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by Syahrul Sariman

ISSN 1533-9211

DOI 10.17605/OSF.IO/J67EK

ANALYSIS OF HORIZONTAL SHEAR FAILURE IN HOLLOW REINFORCED CONCRETE BEAMS: A FULL-SCALE EXPERIMENTAL STUDY

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Abstract

Along with increasing environmental damage due to the use of synthetic materials in large volumes, it has an impact on global warming, so scientists and field practitioners are innovating a lot to use environmentally friendly materials. One type of environmentally friendly concrete structure is the Hollow Reinforced Concrete Beam (HRCB) type, which is usually used as a bridge girder. This study aims to observe the process of horizontal failure of the girder due to shear stress, and analyze the causal factors, to ultimately provide a solution to minimize the failure of the girder due to the horizontal shear failure. This research was conducted with an experimental quantitative approach which was described by using the analysis of the bridge girder structure in accordance with applicable standards. Full-scale experiments were carried out on intact beams (without holes) and hollow beams. This study shows that the failure that occurs in hollow beams is horizontal shear failure, which is caused by the width of the residual beam that is insufficient to carry the main stress due to the combination of horizontal shear forces and bending stresses, which occur in the quarter span zone of the girder. This study recommends that in the use of hollow reinforced concrete girders, care must be taken in the placement of bottles (as holes), so that during casting their position does not experience displacement in the concrete cross section, which causes spalling in the cross sectional area of the girder.

Keywords: Horizontal shear failure, hollow reinforcement concrete beams, spalling, shear stress, deflection.

1. INTRODUCTION

Several types of structural concrete beams are often made with a large beam height with the aim of increasing the stiffness of the beam element, so that the deflection that occurs in the beam when receiving a load does not exceed the permissible number. Among the beams that are often made with a height that tends to be excessive are the bridge girder beams. Logical girder beams must be made high because of the principle of placement which is generally a certain static structure on 2 supports, namely joint placement and roller placement, so that practically the deflection is very dependent on the stiffness of the girder beam itself. Theoretically, a concrete cross-sectional beam is only intended to carry compressive stresses, while the tensile stresses that occur are fully borne by the reinforcing steel material. Therefore, the presence of a concrete cross section in the practical tensile area only contributes to the increase in beam stiffness, as shown in Figure 1.

ISSN 1533-9211

DOI 10.17605/OSF.IO/J67EK

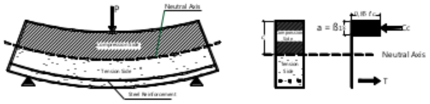


Figure 1: Cross-sectional characteristics of bending beam

With the stress characteristics in the beam cross section as above, several researchers have tried to make concrete efficiency in the tensile area of the beam cross section, with the aim of getting cheaper construction costs and lighter concrete self-weight. In 1999, Besari M.S. and Lauw, C.G.S., examined the characteristics of the hybrid T-beam by differentiating the quality of the concrete in the compression area (LWC, f'_c : 42 MPa), and in the tension zone (NWC f'_c : 35 MPa). The cross-sectional dimensions are 150 mm x 250 mm, the beam length is 6.00 meters, the useful width is 375 mm, and the plate thickness is 60 mm, given a monotonic static load and an alternating load that leads to an earthquake load simulation. The results found that there was a ratio between the ability to carry loads with ductility, and the ratio between the effective moment of inertia and the horizontal shear stress [1]. Djamaluddin et al., in 2014, also conducted a flexural test of reinforced concrete beams with normal concrete in the compression area and Styrofoam concrete in the tensile area but using the reinforcement of the frame system. These tests give results that show that there is no significant difference between normal beams and beams covered with concrete and Styrofoam in carrying bending moments [2]. Olmedo, F.I. et al., in 2016, examined the flexural treatment of layered reinforced concrete beams using different concrete qualities, namely Lightweight Concrete (LC) and Normal Concrete (NC), as sketched in Figure 2.

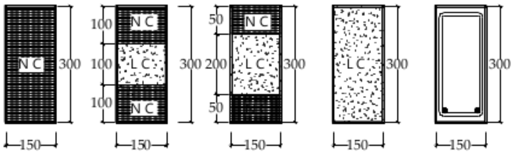


Figure 2: Cross section of beams (Olmedo et al.)

From the test results of Olmedo et al., it proves that there is no significant difference in the ultimate load for homogeneous beams and multilayer beams [3]. Nasr Z. Hassan et al., in 2018, developed a concept by installing circular PVC pipes in the tension zone of reinforced concrete beams because the concrete under the neutral axis acts as a stress transfer medium between the compression zone and the tension zone. A total of 10 reinforced concrete beams measuring 2500mm x 200mm x 300mm were cast and tested by four-point bending test. Observations were made on the crack load, ultimate load, crack pattern, failure mode, load deflection curve, stiffness, ductility index and energy absorbed for all tested and studied beams. The test results show that the pipe diameter less than 0.25 of the bottom or top width of the central reinforced beam at the two investigated locations (0.53 d) and (0.60 d) has no effect on the capacity and stiffness of the beam, where d is the pipe diameter. For larger pipe diameters, the ultimate capacity of the beam depends on its location and the ratio of flexural and shear reinforcement,

ISSN 1533-9211

DOI 10.17605/OSF.IO/J67EK

the crack width of the beam with PVC pipe inserted is wider and the failure mode is brittle diagonal shear failure [4]. Haider M. A. and Murtada A. I., in 2021, investigated experimentally the effect of circular holes depth and geometric shape on the bending behavior of hollow reinforced concrete Tee beams. The experimental program consisted of seven tests on reinforced concrete Tee beams which had a total height of 300 mm, a wingspan of 250 mm, a wing depth of 75 mm and a body width of 150 mm with a beam length of 2000 mm. The first test specimens were solid specimens while the others were divided into two groups. The first group consisted of three specimens having different longitudinal holes depths, namely 105 mm, 170 mm and 235 mm measured from the top fiber of the beam, and the second group included three objects. Tests that have different geometric shapes are sharp parabola (diameter 35 mm x 65 mm), normal parabola (diameter 40 mm x 60 mm) and circular holes with diameter 50 mm. The results showed that increasing the holes depth from 105 to 170 and 235 mm of the top fiber of the beam reduced the relevant first crack load by 3.57%, 7.14% and 17.86% respectively and decreased the ultimate strength by 0.39. %, 1.03%, and 2.31%. Each. In addition, the results showed that the first crack load decreased by 3.57%, 7.14% and 7.14% and the ultimate load strength decreased by 0.26%, 0.39% and 1.03%, respectively. Sharp parabola test, normal parabola and circle [5]. Syahrul Sariman (2020) investigated the effect of holes arrangement on the span of a flexible beam. The results showed that the performance of hollow beams with variations in the length and height of the holes was quite good [6]. Furthermore, several other researchers observed the flexural behavior of hollow reinforced concrete beams, including Muhamad Hilman, et al., in 2016, examining the flexural strength of the beam, the results showed that the flexural strength of reinforced concrete beams with hollow core holes did not decrease because the hollow core holes were placed in the tensile area of the beam. [7]. Rizky FP in 2016, researching the stiffness of the beam structure obtained the results that the stiffness of the concrete beam has decreased due to the deflection that occurs in the hollow concrete beam is greater than that of the intact beam. The stiffness value of hollow concrete beams L5, L7 and L9 is 580.66 kg/mm, respectively; 568.62 kg/mm; and 566.79 kg/mm. This decrease is not significant compared to the decrease in volume weight that occurs [6]. While Mustofa Alaydrus, et al., examined the deformation of hollow beams, and obtained the results that the deformation of hollow concrete beams experienced ups and downs because the maximum acceptable loads were different. Beam L7 has a deformation value of 5.16 mm, which is the largest value among concrete beams with other holes, and beam L5 has a deformation value of 4 mm, while beam L9 has a deformation value of 3.14 mm. The difference in the value of this deformation is not significant compared to the decrease in volume weight that occurs [6]. Sivaneshan P. and Harishankar S. in 2017, conducted a study by reducing the weight of concrete beams by inserting plastic balls into the concrete beams. Balls with a diameter of 75mm are used to replace 10% of the concrete volume, balls with a diameter of 65mm to replace 6% and 12% of the concrete volume, and balls with a diameter of 35mm to replace 2% and 6% of the total concrete volume. From the results of the flexural test they carried out, it proved that the load-bearing capacity and deflection that occurred in all types of beams tended to be the same value [8]. From the series of studies above, the main reason for reducing the use of concrete mixtures in the tensile section area of reinforced concrete beams, both with a layered concrete system and making holes, is an effort to reduce the use of concrete material so that the use of cement material as the main ingredient of concrete produces carbon dioxide (CO_2) gas emissions can also be reduced.

2. METHOD

This research is an experimental research by conducting a series of tests in the laboratory. The main object of the research is the structure of reinforced concrete beams which are made hollow in the tensile section using bottles used for drinking water and then given a static load. The characteristics of the basic materials of concrete and reinforcing steel used are as listed in Table 1 and Table 2.

Table 1: Characteristics of the concrete used

No	Description	Unit	Test results
1	Average compressive strength (f'_{cr})	MPa	27.09
2	Elastic Modulus (E)	MPa	24,403.54
3	Flexural Strength (f_l)	MPa	3.31

Table 2: Characteristics of reinforcing steel used

Description	Unit	Test results	
Steel Diameter	mm	15.9972	8.00
Cross-sectional area	mm^2	200.99	50.26
Melting strength	MPa	481.78	259.95
Max tensile strength	MPa	524.78	361.41
Permission stretch	mm/mm	0.00239	0.00129
Steel's modulus of elasticity	MPa	206,691.07	202,111.30

Dimensions of the beam in this study using bridge girder beams with: beam width (b) = 150 mm, beam height (h) = 350 mm, concrete cover (s) = 20 mm, effective height (d) = 314 mm. Concrete quality (f'_c): 27.89 MPa, while the compression reinforcement used 3D16 mm (As = 599.42 mm2) using steel quality (f_y): 481.78 MPa. Reinforcement for: 2φ8 mm, stirrups, 8–100mm, using steel quality (f_y) = 259.95 MPa. Beam length: L = 3300 mm (effective span: 3000 mm). In the tensile section below the neutral line, a hollow cross section is made from used plastic bottles, volume: 600 ml, diameter: 60 mm, and length: 220 mm per unit. The variables, notations and the number of test objects used in this study consisted of 18 test objects, as listed in table 3.

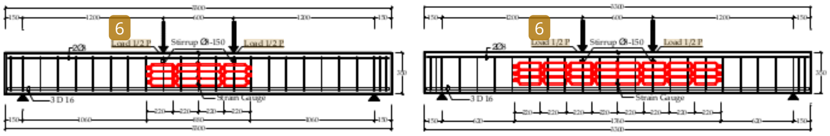
Table 3: Variation of hollow formation, beam notation and number of samples

No	Number of bottles elongated	Number of layers of bottles	Beam notation	Number of test items
1	0 bottles	0 layers	NB	3 beams
2	4 bottles	3 layers	HB3A	3 beams
3	8 bottles	3 layers	HB3B	3 beams
4	12 bottles	3 layers	HB3C	3 beams
5	12 bottles	1 layers	HB1C	3 beams
6	12 bottles	2 layers	HB2C	3 beams

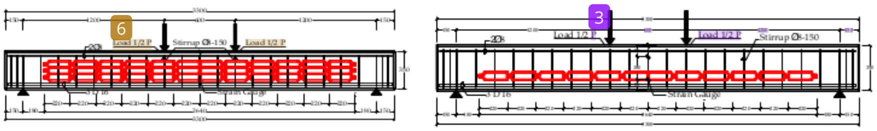
ISSN 1533-9211

DOI 10.17605/OSF.IO/J67EK

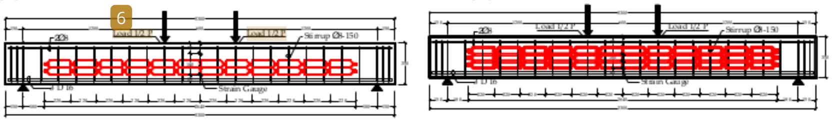
To show the placement of bottles in the cross section of each test beam is as in Figure 3.



(a) Bottle formation in beam HB3A (b) Bottle formation in beam HB3B



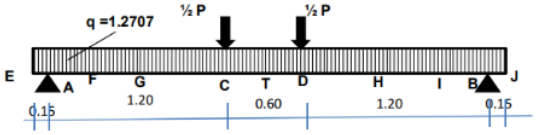
(c) Bottle formation in beam HB3C (d) Bottle formation in beam HB1C



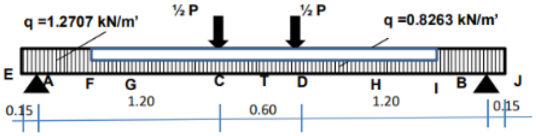
(e) Bottle formation in beam HB2C (f) Bottle formation in beam HB3C

Figure 3: Placement of bottles on each test beam

Each type of beam tested has a moment capacity and transverse force based on the loading applied in this study, and can be calculated based on the sketch shown in Figure 4.



(a) Mechanics of Normal Beams (NB)



(b) Mechanics of Hollow Beams (HB)

Figure 4: Test Beam Mechanics Sketch

From the results of the mechanical calculations on the 6 types of beams tested, the results are summarized in table 4.

Table 4: Summary of Beam Mechanics Calculation Results

Beams	Point	Moment (kN.m)	Transverse force (kN)
NB	A	-0.0143	1.9060 + 0.5 P
	G	0.9006+0.3 P	1.1436 + 0.5 P
	C	1.3581 +0.6 P	0.3812 + 0.5 P
	T	1.4152+0.6 P	0
	D	1.3581 +0.6 P	-0.3812 + 0.5 P
	H	0.9006+0.3 P	-1.1436 + 0.5 P
	B	-0.0143	-1.9060 + 0.5 P
HB3A	A	-0.0143	1.7228 + 0.5 P
	G	1.1083 + 0.265 P	0.3057 + 0.5 P
	C	1.1276 + 0.6 P	0.2479 + 0.5 P
	T	1.1648 + 0.6 P	0
	D	1.1276 + 0.6 P	-0.2479 + 0.5 P
	H	1.1083 + 0.265 P	-0.3057 + 0.5 P
	B	-0.0143	-1.7228 + 0.5 P
HB3B	A	-0.0143	1.5148 + 0.5 P
	G	0.8568 + 0.445 P	0.4875 + 0.5 P
	C	0.9634 + 0.6 P	0.2479 + 0.5 P
	T	1.0006 + 0.6 P	0
	D	0.9634 + 0.6 P	-0.2479 + 0.5 P
	H	0.8568 + 0.445 P	-0.4875 + 0.5 P
	B	-0.0143	-1.5148 + 0.5 P
HB3C	A	-0.0143	1.3193 + 0.5 P
	G	0.5878+ 0.30 P	0.7436 + 0.5 P
	C	0.8853 + 0.6 P	0.22479 +0.5 P
	T	0.9224 + 0.6 P	0
	D	0.8853 + 0.6 P	-0.22479 +0.5 P
	H	0.5878+ 0.30 P	-0.7436 + 0.5 P
	B	-0.0143	-1.3193 + 0.5 P
HB1C	A	-0.0143	1.5082 + 0.5 P
	G	0.8984 + 0.345 P	0.9255 + 0.5 P
	C	1.2218 + 0.6 P	0.3428 + 0.5 P
	T	1.2730 + 0.6 P	0
	D	1.2218 + 0.6 P	-0.3428 + 0.5 P
	H	0.8984 + 0.345 P	-0.9255 + 0.5 P
	B	-0.0143	-1.5082 + 0.5 P
HB2C	A	-0.0143	1.3282 + 0.5 P
	G	0.7919 + 0.345 P	0.8151 + 0.5 P
	C	1.0767 + 0.6 P	0.3019 + 0.5 P
	T	1.1220 + 0.6 P	0
	D	1.0767 + 0.6 P	-0.3019 + 0.5 P
	H	0.7919 + 0.345 P	-0.8151 + 0.5 P
	B	-0.0143	-1.3282 + 0.5 P

The test instruments used in this study consisted of: (1) Actuator, a load with a capacity of 1500 kN, (2) Load Cell, to measure the working load, with a capacity of 200 kN, (3) Data logger, to automatically record data measured by strain gauge, LVDT and Load Cell, (4) Strain gauge to

ISSN 1533-9211

DOI 10.17605/OSF.IO/J67EK

measure steel strain and concrete strain, (5) Deflection measuring instrument (LVDT / Linear Variable Displacement Transducer). The setup of the testing tool used is as shown in Figure 5.

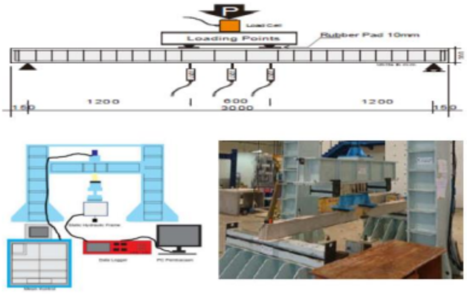


Figure 5: Testing instrument setup

The testing program is carried out with the following procedure:

a. The manufacture of test specimens is carried out sequentially by preparing steel formwork, assembling reinforcement, installing strain gauges, assembling plastic bottles for holes formation, casting test beams, and maintaining test objects.

b. Test beam test, which produces data on strain, maximum stress, and deflection through a PC by a series of strain gauge and LVDT test equipment. (Linear Variable Displacement Transducer). The series of equipment can be seen in Figure 6.

Figure 6: Test beam testing process

From the results of testing on 18 test beams, several parameters of the beam will be analyzed including stiffness, ductility, failure model, and horizontal shear force. In addition, the crack behavior of the beam is observed directly during the testing process, which aims to determine the crack pattern and its development at each stage of loading. The method used in observing the crack pattern is by measuring the width of the instantaneous crack that occurs and making a drawing/sketch on the test object. The failure mode was also observed, namely observing the possible form of failure that occurred between flexural failure and shear failure.

3. RESULTS AND DISCUSSION

To perform a comparative analysis of the various parameters of the 6 variations of girder beams tested, first a comparison of the limit moment capacities of each beam is presented as summarized in table 5.

Table 5: Comparison of ultimate moment (Mu) and weight (W) with variation of beams

Beams	Number of bottles elongated	Number of layers of bottles	Mu (kN.m)	W (Kg)	Mu/W Ratio
NB	0 bottles	0 layers	85.103	419.333	0.203
HB3A	4 bottles	3 layers	84.864	382.667	0.222
HB3B	8 bottles	3 layers	82.349	349.625	0.236
HB3C	12 bottles	3 layers	83.008	315.065	0.263
HB1C	12 bottles	1 layers	83.520	384.185	0.217
HB2C	12 bottles	2 layers	61.060	382.665	0,159

From the results of testing on 6 types of beams, it turns out that there is 1 type of beam that does not meet or approaches the design limit moment value of = 83.52 kNm. Therefore, in the next analysis, the HB2C beam type was excluded as the object of study because it was considered missing data.

The value of the Mu/W ratio for all types of holes beams shows a higher ratio value than normal beams. Especially for holes beams with the number of bottles in the longitudinal direction HB3A, HB3B, and HB3C the increase in the ratio of Mu/W to normal beams (NB) is 9.3%, 16.1% and 29.8%, respectively. Meanwhile, the value of the Mu/W ratio in the HB1C and HB3C holes beams was 7.1% and 29.8% higher, respectively, compared to the Mu/W ratio in the normal beam (NB). This shows that the performance of the hollow beam is effective, both for variations in the number of bottles in the longitudinal direction and variations in the number of bottle layers. This finding is in line with the results of Syahrul Sariman's research [6]. For the ratio of weight reduction of holes beams to normal beams, in this study there was a reduction in the weight of HB3A, HB3B and HB3C to NB respectively 8.7%. 16.7% and 26.6%. While on the HB1C beam the weight reduction of NB is 8.1%. And from the results of the weight reduction test on 4 types of holes beams it does not affect the ultimate moment capacity significantly. This is more conservative than the research of Ilham Permana et al. as described earlier [7]. This phenomenon is also relevant and in line with the research results of Sivaneshan P. and Harishankar S. which have been described above [8]. The stiffness of each test beam is the ratio between the load at the initial crack (P_{cr}) and the deflection at the initial crack (δ_{cr}). The stiffness value (k) of each type of beam tested in this study can be seen in table 6.

Table 6: Stiffness value of each type of beam

Beams	P_{cr} (N)	δ_{cr} (mm)	K (N/mm)
NB	16,061	1.13	14,276.09
HB3A	16,194	1.30	12,553.10
HB3B	15,927	1.50	10,618.00
HB3C	15,928	1.56	10,177.51
HB1C	15,727	1.26	12,531.47

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ISSN 1533-9211

DOI 10.17605/OSF.IO/J67EK

From the beam stiffness value above, it turns out that the smallest stiffness value for the beam with 3 layers of bottles occurs in the HB3C beam with a stiffness value of 10,177.51 (71% of the stiffness value in NB), and the largest stiffness value occurs in the HB3A beam of 12,553.10 (87.96% of the stiffness value on NB). While the HB1C beam stiffness value is 12,531.47 (87.78% of the stiffness value in NB). It is interesting that with approximately the same holes volume (containing 24 bottles), the stiffness of the HB3A holes beam was also not significantly different from that of the HB1C holes beam, although the bottle placement formation was different. This brings us closer to the conclusion that the stiffness value of the holes beam depends on the total area of the holes in the beam.

The cross-sectional ductility of the beam is expressed as the ratio between the strain that occurs when the concrete compression reaches the limit value (Δ_{max}) and the strain when the steel reinforcement reaches the yield state (Δ_y). The ductility value (μ) of each type of beam tested in this study can be seen in table 7.

Table 7: Ductility value of each type of beam

Beams	P_{max} (kN)	Δ_{max} (mm)	Δ_y (mm)	$\mu = \frac{\Delta_{max}}{\Delta_y}$
NB	139.480	27.13	12.757	2.127
HB3A	139.478	27.05	13.485	2.006
HB3B	135.546	27.10	13.695	1.979
HB3C	136.812	25.70	14.840	1.732
HB1C	137.942	27.03	13.210	2.045

From the data in table 7, it can be seen that the ductility value of the hollow beam is relatively the same as the ductility value of the normal beam. Even the HB3A and HB1C beams have ductility values that are close to normal beams (NB), which is 99%. While the ductility of HB3B and HB3C beams have ductility values of 94% and 84%, respectively, of normal beam ductility (NB). The phenomenon that the ductility of the HB3A beam and HB1C beam is the same, gives an illustration that the ductility value of the holes beam depends on the total area of the holes in the beam, because both types of beams use the same number of bottles as much as 24 pieces. Early failure is a failure in the test beam that cannot reach its flexural capacity. The failure was initially initiated by the occurrence of cracks in the beam body at 1/4 the length of the beam span then continued with spalling on the beam body with increasingly wide cracks, as shown in Figure 7.

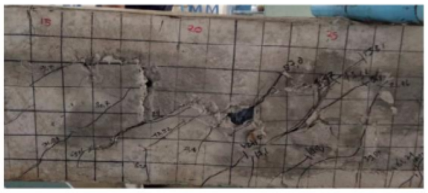


Figure 7: Spallings on the beam body

The phenomenon of spalling on the beam body shows a tendency to be caused by the thinness of the concrete blanket due to the displacement of the holes mold (bottle) during the casting process. Of the 18 samples tested, there were 7 samples that experienced premature collapse, which can be seen in table 8.

Table 8: List of beams experiencing premature collapse

No.	Beams	P_{max} (kN)	$P_{theoretical}$ (kN)	Description
1	$HB2C_1$	91.76	131.90	premature collapse
2	$HB2C_2$	93.30	131.90	premature collapse
3	$HB2C_3$	99.89	131.90	premature collapse
4	$HB3B_1$	101.49	132.10	premature collapse
5	$HB3B_2$	118.49	132.10	premature collapse
6	$HB3C_2$	94.03	132.10	premature collapse
7	$HB3C_3$	99.03	132.10	premature collapse

From the maximum force capacity produced above, it can then be calculated the effective width (b') of each beam achieved in the test. For example, for the $HB2C_1$ beam, the measurement results are as follows:

$$P_{max} \text{ (test)} = 91.76 \text{ kN; Mu (test)} = 32.4491 \text{ kNm, and } V = 46.6951 \text{ kN}$$

By trial and error, look for the value of b' with a target value of $\sigma_{ult} = 18,2178$ MPa

Retrieved: for b' = 11.0854 mm: $y_a = 173.43$ mm, and $y_b = 176.57$ mm, and the cross-sectional distance of the crack with the neutral axis y = 66.567 mm

Obtained: $I = 596{,}379{,}721.25 \text{ mm}^4$, and $G = 2{,}308{,}559.04 \text{ mm}^3$

The b' value obtained is 11.0854 mm, meaning that the maximum force value (Pmax) that can be achieved is only 91.76 kN, because the effective width of the beam (b') that occurs is only = 11.0854 mm. While the thickness of the concrete cover plan is 10 mm on each side, or 20 mm for two sides of the beam. This indicates that there is a displacement of the bottle in the cross section when the casting is carried out, so that the concrete cover is thinned. In the same way, the effective width is obtained for 7 beams that experience premature failure as shown in table 9.

Table 9: P_{max} and b' on the beam experiencing premature collapse

No.	Beams	P_{max} (kN)	b' (mm)	Description
1	$HB2C_1$	91.76	11,08	premature collapse
2	$HB2C_2$	93.30	11,29	premature collapse
3	$HB2C_3$	99.89	12,20	premature collapse
4	$HB3B_1$	101.49	10,62	premature collapse
5	$HB3B_2$	118.49	12,43	premature collapse
6	$HB3C_2$	94.03	9,79	premature collapse
7	$HB3C_3$	99.03	10,32	premature collapse

From the calculation of the effective width of the 7 hollow beams that experienced premature failure as shown in table 9 above, all of them experienced a reduction from the planned concrete cover. This indicates that the premature failure tends to be caused by the reduced thickness of the concrete cover due to the displacement of the bottle during casting. Visually the thinning of the concrete blanket is shown in Fig. 8.

Figure 8: Measurement of concrete blanket thickness on HB2C₁ and HB2C₂ beams

The shear stress (σ_b) that occurs in the early damaged beam exceeds the limit stress value (σ_{ult}). For example, the stresses that occur in the HB2C$_1$ beam can be calculated as follows:

P_{max} = 91.76 kN

At 1/4 the length of the beam;

$M = 0.7919 + 0.345\ P = 0.7919 + 0.345 \text{ x } 91.76$

$= 32.449$ kN.m = 32,449,000 kN.mm

$V = 0.8151 + 0.5\ P = 0.8151 + 0.5 \text{ x } 91.76$

$= 46.695$ kN = 46,695 N.

By trial and error, look for the value of b' with the target value of the ultimate stress σ_{ult}= 18, 2178 MPa

Retrieved: for b' = 11.0854 mm,: y_a = 173.43 mm, y_b = 176.57 mm, and the cross-sectional distance of the crack with the neutral axis y = 66.567 mm

Obtained: I = 596,379,721.25 mm^4, and G = 2,308,559.04 mm^3

The stress that occurs, is calculated by:

$$\sigma_y = \frac{f}{2} \pm \sqrt{\left(\frac{f^2}{2} + v^2\right)}$$

Where:

$$f = \frac{M.y}{I} = \frac{32{,}449{,}000\,x(66.567)}{(596{,}379{,}721.25)} = 3{,}62 \text{ MPa}$$

$$v = \frac{V.G}{I.b} = \frac{(46{,}695)\,x(2{,}308{,}559.04)}{(596{,}379{,}721.25)\,x(11.0854)}$$

$$\nu = \frac{107{,}798{,}164{,}370}{6{,}611{,}107{,}761.90} = 16.306\,\text{MPa.}$$

$$\text{So: } \sigma_y = \frac{3.64}{2} \pm \sqrt{\left(\frac{3.62^2}{2} + 16.306^2\right)}$$

$$\sigma_y = 1.82 \pm 16{,}51 = 18{,}32\,\text{MPa} > \sigma_{ult} = 18{,}2178\ \text{MPa}$$

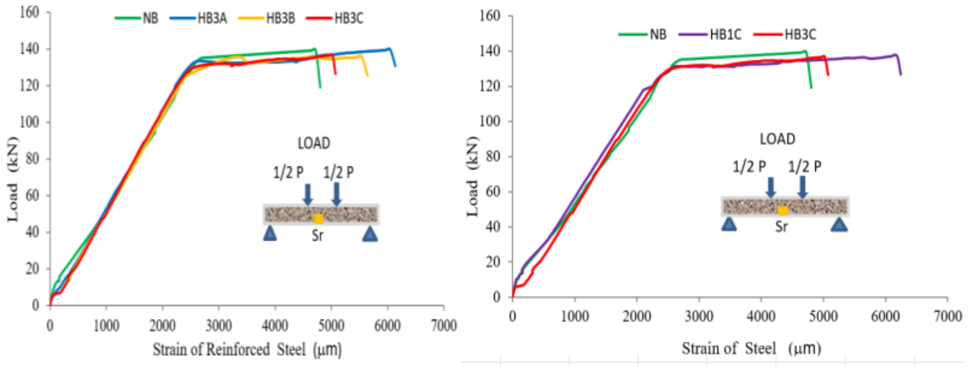
So that the HB2C$_1$ beam experiences premature collapse.

While the cross-sectional shear stress that occurs in the beam that does not experience premature failure, can be seen in table 10.

Table 10: P$_{max}$ and shear stress in undamaged beams

No.	Beams	P$_{max}$ (kN)	σ_b (MPa)	σ_{ult} (MPa)	Description
1	HB3A$_2$	139.48	17.1000	18.2178	don't collapse early
2	HB3B$_3$	135.50	16.5902	18.2178	don't collapse early
3	HB3C$_1$	136.81	17.3703	18.2178	don't collapse early
4	HB1C$_2$	137.08	18.1540	18.2178	don't collapse early

By trial and error method, the researcher found that the value of b' which indicates the value of the effective width of the beam in the cross section of the holes so that premature collapse does not occur is at least b' = 14.3712 mm. Observations on the relationship between the limit load and the reinforcement strain can be seen in Figure 9.



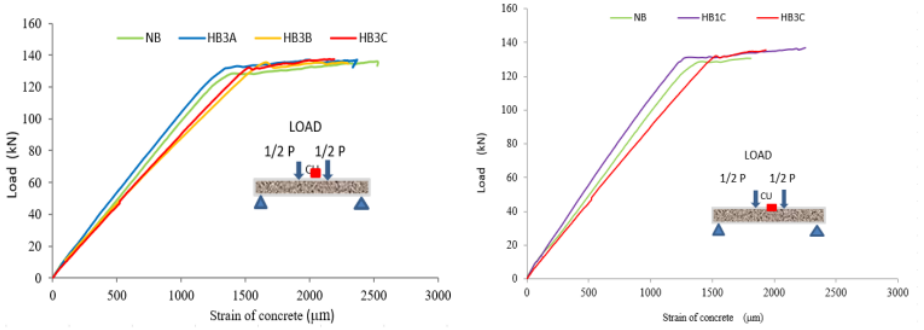
(a) NB, HB3A, HB3B, and HB3C Beams (b) NB, HB3C and HB1C

Figure 9: Relationship between load (Pu) vs Reinforcement Strain (ε_r)

While the relationship between the limit load and the concrete strain as shown in Figure 10.

ISSN 1533-9211

DOI 10.17605/OSF.IO/J67EK



(a) NB, HB3A, HB3B, and HB3C Beams (b) NB, HB3C and HB1C

Figure 10: Relationship between load (Pu) vs Concrete Strain (ε_c)

From the graph of the relationship between the limit loads with both reinforcing strain and concrete strain shown in Figure 9 and Figure 10 above, the difference in the magnitude of the limit load at the time of concrete failure and steel fatigue is not significant, which means that the failure of the concrete material is almost simultaneously with the achievement of yield stress in the reinforcing steel. This phenomenon shows that the composite action between the concrete material and the reinforcing material is quite perfect.

4. CONCLUSION

This study has shown several significant phenomena to be concluded and require attention in the manufacture of hollow reinforced concrete beams, as follows:

1. Early failure will occur in hollow reinforced concrete beams, if the effective width of the beam is less than 14,3712 mm, which causes the concrete cover to thin. The reduction in the effective width of the hollow beam is mostly due to the displacement of the bottle in the horizontal direction, so that it will push the concrete mortar on the side of the beam and result in thinning of the concrete blanket. As a result of thinning the concrete blanket on the sides of the beam, the shear stress will increase rapidly beyond the allowable cross-sectional stress, so that the beam will experience premature failure. This needs to be a concern when casting so that the position of the bottle does not experience displacement in the beam.
2. The beam stiffness values that occur in the HB3A beam and HB1C beam are approximately the same value. This finding shows that with approximately the same volume of holes (using 24 bottles), will give the same stiffness value, although the formation of bottle placement is different. This shows that the stiffness of the hollow beam depends on the total volume of the hole in the beam.
3. The phenomenon that the ductility of the HB3A beam and HB1C beam is the same, indicates that the ductility value of the hollow beam depends on the total volume of voids in the beam, because both types of beams use the same number of bottles as 24 bottles.

Acknowledgement

This research was fully supported by the Head of the Concrete and Materials Laboratory, University of Bosowa Makassar, along with all the laboratory staff. Thank you for the support and assistance from various parties, so that the research team was able to complete the testing in the laboratory to the final stage of this manuscript.

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