to a certain degree. The shear strength increased (35%) and (47%) for beams containing one and three internal diaphragms respectively. The change of beam state from the hollow section to solid section led to increasing the capacity for about (100%).

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