Structural Behavior of Voided Reinforced Concrete Beams Under Combined Moments

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Abstract
The ability of reducing the reinforced concrete beams weights without significantly affecting its structural adequacy especially when combined loads are more eventual, is the aim of present paper. Therefore, the structural behavior of reinforced concrete beams containing air voids and subjected to combined moments of equal bending moment and torsional moment was observed.Five identical beams in external dimensions and internal reinforcement were the specimens of the study. The five beams were divided into two solid, two contain series of plastic balls and one contains a single plastic pipe. The plastic balls and pipe were used to create air voids inside the beams to reduce its concrete amount for economic and environmental considerations. All the beams were tested until failure, but two from its (one solid and one contains plastic balls) were tested under pure bending moment while the rest three beams were tested under combined moments. Cracking load, ultimate load, deflection and twisting angle were measured during tests as well as angle and width of cracks at failure.The experimental results revealed the similarity in structural behavior between voided and solid tested specimens is clear even when the values are different. For the section strength, when the beam containing voids, it may be lost about (13 – 23) % of its solid ultimate strength under combined load of equal fractions of bending and torsion moments. Also, the cracking load of the beam may be unaffected by voids presence under this combined load. When deformability is focused, the voided beams stiffness against bending moment is better than the torsional one; therefore, the twisting angle can be more noticeable than the deflection. Besides, the torsional moment governs over the bending moment, so that inclined cracks caused in failure. Finally, creating the voids by small size plastic pipe can make the beam stronger but more deformable than counter beam containing big size plastic balls under the combined moments.
Keywords: Structural behavior, Combined moments, Concrete amount, Voids presence, Spherical voids, Tubular void

1. Introduction

Because of its acceptability in strength and it is versatile, available and durable, concrete became the dominant construction material. So that, the high concrete demand latterly needs to be mitigated on order to save cost and preserve environment from natural resources depletion and carbon dioxide emission in cement production process. However, the reducing of concrete amount in construction members must be not defective on its structural adequacy. Therefore, in recent technique which keeps geometry and shape of the structural member, concrete is partially replaced by air voids through using recycled plastic balls or plastic pipes [1,2].

Firstly, recycled polythene balls of 3.5 mm size were used to reduce the concrete amount in reinforced concrete beams by about (4 – 8) %. Those balls were distributed longitudinally below the neutral axis of the beam because of regarding the concrete within the tension zone acts as a "stress transfer medium" [1]. Then, concrete stress in the compression zone is considered minimum. So, recycled polythene balls with different sizes (35, 65 and 90) mm were distributed longitudinally above the neutral axis in different beams to reduce its concrete amount by about (2 – 12) % [3]. Through this technique; the structural behavior of the reinforced concrete beams and its ultimate strength against flexure did not significantly affected [1,3]. PVC pipes were also used below the neutral axis depending on the same concept of Ref. [1]. Single PVC pipe of 54 mm size at variable depths [2] while multiple (1 - 3) PVC pipes assembly 50 mm size [4] were used to make hollow cores can reduce the concrete amount by about (3.7 and 4.9) % respectively. The results confirmed that, the structural behavior of the beams with hollow cores is similar to that of conventional concrete beams and an increase in the ultimate strength about 21% can be gained [2,4].

On other wise, spandrel beams and bridges exterior girders are designed to resist combined bending, shear and torsion stresses which are more hazardous than of any stress of them lonely. When a solid reinforced concrete beam is under combined moments but the bending moment governs over the torsional moment ($M/T \geq 1.7$), the beam can be stronger than its resistance to pure bending or pure torsion only. However, the beam stiffness under combined moments is less than that when the beam is under one of the pure moments; but increasing the torsional moment fraction can improve the stiffness [5]. In case of hollow reinforced concrete beam, its cracking load, ultimate load and stiffness are less that ones' values when the beam is solid. Also, the ultimate strength is defected when the torsional moment presence [6]. Therefore, it is desirable to design a solid structure to gain more cracking and ultimate strength when bending moment is dominant [5,6] and to design a hollow structure to save the concrete materials when torsional moment is dominant [6].

From this brief introduction, it is remarked that the technique of creating air voids inside reinforced concrete beams for reducing its concrete amount has limited to flexural behavior investigation. Whereas under torsional moments or in case of presence of torsion in combined moments, hollow beams are adopted to reduce the concrete amount. So, the present paper intends to cast reinforced concrete beams containing air voids and then examine this reduced weight beams under combined moments has a considerable torsion value to investigate how its structurally behave.

2. Research Significance

The structural behavior of voided reinforced concrete beams under combined loads is aimed to be investigated. To accomplish the aim, solid specimens and voided specimens having plastic balls once and plastic pipes other could be tested under pure bending moment at a case and under combined of bending moment and torsional moment at another. The cracking load, ultimate load, deflection, twisting angle, and failure angle with crack width at different failure modes will be observed through the investigation.

3. Experimental Program

The present paper objective is planned to be investigated through five reinforced concrete beams. Two from the beams are solid while the rest three beams are voided either with series of spherical voids (two beams) or with single tubular void (one beam). All the five beams were tested until failure, but not due to single type of loading. Thus, two beams (one solid and one spherically voided) were tested under flexure load represented by pure bending moment (M) at its middle third. The rest three beams were tested under combination of bending moment (M) and torsional moment (T) arranged in a manner to equalize the applied values of both torque and bending moment (M/T = 1). Tests are performed by subjecting the beams to two-point loads at its span middle third where in shear force is vanished, as illustrated in Figure 1.

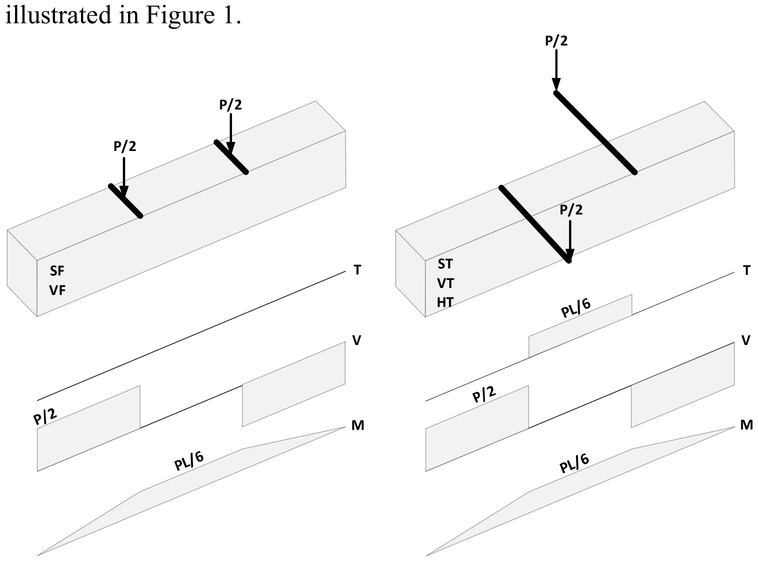


Figure 1. Loading setup for specimens

3.1. Specimens Details

All the five beam specimens have normal strength concrete in 150 x 200 mm cross-sectional area and 1300 mm length, however, the three voided specimens have some internally different. For reducing the concrete amount, air voids are entrapped inside the beams. So, two voided beams each of them is provided with ten plastic balls (spherical voids) of 90 mm size are spaced at 110 mm along 1080 mm of its span. Whereas, the third beam is provided with a plastic pipe (tubular void) of 50 mm size and along 1000 mm. Both the plastic balls and plastic pipe are placed to be congruous with neutral axis and symmetrical along the specimen span. The reasons of using plastic pipe of less size than the used plastic balls are to diverge from hollow section which is weak against bending moment [6] and to check the activity difference of seamless large size air voids achieved by plastic balls and small size air voids achieved by plastic pipe. Thus, mitigation in specimen weight was about 10% and 5% gained by plastic balls and plastic pipe respectively. Table 1 shows the specimens details which are complementary illustrated in Figure 2.

All specimens are identical in reinforcement details. The longitudinal reinforcement and transverse reinforcement of the beams are selected to be within the flexure limitations specified by ACI Code 318M-14 [7], as shown in Figure 3.

Table 1. Specimens details

Designation	Loading Type	Voiding Type	Weight Mitigation
SF	Flexure	-	-
VF	Flexure	Plastic Balls	10%
ST	Combined	-	-
VT	Combined	Plastic Balls	10%
HT	Combined	Plastic Pipe	5%

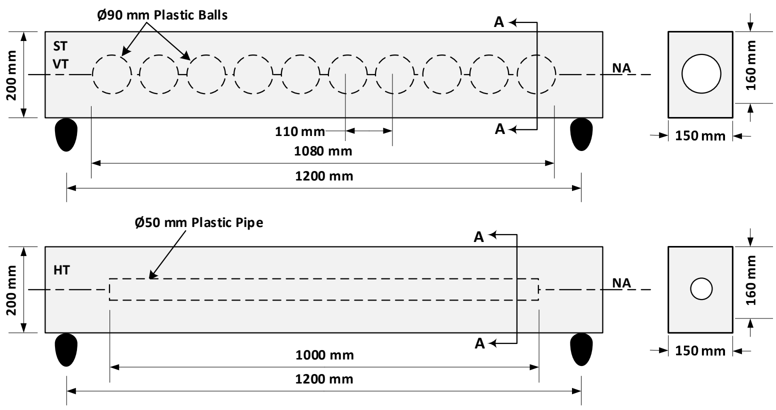


Figure 2. Voiding details

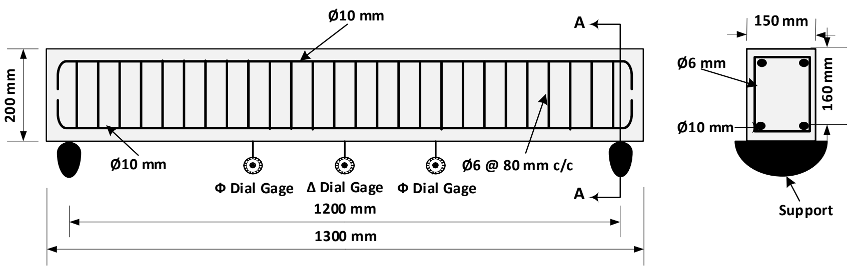


Figure 3. Reinforcement details

4. Materials Properties

4.1. Concrete

The concrete constituents which comply the Iraqi specifications (IQS) are listed in Table 2. These materials were mixed and then cured with tap water. However, the mix proportions are listed in Table 3. According to ASTM C39/C39M-16 [8], cylindrical concrete samples were tested. So, the compressive strength (f'_c) of hardened concrete was about 37.5 MPa.

Table 2. Properties of concrete constituents

<table>
<tr><th>Material</th><th>Description</th><th>Iraqi Specification</th></tr>
<tr><td>Cement</td><td>Ordinary Portland cement type I.</td><td>No. 5/1984 [9]</td></tr>
<tr><td>Fine Aggregate</td><td>Natural sand has 4.75 mm maximum size and 2.72 fineness modulus.</td><td rowspan="2">No. 45/1984 [10]</td></tr>
<tr><td>Coarse Aggregate</td><td>Crushed gravel passing from sieve 14 mm and has 2.63 bulk specific gravity.</td></tr>
</table>

Table 3. Mix Proportions

Cement (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Water (L/m^3)
450	600	1200	180

4.2. Reinforcing Bars

Deformed steel bars of 10 mm diameter were used as longitudinal reinforcement distributed into two bars at top and bottom of each beam specimen. While, 6 mm diameter bars were spread at each 80 mm of the specimen span as transverse reinforcement. Properties of the steel bars represented by diameter (Ø), yield stress (f_y) and ultimate strength (f_u) are listed in Table 4.

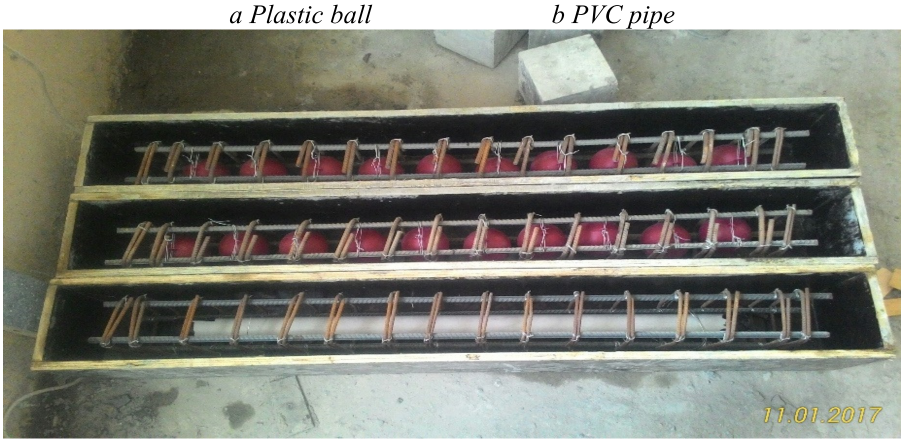
Table 4. Properties of reinforcing steel

Ø (mm)	Description	f_y (MPa)	f_u (MPa)	Iraqi Specification
6	Deformed	436	573	No. 2091/1999 [11]
10		492	655	

4.3. Voiding Materials

Locally manufactured recycled plastic (polythene) balls have about 24 gm weight were used as voided in two specimens (VF and VT). Whereas, standard polyvinyl chloride (PVC) pipe of 50 mm diameter and about 320 gm used to make longitudinal void of 1000 mm length in specimen (HT). Figure 4 illustrates the used voiding materials.

a Plastic ball *b PVC pipe*



c Positioned voiding materials

Figure 4. Voiding materials

5. Testing and Instrumentations

Universal testing machine of 3000 kN capacity, shown in Figure 5.a, was used for applying the loads on the specimens in continuous ascending stages of 2.5 kN up to failure. During the test, mid span deflection and/or twisting angle were measured as well as noticing the cracks.

For deflection recording, a dial gage of 50 mm capacity and 0.01 mm divisions was attached at bottom of the specimen mid span. Also, in combined loading tests as in Figure 5.b, two dial gages of 30 mm capacity and 0.002 mm divisions were fixed under the points of loading to measure the vertical movements of the bottom fibers at the opposite edges of the specimen. Thereby, approximate value for twisting angle can be calculated in simple method shown in Figure 5.c. All the beams were firstly painted to be white so as to simplify the cracks detection and pursuing. Then, crack width is measured by steel filets shown in Figure 5.d.

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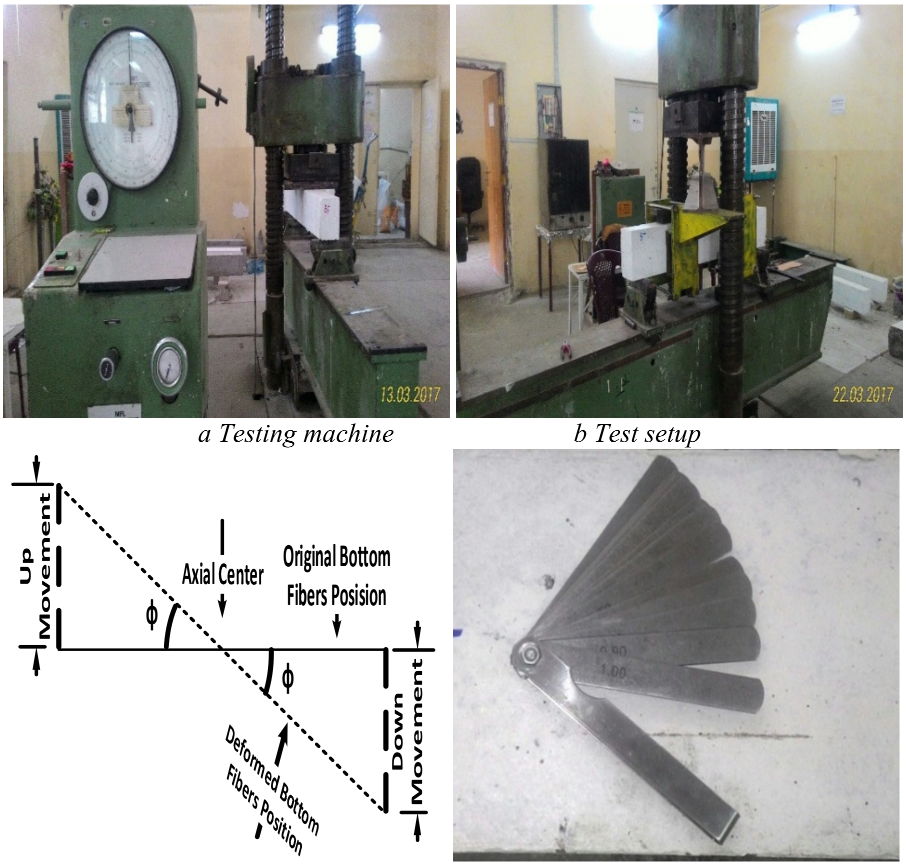


a Testing machine *b Test setup*

c Twist angle measuring *d Crack width measurement*

Figure 5. Testing details

6. Results and Discussion

From tests, the obtained results are arranged in Table 5 under titles of cracking load (P_{cr}), ultimate load (P_u), midspan deflection (Δ), crack width (w) and failure mode as well as twisting angle (Φ) and failure angle (θ) caused by applied torque (T) in combined loading. It is important to emphasize that all the tabulated results were achieved at the combined moments zone and will be discussed in more detailed under specific topics therein.

Table 5. Test Results

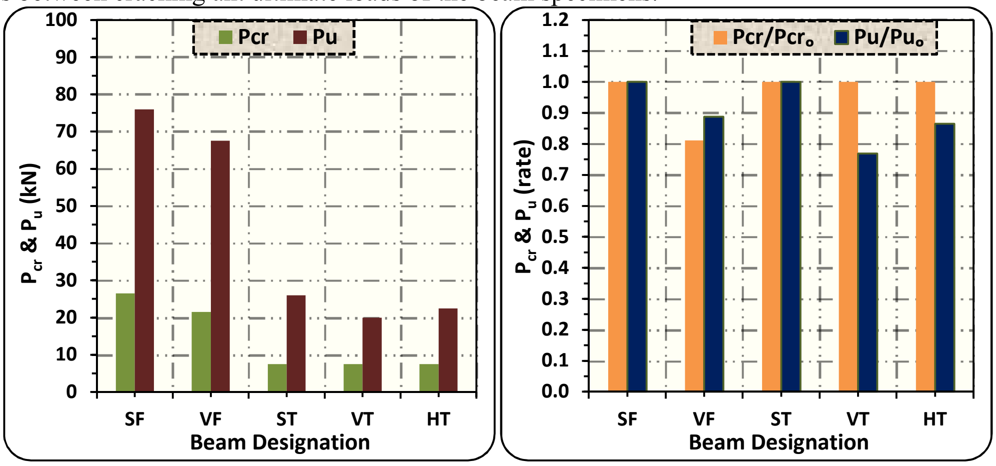
Designation	P_{cr} (kN)	P_u (kN)	Δ (mm)	Φ (deg.)	Failure Mode	θ (deg.)	w (mm)
SF	26.5	76	8.33	-	Flexure	-	0.5
VF	21.5	67.5	11.21	-	Flexure	-	0.6
ST	7.5	26	0.18	0.71	Shear	45	0.8
VT	7.5	20	0.22	1.24	Shear	45.3	0.8
HT	7.5	22.5	0.69	1.41	Shear	41	1.0

6.1. Cracking and Ultimate Loads

The cracking load (P_{cr}) of specimen infers the load value at first detection of visible cracks, while the ultimate load (P_u) infers the total applied loads at or closely near the specimen failure.

Generally, it is clear from Table 5 that the cracking and ultimate loads of beams subjected to bending moment were greater that of that counter beams subjected to combined moments regardless of voids presence. For all beams, the cracking load value was about (24 – 38) % of ultimate load value. Also, both cracking load and ultimate load values of specimens subjected to bending moment are greater than those counter values under combined moment. This result reveals that under the present loading setup where (M/T = 1), the specimen adequacy is defected due to combine moments. Thus, the capacity of the voided beam (VT) under combined moments reduced into about 35% for cracking load and into about 30% for ultimate load in comparison with the counter values under bending moment only (VF). By focusing on test under bending moment, the cracking and ultimate loads of the voided beam (VF) were about 81% and 89% of the counter solid beam (SF) values respectively. So, the voids presence accelerates both the cracking and the failure obviously.

On the wise of combined moment tests, the voids did not affect the cracking load values, because the value of 7.5 kN was the same for all the beams (ST), (VT) and (HT). In contrary, the voids are effective on ultimate load thereby the two voided beams (VT) and (HT) have strengths about (77%) and (87%) of the counter solid beam (ST) strength respectively. Since, the beam (HT) has 10% strength higher the beam (VT) then the effect of longitudinal void with small size is better than the distributed big size spherical voids. Figure 6 shows the differences between cracking ant ultimate loads of the beam specimens.

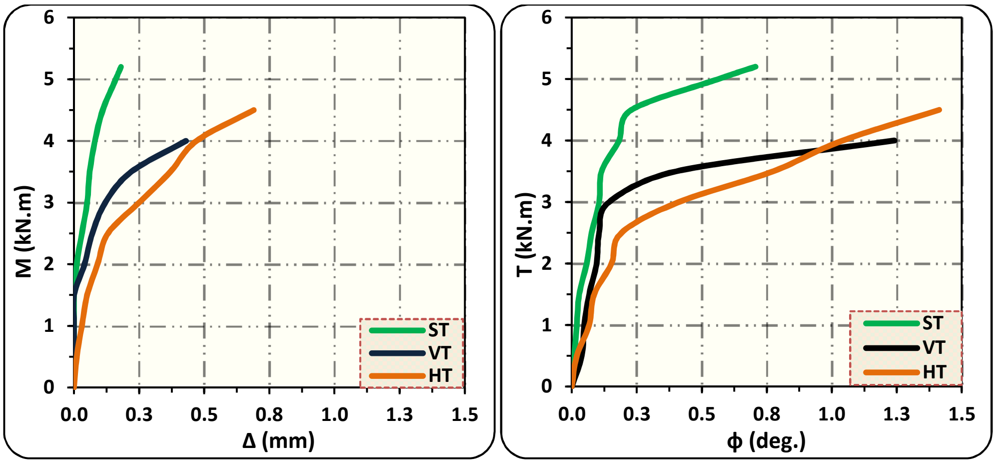


a Load values *b Rate values*

Figure 6. Cracking and ultimate loads

6.2. Flexural and Torsional Stiffness

The specimen stiffness can be experimentally measured form its response to applied load, so that, at a certain load, minimum deformation means high stiffness. Therefore, by relating the midspan deflection (Δ) to the applied bending moment (M), the beam flexural stiffness can be clarified. Similarly, the torsional stiffness of the beam can be clarified by relating the twisting angle (Φ) to the applied torsional moment (T) as illustrated in Figure 7.



a Flexural stiffness *b Torsional stiffness*

Figure 7. Stiffness of the tested beams

From Table 5, it noticeable that the deflection values of flexure beams (SF) and (VF) were greater that counter beams subjected to combined moments. That happened because of the high ultimate load values of (SF) and (VF) where deflection continued with loading increase. Also, the deflection values of the voided beams (VF) and (VT) were higher than the counter values of the solid beams (SF) and (ST). That reflected the effect of voids presence, which leads to reduce the beam stiffness under the two types of loading, bending and combined moments. However, similarity in behavior of the tested specimens is clear from the illustrated curved even when the values are different. Under the combined moment tests, the voided beams (VT) and (HT) are less than flexural and torsional stiffness in comparison with the solid beam (ST) because of reduction in inertia moment of the section. So, that clarified the effect of voids presence on the beam stiffness despite this effect in flexure is less than in torsion. Besides, the distributed big size spherical voids are less effective than the longitudinal void with small size on the beam stiffness. Therefore, the beam (VT) had better stiffness and exhibited less deflection and twisting angle in comparison with the beam (HT).

6.3. Failure Mode

In correlation to current loading types, two failure modes occurred; flexure mode and shear mode as shown in Figure 8. Flexure failure mode characterized by vertical wide cracks comitant with excessive deflection and crushed in top concrete fiber. This failure mode occurred on the beams (SF) and (VF) which tested under bending moment. The voids action in this failure mode is clear through the values of 11.21 mm deflection and 0.6 mm crack width (w) belonging to the beam (VF) which were greater than 8.33 mm deflection and 0.5 mm crack width belonging to the beam (SF). That indicates the defective of voids on the section behavior.

Inclined tension cracks indicated the shear failure mode occurred on beams suffered from the combined moment which are (ST), (VT) and (HT). The inclined cracks were bounded by the middle third of the specimen span and comitant with major twisting angle and minor deflection caused by bending moment effect. The deformation values of deflection and twisting angle increased through the beams (ST), (VT) and (HT) to record (0.18, 0.22 and 0.69) mm deflection and (0.71, 1.24 and 1.41) deg. Twisting angle respectively. Also, the inclined cracks have failure angle (θ) with theoretical value of 45 deg. which was achieved actually at the solid beam (ST) and approximately at the voided beam (VT) but decreased in the beam (HT) to be 41 deg. In addition to that, the inclined cracks width was 0.8 mm without spalled concrete in the solid beam (ST), 0.8 mm without spalled concrete in the voided beam (VT) and 1.0 mm with excessive spalled concrete in the second voided beam (HT). Finally, for beams subjected to equally combined bending and torque, the torsional moment is dominant over bending moment and does not affected by the voids presence. However, voided beams are more deformable than solid beam and beam has longitudinal small size void is more deformable than beam has distributed big size spherical voids.

a Flexure mode *b Crushed concrete*

c Shear mode *d Spalled concrete*

Figure 8. Failure Modes

7. Conclusions

Relating to reinforced concrete beams voided by symmetrical manners about its neutral axis, tested under either bending moment or combined of equal bending moment and torsional moment (M/T = 1) with two-point loads at middle third of span and compared to counter solid reinforced concrete beams. The following conclusions can be summarized:

The torsional moment is the dominant over the bending moment on structural behavior of the beam. So, the failure

is restricted to shear mode.
For both two types of loading, the ultimate strength of voided beam is less that of the counter solid beam by about (13 – 23) % and also less in stiffness and crack resistance.
While the voids can reduce the cracking load about 10% less than solid beam under bending moment, the cracking load value may be unaffected by those voids under combined moments.
The voided beams can be lost 35% from its cracking load and 30% from its ultimate load when loading type is transformed from bending moment into combined moments.
The flexural stiffness of the voided beams is better than the torsional stiffness; therefore, the twisting angle can be more noticeable than the deflection.
Small size tubular void can make the beam more strength but more deformable than counter beam has big size spherical voids under combined moments.
Similarity in structural behavior between voided and solid tested specimens is clear even when the values are different.
The present experimental results are compatible with the previous cited works.
Further work is suggested to study the strength and ductility of voided reinforced concrete beams under unequal combined moments ($M/T \neq 1$) and comitant shear.

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References

[1] Kumar, A. S. and Joy, A. (2015). Experimental Investigation on Partial Replacement of Concrete Below Neutral Axis of Beam. *International Journal of Science and Research (IJSR)*, 4(8), 1670-1674.
[2] Varghese, N. and Joy, A. (2016). Flexural Behaviour of Reinforced Concrete Beam with Hollow Core at Various Depth. *International Journal of Science and Research (IJSR)*, 5(5), 741-746.
[3] Sivaneshan, P. and Harishankar, S. (2017). Experimental Study on Voided Reinforced Concrete Beams with Polythene Balls. IOP Conf. Series: Earth and Environmental Science 80, doi:10.1088/1755-1315/80/1/012031.
[4] Parthiban, N. and Neelamegam, M. (2017). Flexural Behavior of Reinforced Concrete Beam with Hollow Core in Shear Section. *International Research Journal of Engineering and Technology (IRJET)*, 4(4), 2263-2274.
[5] Ajeel, A. E. (2016). Torsion Plus Bending and Shear on Reinforced Concrete Beams. *Journal of Engineering and Sustainable Development (JEASD)*, 20(40), 269-286.
[6] Alnuaim, A. S., Al-Jabri, K. S. and Hago, A. (2008). Comparison Between Solid and Hollow Reinforced Concrete Beams. *Materials and Structures*, 41, 277-288.
[7] ACI Code 318M-14. (2014). Building Code Requirements for Structural Concrete and Commentary. American Concrete Institute, September.
[8] ASTM C39/C39M. Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. American Society for Testing and Materials.
[9] Iraqi Specification, No.5. (1984). Portland Cement. Central Organization Standardization & Quality Control, Baghdad, Iraq.
[10] Iraqi Specification, No.45. (1984). Aggregates from Natural Sources for Concrete and Construction. Central Organization Standardization & Quality Control, Baghdad, Iraq.
[11] Iraqi Specification, No.209. (1999). Carbon Steel Bars for the Reinforcement of Concrete. Central Organization Standardization & Quality Control, Baghdad, Iraq.