Flexural Behaviour of Hollow Reinforced Concrete T-Beams

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Abstract. Hollow reinforced concrete Tee beam (HRCTB) is a beam that has longitudinal cavities that can be made usually by placing recycled plastic pipes in the web of beam within the tension zone. These cavities are used to pass electrical and mechanical equipment as well as the economic and sustainable benefits coming from subtraction some amount of concrete from these beams. This study tries to investigate experimentally the effect of circular cavities depth and its geometrical shape on the flexural behaviour of hollow reinforced concrete Tee beams. The experimental program comprises constructing and testing seven reinforced concrete Tee beams that have total height of 300 mm, flange width of 250 mm, flange depth of 75 mm as well as web width of 150 mm with beam length of 2000 mm. The first specimen is solid specimen while the others are divided into two groups, the first group consists of three specimens that have different longitudinal cavities depth which are 105 mm, 170 mm and 235 mm measured from top fibre of beam, and the second group includes three specimens that have different geometrical shape which are sharp parabolic (diameters are 35 mm by 65 mm), normal parabolic (diameters are 40 mm by 60 mm) and circular cavity of 50 mm diameter respectively. The results showed that increasing cavities depth from 105 to 170 and 235 mm from the top fibre of beam reduced the relevant first crack load by 3.57 %, 7.14 % and 17.86 % respectively and reduced ultimate strength by 0.39 %, 1.03 %, and 2.31 % respectively. In addition, the results revealed that the first crack load decreased by 3.57 %, 7.14 % and 7.14 % and ultimate load strength decreased by 0.26 %, 0.39 % and 1.03 % respectively for sharp parabolic, normal parabolic and circular specimen respectively.

Keywords: Concrete; flexural behavior; hollow beams; reinforcement; tee-section.

1. Introduction

Generally, conducting a practical technique to reduce the self-weight of structures represents a justified task in civil engineering works since it means reducing the accumulated loads that usually carried by the foundation as well as decreasing its relevant size.

For many recent decades ago, using lightweight concrete was considered as one of the best ways to get such general goal in all types of structural reinforced concrete members. Additionally, it can be recognized clearly that the civil engineering literature is filled of practical procedures that reduce the floor self-weight like hollow core slabs, bubbled slabs, and waffle slabs.

On the other hand, beam can be considered as a pivotal structural element within the reinforced concrete skeleton which has a considerable share in the whole structure self – weight. Using longitudinal cavities with RC beams is one of the common systems for subtracting the concrete and
getting lightweight beams. These cavities provide capability to decrease concrete volume as well as it can be used for passing electrical and mechanical equipment [1-3]. However, it is noticed that there are several contributions throughout the literature were devoted to investigate the structural behaviour of hollow reinforced concrete slabs [4].

In the last decade, a number of experimental works have been carried out to investigate the behaviour of hollow core beam. Murugesan et al. [5] concluded that both solid and hollow beams exhibited the same failure trend by the formation of additional flexural cracks and widening of the first cracks until failure. Altun et al. [6] deduced that the ultimate strength capacity decreased 29% for hollow beams when the percentage of concrete subtraction was 44%. Alshimmeri et al. [7] concluded experimentally that increasing the shear reinforcement in hollow reinforced concrete beams (HRCBs) reduced the relevant deformations for each stage of load especially at initial stage. Such reinforcement enabled the concrete cover spalling down to be avoided if its quantity was doubled. Joy et al. [8] figured out that the HRCBs with hollow axis illustrate flexural behaviour similar to the solid beams. Manikandan et al. [9] concluded that the deflection at yield and ultimate stages were similar for circular cavity HRCBs and solid section beams while the rectangular HRCBs illustrated lower levels of such behaviour. In addition, Varghese et al. [10] deduced that the optimum depth cavity is 160 mm from extreme fibre of compression which is just below the neutral axis. Soman et al. [11] stated that there was no significant reduction in load capacity could be observed if the circular cavity made immediately under the natural axis.

As a matter of fact, the proper execution of HRCB is very governing issue in the civil engineering projects for both strength and service ability requirements. More precisely, collecting reliable experimental results about HRCB is very useful to compare its performance with the traditional reinforced concrete beams. However, it can be concluded that the flexural behaviour of hollow reinforced concrete T beams had not been dealt with enough interest, thus, this study attempts to investigate such behaviour through the implementation of experimental program.

2. Experimental Scheme

2.1. Specimens description

The experimental scheme of the present study includes constructing and testing seven reinforced concrete Tee beams. All beams are of 250 mm flange width (bf), 75 mm flange depth (hf), web width of 150 mm (bweb) and total height of 300 mm (h) and total length (L) of 2000 mm as shown in Figure (1). The reference beam is solid and casted to get comparison base point with other specimens. The first group comprises three specimens to investigate the effect of cavity depth of 105, 170 and 235 mm (of 50 mm diameter) measured from top fibre of beam to the cavity centre. The second group comprises three specimens to compare the behaviour of different cavities geometry; (sharp parabolic shape with small diameter = 35 mm and other diameter = 65 mm), (normal parabolic shape with small diameter = 40 mm and another diameter = 60 mm) as well as 50 mm in diameter circular cavity as shown in Figure (2). Table (1) shows the beams details.

![Figure 1. Beam dimensions and reinforcement.](image-url)
Table 1. Beams details.

| Group | Variable | Beam designation | Description                                      |
|-------|----------|------------------|--------------------------------------------------|
| 1     | Cavity position | Ref. | Reference beam                                  |
|       |          | BP105 | Cavity center located at 125 mm from top fiber of beam |
|       |          | BP170 | Cavity center located at 190 mm from top fiber of beam |
|       |          | BP235 | Cavity center located at 255 mm from top fiber of beam |
| 2     | Cavity geometry | PAR3565 | Sharp parabolic cavity                        |
|       |          | PAR4060 | Normal parabolic cavity                       |
|       |          | CIR50 | Circular cavity                                |

2.2. Materials
Self-compacting concrete (SCC) was used to casting the beam specimens of this research, the properties of SCC ingredients, steel reinforcement and the recycled plastic pipes which were used to create the longitudinal cavities are mentioned in this article.

2.2.1. Cement. The commercial brand of Tasluoja which is type I of Portland cement was used to form SCC. The chemical composition and the physical properties of the used cement conform Iraqi standard specification No. 5, 1984 [12].

2.2.2. Fine aggregates. The sand was brought from Al-Sudour suburb near Diyala governorate, Iraq, the grading and the physical properties of the sand is within the limits of zone two in Iraqi specification No.45, 1984 [13].

2.2.3. Coarse aggregates. The coarse aggregate that wholly used in the present study was also brought from Al-Sudour suburb with maximum size of 10 mm. The grading and the physical properties of the sand is located within the limits of zone two in Iraqi specification No.45, 1984 [13].
2.2.4. Limestone powder. In order to ensure butter cohesiveness and segregation resistance, grinded limestone powder (LSP) was used as a filler within the self-compacted concrete mix. Such powder has a particle size of less than 0.125 mm according to EFNARC, 2002 [14].

2.2.5. Water. The traditional tap water was used throughout the present study for concrete mixing and curing purposes.

2.2.6. Steel reinforcement. The deformed bar of 12 mm in diameter and yielding stress (fy) of 430 MPa was used as the main flexural reinforcement during the current study while 10 mm bars of fy = 450 MPa were used as shear reinforcement. In addition, 4 mm in diameter bars of fy = 497.1 MPa were put in the flange area within the proposed beams section. These bars were tested at the laboratory of construction materials / college of Engineering / University of Diyala according to ASTM A615/A 615M, 2009 [15].

2.2.7. The recycled plastic pipes. Recycled pipes are used in the present study to create the longitudinal cavities in the tension zone of the section. The recycled plastic is inert material and does not react with concrete mix materials and / or reinforcement bars. The recycled pipes have 1.5 mm thickness and the parabolic pipes were fabricated and located vertically as shown in Figure (2). Finally, such pipes were industrialized commercially at Alakaween manufactory which is located in Alzaaffarania suburb, Baghdad, Iraq.

2.3. Concrete mixture
In this study, many trail mixes were done to get the concrete mixes that satisfies the specification of the self-compacted concrete in EFNARC [14] and to get about 28.6 MPa compressive strength at 28 days. Table (2) shows the components of the concrete mixture and their quantities per cubic meter.

| Materials          | Cement kg/m³ | Sand kg/m³ | Gravel kg/m³ | Limestone powder kg/m³ | Water kg/m³ | Superplasticizer kg/m³ |
|--------------------|---------------|------------|--------------|------------------------|-------------|------------------------|
| Quantities         | 430           | 760        | 700          | 200                    | 205         | 2.5                    |

2.4. Mechanical Properties of Hardened Concrete
Table (3) lists mechanical properties of the hardened concrete.

| Property                        | f’c (MPa) | Modulus of rupture (fr) (MPa) | Modulus of splitting strength (fct) (MPa) | Modulus of elasticity (MPa) |
|---------------------------------|-----------|-------------------------------|------------------------------------------|-----------------------------|
| Average value                   | 28.6      | 3.456                         | 3.105                                    | 25132                       |

2.5. Testing of the beam specimens
All the beams were cleaned and coated with white color painting for illustrating the propagation of the cracks, then the beams were tested in the laboratory of civil Engineering of Diyala University by a universal hydraulic testing machine of capacity of 600 kN. The linear variable deflection transducer (LVDT) sensor was fixed at the center of mid span of beams to measure the deflection during loading each beam was tested under two-point static load as shown in Figure (3). In addition, strain gauges (PFL-10-11) were installed at the top fibre of concrete as well as in the tension steel reinforcement in order to monitor structural response as much as possible.
3. Results and discussion

3.1. Testing of the beam specimens

Table (4) shows the result values of the tested specimens. It can be noted from this table that in the first group, increasing cavities depth from 125 to 190 and 255 mm from the top fibre of beam reduces the relevant first crack load by 3.57 %, 7.14 % and 17.86 % respectively. In the other hand, such increment decreases the yield load by 0 %, 0.76 % and 4.58 % for 105 mm, 170 mm and 235 mm depth levels respectively. Additionally, a reduction in ultimate load strength was also reported by 0.39 %, 1.03 %, and 2.31 % respectively. This behaviour can be interpreted by the loss in flexural rigidity dictated by the decrease in moment of inertia resulted from falling down of the internal resistance moment arm. In addition, when the cavity is just below the natural axes, the tension stress is low at the initial levels of load and ingressive failure stress would be late until cracks was. When the cavity is located nearby the main reinforcement, the first crack level is low because such zone would undergo the earliest tension cracking. In the second group, it is reported that the first crack load decreased 3.57 %, 7.14 % and 7.14 % and the yielding load increased 0.38 %, 0.76 % and 0.76 % for PAR3565, PAR4060 and CIR50 respectively. Additionally, a reduction in ultimate load strength was also reported by 0.26 %, 0.39 % and 1.03 % respectively for the same specimens. Such performance order between the defined specimens can be interpreted by the fact that the PAR3560 (sharp parabolic configuration) have the best linkage for concrete medium within the zone around the cavities since this fashion have the lowest level in beam web width subtraction (25.33 %) while such abatement in web width is (28.67 %) in PAR4060 and (35.33 %) for CIR50. Consequently, since the vertical components which capacitates parabolic cavities to resist moment more than the circular, thus, parabolic cavity beams will provide better performance than the circular beams. Table (4) shows the result values of the tested specimens.

Table 4. First crack load, yield load, and ultimate strength result values of the tested beams.

| Beam designation | Red. in vol. of beams % | Cracking load Pe (kN) | Decrease in Yield load Py (kN) | Decrease in Pu (kN) | Decrease in Pu % |
|------------------|------------------------|-----------------------|-------------------------------|--------------------|-----------------|
| Reference        | /                      | 28                    | 131                           | /                  | 155.6           |
| BP105            | 4.2                    | 27                    | 3.57                          | 131                | 0               |
| BP170            | 4.2                    | 26                    | 7.14                          | 130                | 0.76            | 154             | 1.03            |
| BP235            | 4.2                    | 23                    | 17.86                         | 125                | 4.58            | 152             | 2.31            |
| PAR3565          | 4.2                    | 27                    | 3.57                          | 130.5              | 0.38            | 155.2           | 0.26            |
| PAR4060          | 4.2                    | 26                    | 7.14                          | 130                | 0.76            | 154             | 0.39            |
| CIR50            | 4.2                    | 26                    | 7.14                          | 130                | 0.76            | 154             | 1.03            |
3.2. Load-Deflection Relationship

Generally, it can be noticed that the load – deflection diagram is consisted of two parts, the first is below the yielding limit which has linear fashion when the deflection levels are close to each other and the difference between them are barely to be distinguished till the yielding. The second stage is recognized after the yielding limit of steel reinforcement when the cracks developed rapidly and a huge deflection response can be observed.

In the first group, it is reported that increasing longitudinal cavities depth from 105 to 170 and 235 mm increases the relevant yield deflection by 0.65 %, 1.09 % and 1.85 % respectively as well as increasing the ultimate deflection by 4.90 %, 6.33 % and 7.34 % respectively. In the second group, it is reported that the yield deflection increased 0.33 %, 0.76 % and 1.09 % for PAR3565, PAR4060 and CIR50 respectively. Additionally, the ultimate deflection increased by 4.16 %, 5.78 % and 6.33 % for the same defined specimens. Table (5) shows the load – deflection results and Figure (4) shows the load mid span deflection diagrams for both groups 1 and 2.

![Table 5. The load – deflection results.](image)

| Beam designation | Reduction in vol. of beams % | Yield deflection Δy (mm) | Increase in Δy % | Ultimate deflection Δu (mm) | Increase in Δu % | Ductility ratio Δu/Δy |
|------------------|-----------------------------|--------------------------|------------------|-----------------------------|------------------|----------------------|
| Ref. / 9.2 / 49 / 5.32 | 4.2 / 9.26 / 0.65 | 49 / 51.40 | 4.90 / 5.57 | 4.16 / 5.53 | 5.78 / 5.59 | 6.33 / 5.60 |
| BP105 / 4.2 / 9.30 / 1.09 | 52.10 | 6.33 | 5.60 |
| BP170 / 4.2 / 9.37 / 1.85 | 52.60 | 7.34 | 5.61 |
| BP235 / 4.2 / 9.23 / 0.33 | 51.04 | 4.16 | 5.53 |
| PAR3565 / 4.2 / 9.27 / 0.76 | 51.83 | 5.78 | 5.59 |
| PAR4060 / 4.2 / 9.30 / 1.09 | 52.10 | 6.33 | 5.60 |
| CIR50 / 4.2 / 9.30 / 1.09 | 52.10 | 6.33 | 5.60 |

![Figure 4. Load – mid span deflection curves: (a) Group 1. (b) Group 2.](image)

3.3. Load-Strain Relationship

In general, the load tension steel strain is consisted of three stages; the first stage is before the first crack limit when the effect of cavities depth is still inconsiderable. The second is after such limit till the yielding when the effect of cavities depth is more evident. The third stage begins beyond the yielding of steel reinforcement and the diversity between cavities depth levels is also clear till failure, the load compression concrete strain is consisted of two distinct stages, the first is the linear portion
before yielding when the deference between the specimens can be recognized while the second stage started after the yielding of the steel when no significant behaviour is obvious between the specimens due to the change in the existing circumstances till failure. In the first group, it is reported that increasing longitudinal cavities depth from 105 to 170 and 235 mm increases yield concrete strain by 5.29 %, 11.43 % and 17.58 % respectively and ultimate concrete strain by 17.49 %, 24.47 % and 32.50 % respectively. On the other hand, ultimate steel strain was also increased by 8.81 %, 11.33 % and 19.97 %. It is deduced that the progressive increase in concrete strain in HRCTBs is occurred to compensate the incremental loss in rigidity as the depth of cavity is falling down, on the other hand, the tension steel has a share in such compensation process to reach the equilibrium state, so, tension strain levels were also increased as cavities depth increased. In the second group, it is reported that the yielding concrete strain was increased by 3.92 %, 8.87 % and 11.43 % for PAR3565, PAR4060 and CIR50 respectively and ultimate concrete strain by 17.49 %, 24.47 % and 32.50 % respectively. On the other hand, ultimate steel strain was also increased by 8.81 %, 11.33 % and 19.97 %. It is recorded that such diversity is dictated by the difference between specimens with respect of flexural rigidity. Figure (5) shows the load – strain diagrams for group 1 and 2 while table (6) lists the load strain results.

![Figure 5. The load – strain diagrams: (a) Group 1. (b) Group 2.](image-url)
3.4. Crack Pattern and Mode of Failure

In the first group, increasing longitudinal cavities depth from 105 to 170 and 235 mm increases the yielding crack width 10 %, 13.33 % and 26.67 % respectively. That behaviour happens because such action means that the cavities approach more and more to the cracked zone in the extreme fibre of tension. In the second group, the reported crack level for PAR3565, PAR4060 and CIR50 are 0.053, 0.058 and 0.060 respectively. In addition, the increase in crack width at yielding is 6.67 %, 10.00 % and 13.33 % for the same defined specimens respectively. Such behaviour can be ascribed also to the difference between the defined specimens with respect to flexural rigidity.

Table 7 shows the crack width results for the two groups. In addition, the mode of failure of all solid and HRCTBs was flexural failure mode as shown in Figure (6).

### Table 6. The load – strain results.

| Beam designation | Reduction in vol. of beams % | Yield concrete strain $\varepsilon_y \times 10^{-6}$ | Increase in yield concrete strain $\varepsilon_y$ % | Ultimate concrete strain $\varepsilon_u \times 10^{-6}$ | Increase in ultimate concrete strain $\varepsilon_u$ % | Yield steel strain $\varepsilon_y \times 10^{-6}$ | Increase in yield steel strain $\varepsilon_y$ % | Ultimate steel strain $\varepsilon_u \times 10^{-6}$ | Increase in ultimate steel strain $\varepsilon_u$ % |
|------------------|-------------------------------|---------------------------------|----------------------|-----------------------------|---------------------------------|----------------------|----------------------|-----------------------------|---------------------------------|
| Ref.             | 0                             | 586                             | /                    | 2991                       | /                              | 1694                 | /                    | 2930                       | /                              |
| BP105            | 4.2                           | 617                             | 5.29                 | 3514                       | 17.49                          | 1736                 | 2.48                 | 3188                       | 8.81                           |
| BP170            | 4.2                           | 653                             | 11.43                | 3723                       | 24.47                          | 1871                 | 10.45                | 3262                       | 11.33                           |
| BP235            | 4.2                           | 689                             | 17.58                | 3963                       | 32.50                          | 1933                 | 14.11                | 3515                       | 19.97                           |
| PAR3565          | 4.2                           | 609                             | 3.92                 | 3377                       | 12.91                          | 1731                 | 2.18                 | 3076                       | 4.98                            |
| PAR4060          | 4.2                           | 638                             | 8.87                 | 3556                       | 18.89                          | 1812                 | 6.97                 | 3164                       | 7.99                            |
| CIR50            | 4.2                           | 653                             | 11.43                | 3723                       | 24.47                          | 1871                 | 10.45                | 3262                       | 11.33                           |

### Table 7. Effect of longitudinal cavities geometry on crack width.

| Beam designation | Reduction in vol. of beams % | Crack width at $P_{cr}$ (mm) | Crack width at $P_y$ (mm) | Increasing the crack width at $P_y$ % |
|------------------|-------------------------------|-----------------------------|---------------------------|-------------------------------|
| Ref.             | /                             | 0.047                       | 0.3                       | /                             |
| BP105            | 4.2                           | 0.051                       | 0.33                      | 10                            |
| BP170            | 4.2                           | 0.060                       | 0.34                      | 13.33                         |
| BP235            | 4.2                           | 0.073                       | 0.38                      | 26.67                         |
| PAR3565          | 4.2                           | 0.053                       | 0.32                      | 6.67                          |
| PAR4060          | 4.2                           | 0.058                       | 0.33                      | 10.00                         |
| CIR50            | 4.2                           | 0.060                       | 0.34                      | 13.33                         |
4. Conclusion
The following are the main conclusions that can be evaluated during the current study:
- HRCTBs have ultimate deflection levels more than solid beams.
- The ultimate deflection increased as the cavities depth increased.
- The ultimate deflection of circular cavity beams is more than parabolic HRCTBs.
- HRCTBs have ultimate strain levels more than solid beams.
- The ultimate strain increased as the cavities depth increased.
- The ultimate strain of circular cavity beams is more than parabolic HRCTBs.
- Increasing cavities depth 105 to 235 mm reduces ultimate load strength between 0.39 to 2.31 % and first crack load by 3.57 % to 17.86 % because the cracks would be initiated at the extreme tension zone and delayed to reach the area under the natural axes. In addition, a reduction in yielding load was reported between 0 % and 4.58 %.
- Increasing cavities depth 105 to 235 mm increases ultimate deflection between 4.90 % and 7.34 % as well as reduction in yielding deflection between 0.65 % and 1.85.
- Increasing cavities depth 105 to 235 mm increases ultimate concrete strain between 17.49 % and 32.50 % as well as increment in yielding compressive strain between 5.29 % and 17.58 %.
- Increasing cavities depth 105 to 235 mm increases ultimate steel strain between 8.81 % and 19.97 % as well as increment in yielding tension strain between 2.48 % and 14.11%. Increasing cavities depth 125 to 255 mm increases yielding crack width between 10 % to 26.67 %.

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