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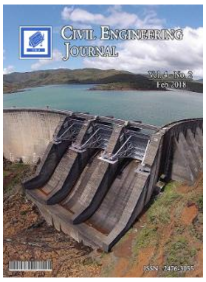

Flexural Behaviour of Lightweight Foamed Concrete Beams Reinforced with GFRP Bars

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Abstract

Lightweight foamed concrete is a type of concrete characterized by light in self-weight, self-compaction, self-leveling, thermal isolation, and a high ratio of weight to strength. The advantages of GFRP bars include lightweight, high longitudinal tensile strength, non-conductivity, and resistance to corrosion. This study investigated the behavior of LWFC beams reinforced with GFRP bars under flexural loading. A total of four reinforced concrete beams were cast, where it consisted of two LWFC beams and two normal weight concrete beam which acted as control specimen. One of the lightweight foamed concrete beams and the normal concrete beams is reinforced with two GFRP bars and the other reinforced with two steel bars. All beams were designed with singly reinforced of two bars of diameter 12 mm. The LWFC beams were with cement to sand ratio (1:1) and average dried density of 1800± kg/m^3. The main variables considered in this study was type of concrete and type of reinforcement. The flexural parameters investigated are ultimate load, crack width, ductility, deflection and stiffness. The lightweight foamed concrete beam reinforced with GFRP bars showed deflection and crack width greater than in beam reinforced with steel bars due to the low modulus of elasticity of GFRP bars.

Keywords: Foamed Concrete; GFRP Bars; Flexural Behavior; Light Weight.

1. Introduction

Lightweight foamed concrete is a building material characterized by satisfactory properties such as lightweight, thermal and sound isolation. The first attempt to produce foamed concrete was back to 1923, when J. A. Eriksson got a patent in the foamed concrete. The future need for construction materials which are light, durable, economic and more environmentally sustainable has been specified by many researchers around the world [1-3]. Significant improvements in the production process and the quality of foaming agents over the last fifteen 15 years have led to increased production and expansion the range of its applications [4-7].

The properties and structural behavior of lightweight foamed concrete such as compressive strength, shear and flexural behavior has been studied by several researchers[8, 9, 10].In (2011) Tan, et al. studied the flexural behavior of two reinforced lightweight foamed concrete beams with hardened density (1750 ± 50 Kg/m^3). They found that the ultimate load of reinforced lightweight foamed concrete beams lower than normal concrete beam by (22%) to (24%) [9].

In (2005) Jones and McCarthy studied the scale of two reinforced coarse fly ash foamed concrete beams (200 mm x 300 mm x 2000 mm) with densities (1400 and 1600 Kg/m^3) under flexural loading compared it with a 25 MPa normal weight concrete beam. They found that the deflections at the failure of foamed concrete were up to 2.3 times greater than that of the normal concrete beam [11]. In 2017, Lee et al. presents the experimental results on flexural behavior of

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reinforced concrete beams and slabs made of lightweight foamed mortar with density ranged from 1700 to 1800 kg/m^3. Beam specimens consist of seven lightweight foamed mortar beams and three normal weight concrete beams acted as the control sample. Four types of lightweight foamed mortar with different cement-sand ratios and water-cement ratios designated as LW-1, LW-2, LW-3 and LW-4 were produced in order to achieve targeted compressive strength of 20 MPa at 28 days for structural usage. The results showed that reinforced lightweight foamed mortar beams sustained about 8% to 34% lower ultimate load as compared to normal weight reinforced concrete with same reinforcement configuration [12]. In (2005) Sam and Swamy studied the results of tested concrete beams reinforced with glass fibers reinforced polymer GFRP bars as main reinforcements under flexural load. The experimental results show that beams reinforced with GFRP bars experienced lower ultimate load, lower stiffness, and larger deflection at the same loads level compared with control beam due to the low elastic modulus of the GFRP bar [13]. In (2014) Roja et al. investigated the flexural behavior of concrete beams reinforced with GFRP bars. From tested beams showed a reduction of 15.1 percent in ultimate load carrying capacity was found in beams reinforced with GFRP bars when compared with the beams reinforced with steel bars [14].

This study is about the investigation of flexural and serviceability of lightweight foamed concrete and normal concrete reinforced with the same number of GFRP and steel bars.

2. Materials and Methods

2.1. Materials and Mix Proportion

A total of four reinforced concrete beams were cast, where it consisted of two lightweight foamed concrete beams and two normal weight concrete beams. For lightweight foamed concrete beams the target density was 1800 kg/m^3.The ingredients of the lightweight foamed concrete consisted of Type I Ordinary Portland Cement (OPC), silica sand, silica fume, water and pre-foamed foam. The pre-formed foam was produced by dilute a foaming agent liquid with water into the foam generator in a ratio of 1:30 based on volume. And after the density of mix is checked, steel fiber (0.4%) and polypropylene fiber (0.2%) volume fraction are added to the mix.

Table 1. Mix Proportion of Lightweight Foamed Concrete

Cement kg/m^3	Sand kg/m^3	Water Lt./ m^3	Sp* %	Silica fume %	Steel fiber %	Polypropylene fiber
733.8	733.8	226	0.8	10	0.4	0.2

Table 2. Mix Proportion of Normal Concrete

Cement kg/m^3	Sand kg/m^3	Coarse aggregate kg/m^3	Water kg/m^3	w/c
450	750	790	180	0.4

2.2. GFRP Reinforcement

The GFRP bars used were the high durability, which manufactured by Nanjing Fenghui Composite Material Co., Ltd. with 12 mm diameter, an average tensile strength of (758 MPa), tensile modulus of elasticity of 46 GPa, and ultimate deformation of 2.8%. The surface of the GFRP bar is characterized by a helical fiber strand with tightly wrap to develop mechanical bond with the concrete, as shown in Figure 1.

Figure 1. The geometry of GFRP bars used in this work

2.3. Test Specimens

All beams were designed as under-reinforced simple span to fail by rupture of GFRP bars or steel bars yield. Two 8 mm steel bars were used as top reinforcement to hold stirrups. The beam types were identified as XY. The first term of the identification corresponded to a concrete type (F: foamed concrete, N: normal concrete). The second parameter identifies the main reinforcement bars type (G: GFRP, S: Steel bar). The details of beam reinforcement shown in Table

3 and Figure 2 below. Deformed bars of high tensile steel were used as tension with diameter 12mm and compression reinforcement with diameter 8 mm, as well as steel bars were bended and used as stirrups 8mm@80 mm in shear zone.

Table 3. Reinforcement details

Group	Beam code	Concrete type	Reinforcement type
F group	FG	Foamed concrete	2x12mm GFRP bars
	FS	Foamed concrete	2x12mm Steel bars
N group	NG	Normal concrete	2x12mm GFRP bars
	NS	Normal concrete	2x12mmSteel bars

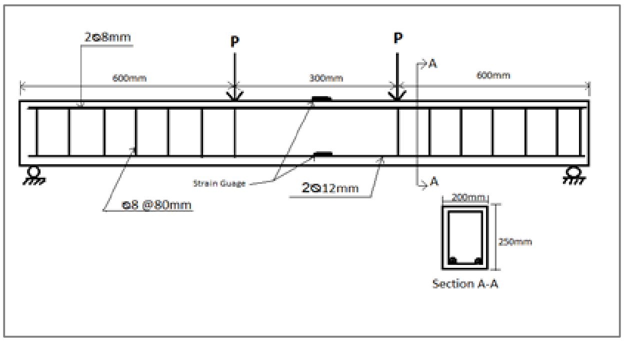


Figure 2. Reinforcement Details of beam

2.4. Test Setup

All beams specimens were tested under four-point bending, with 1500mm total length, 1300mm clear span, and 500mm shear span. The cross section of beam was 200mm width and 250mm height. The deflection readings were taken using three dial gauges were used to measure deflection under beams, two under points load, and one under the center of beam. The cracks of the specimens were mapped and test observations were recorded during loading and at the time of failure. The strain gages, electrical pressure sensors, were used to obtain the tension strain at reinforcement level. Concrete surface strains were measured at the top face of the beam at the middle length of the beam. For each load increment, deflection, crack width, and strain were recorded. Figure 3 shows test setup for beams in this work.

(a)

(b)

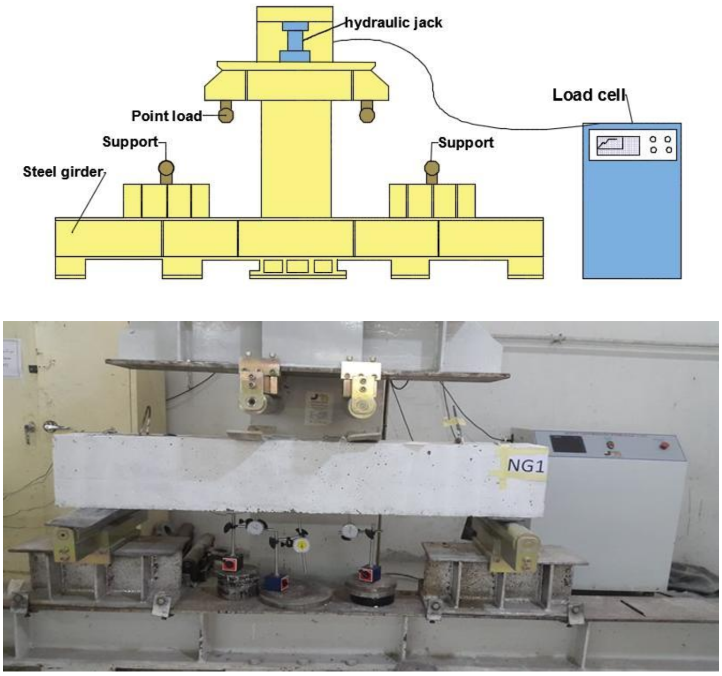


Figure 3. Test Setup (a) Schematic diagram for testing Machine (b) Actual Beam Specimen under Testing

3. Test Results and Discussion

3.1. Load – Midspan Deflection Behavior

The experimental load to midspan deflection curves and failure loads of the steel and GFRP reinforced concrete beams are presented in Table 4 and Figure 4 and 5.

Table 4. Test results

Beams	Ultimate Load (KN)	Crack Load (KN)	Ultimate Deflection (Δu mm)	Service Load (KN)	Crack width at service load (mm)	Deflection at service load (mm)	Stiffness at service load (KN)
FG	145	18	22.4	50.75	1.1	5.39	8.5
FS	130	25	10.6	45.5	0.07	3.09	14.65
NG	140	20	17.1	49	1.4	5.4	9.2
NS	147.8	30	14.2	51.45	0.1	2.68	18.65

As expected, due to the linear-elastic behaviors of GFRP bars, the GFRP reinforced beams showed no yielding. The curves went up almost linearly until the crushing of concrete. Initially, the first phase of the curve the un-cracked part for all beams show relatively linear elastic behavior up to the crack load when the concrete cracked at the tension zone. In this phase, the deflection is very little and neglected because of the high stiffness of the member. In the second stage of the curve expresses the behavior of the cracked concrete beams with reduced stiffness, as a result of the appearance of cracks gradually that leads to that load dropping and rising which leads to being meandering in the load-deflection curve.

From the load-midspan curve for the lightweight foamed concrete beams, FG and FS, the deflection of beam reinforced with GFRP bars is higher than that beam reinforced with steel bars. Also, from the load-midspan deflection curve for the normal concrete beams, NG and NS, the deflection of beam reinforced with GFRP bars was higher than that beam reinforced with steel bars. This due to the low modulus of elasticity of GFRP bars compared with steel bars. From the load-midspan curve for the beams reinforced with GFRP bars, FG and NG, the deflection of lightweight foamed concrete beam, FG, is greater than the deflection of normal concrete beam, NG. Also, from the load-midspan deflection curve for the beams reinforced with steel bars, the deflection of lightweight foamed concrete beam FS is greater than normal concrete beam. The stiffness of the beams describes the slope of the load-deflection curve of the beam under flexural loading test. From Figure 5a and 5c the stiffness of beams reinforced with GFRP bars is less than that for beams reinforced with steel bars. This is because the low modulus of elasticity of GFRP bars compared with steel bars.

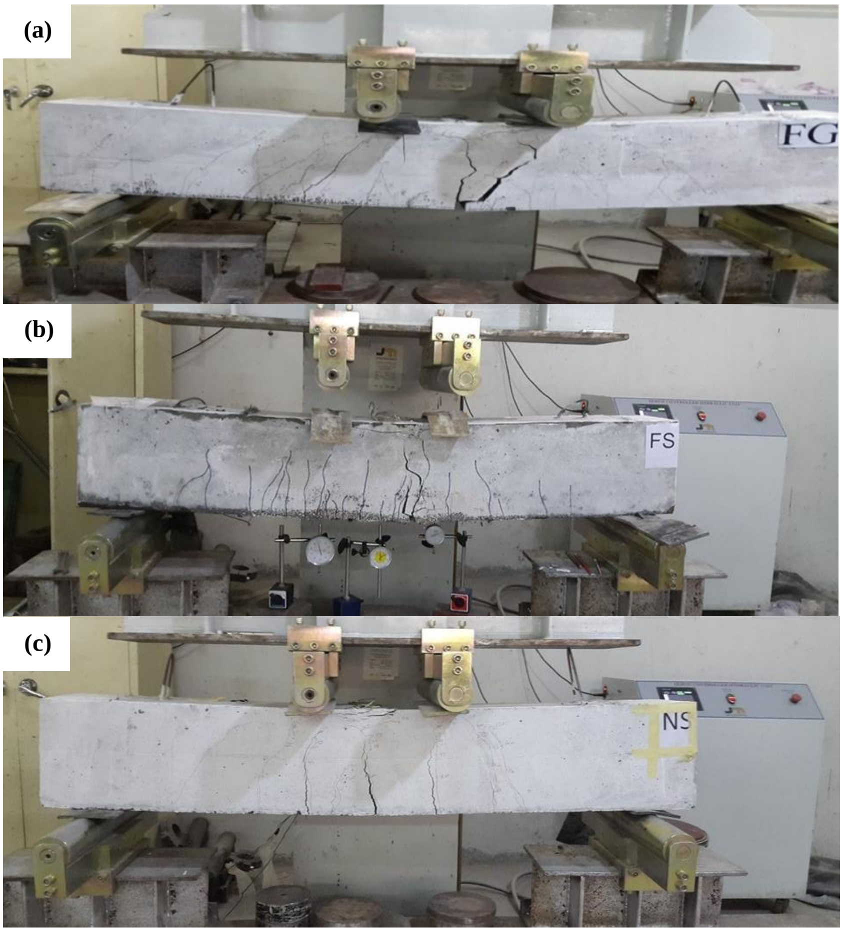
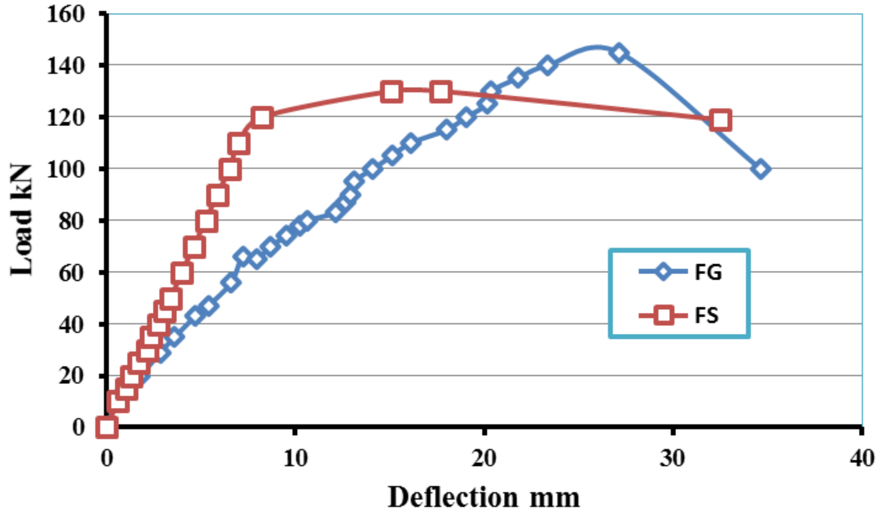
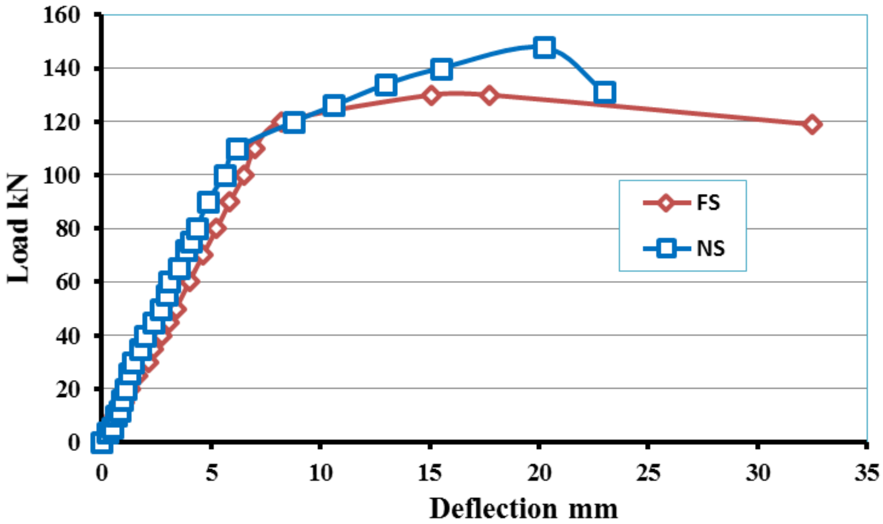


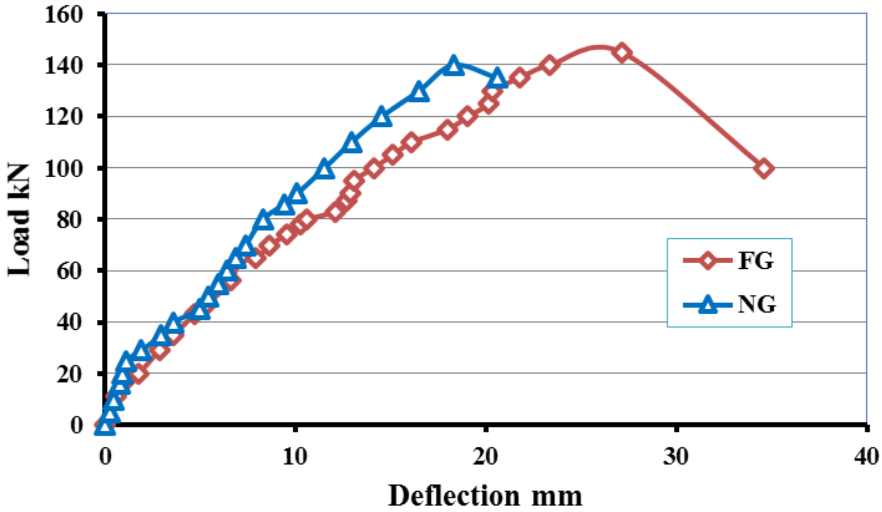
Figure 4. Mid-span deflection for (a) Foamed concrete with GFRP (b) Foamed Concrete with Steel reinforcement and (c) Normal Concrete with Steel Reinforcements



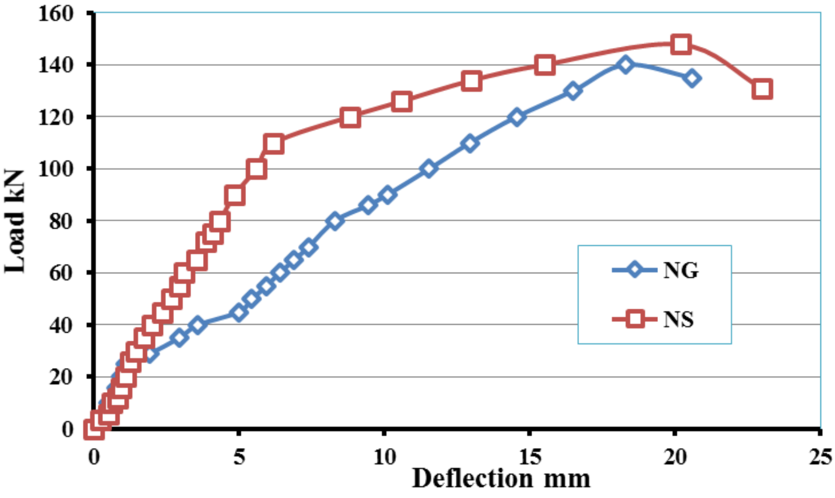
a) Beams FG and FS



b) Beam FS and NS



c) Beams FG and NG

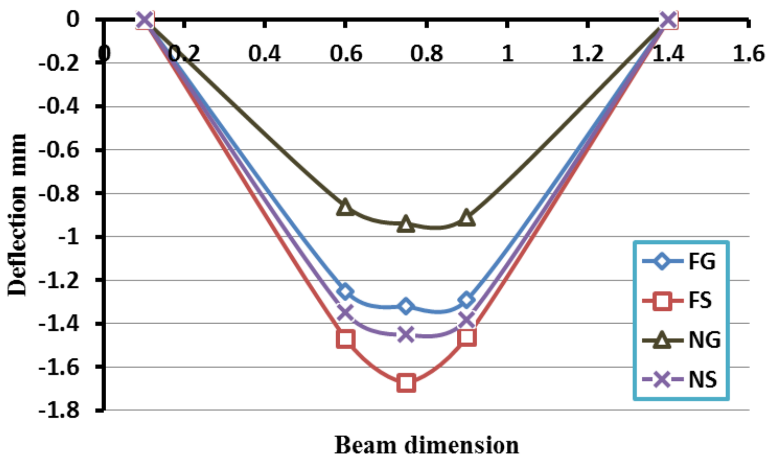


d) Beams NG and NS

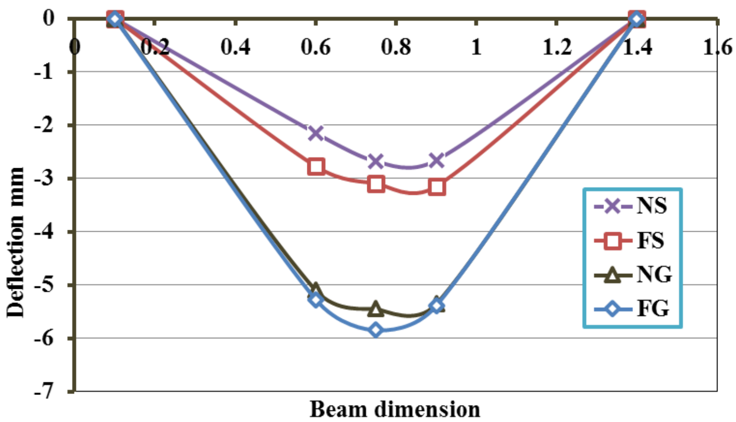
Figure 5. Load-Midspan Deflection of all beams

3.2. Deflection Profile of Beams

For comparison purpose, the deflection profile of all tested beams at first crack load and service load were drowned to recognize the flexural behavior of beams. Figure 6 shows the deflection profile of all tested beams. As seen in figure, at the first crack load the defection of steel reinforced beams is greater than that of GFRP reinforced beams. At the service load (35% of ultimate load) the deflection of GFRP reinforced beams is greater than that steel reinforced beam.



a) Deflection profile at first crack load



b) Deflection profile at service load

Figure 6. Deflection profile for all beams

3.3. Crack Width

As in the traditional steel reinforced concrete beams, the flexural cracks initiate at the pure bending regions when the tensile stress in the concrete exceeds the tensile strength of concrete f_t. Figure 7 shows the variation of crack width with applied load for all tested beams. As shown in Figure 7. The cracks width of GFRP reinforced concrete beam is greater than that in the steel reinforced concrete beams.

The normal concrete beams exhibit crack width greater than of the lightweight foamed concrete beams, this can be related to the presence of steel and polypropylene fibers in the lightweight foamed concrete beams.

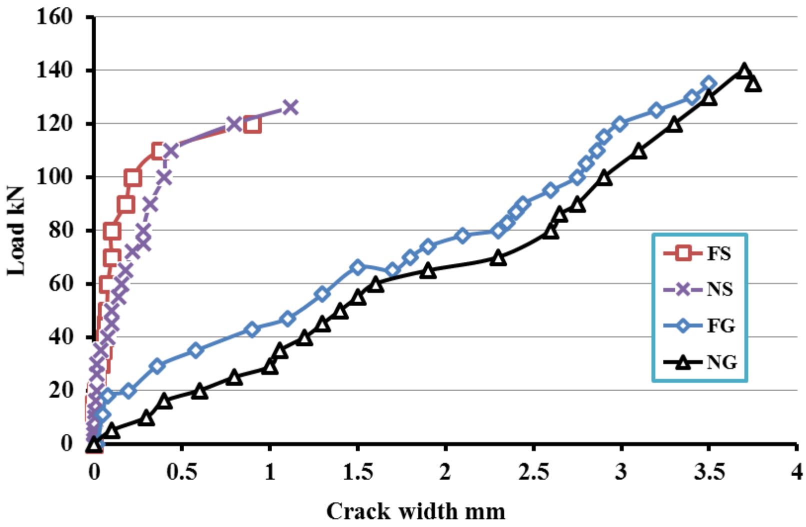
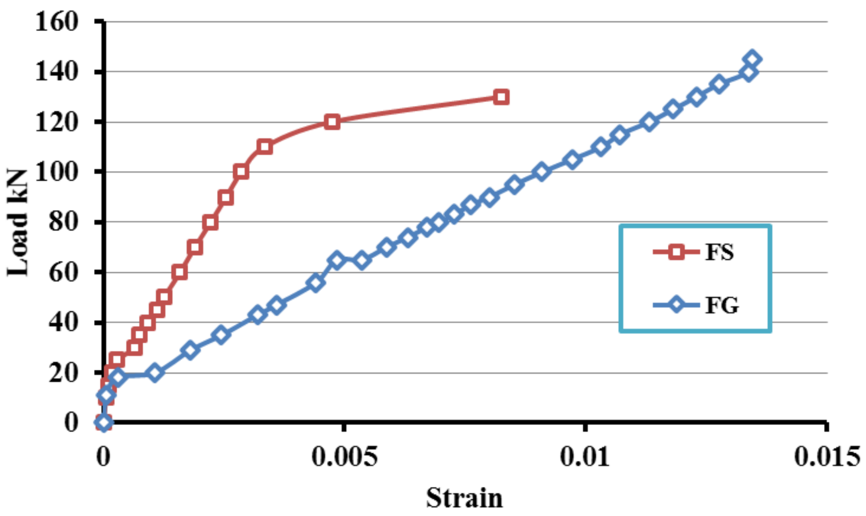


Figure 7. Crack width with load for all tested beams racking ratio of the circular tunnel

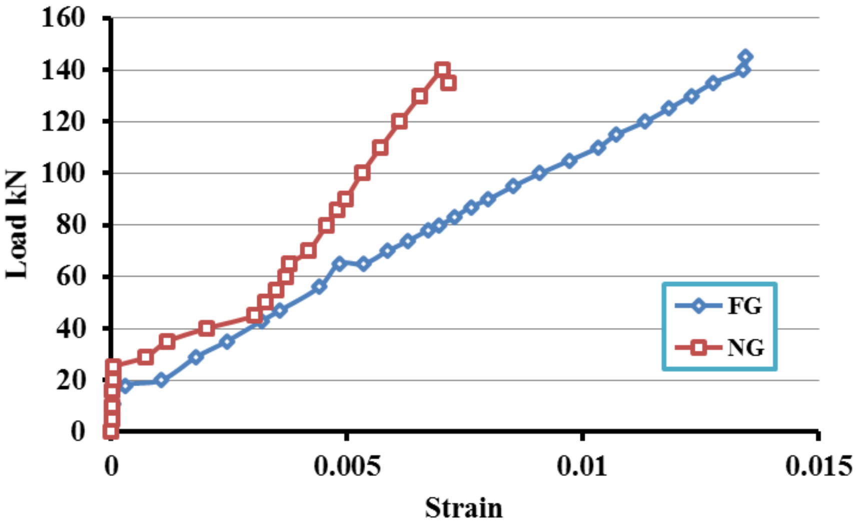
3.4. Main Reinforcement Strain at the Mid-Span Section of Beams

The GFRP strain curve was linear up to the failure without yielding behavior, as seen in Figure 8a and 8c , while the steel strain shows yield behavior before failed. The strain of GFRP bars was higher than the strain in the steel bars, this is because the low modulus of elasticity of GFRP bars. The GFRP bars strain in lightweight foamed concrete beams is greater than that in normal concrete beams.

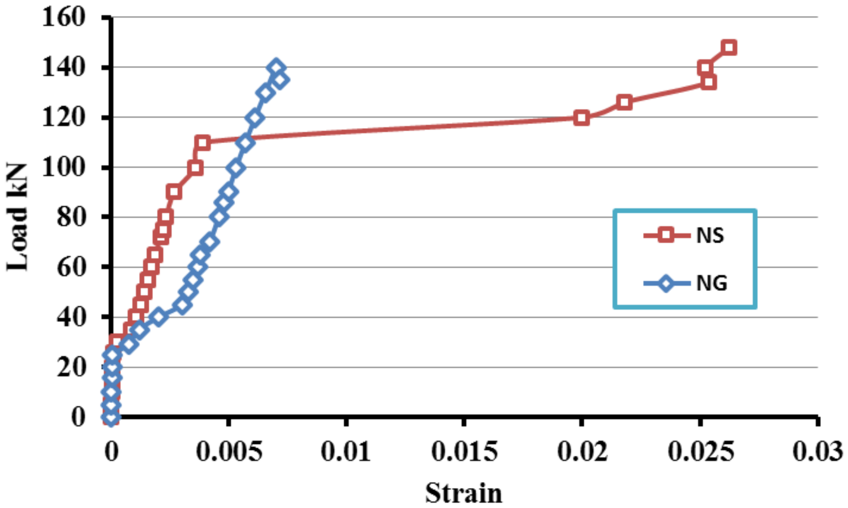
When the first crack forms, the strains increases noticeably, while, the strains in the reinforcement are compatible with the strains in the surrounding concrete, and are therefore of negligible magnitude before cracking.. The magnitude of the increase in strain is highest at the crack, and gradually reduces away from the crack as the tension carried by the uncracked concrete increases. Thereafter the strains between the cracks follow an almost linear relationship with load until failure occurs either by rupture of the rebars or crushing of the concrete somewhere within the constant flexure zone. Moreover, for both types of concrete (normal and foamed concrete) the behavior is almost similar until first crack formation as shown from Figure 8 (a, b and c).



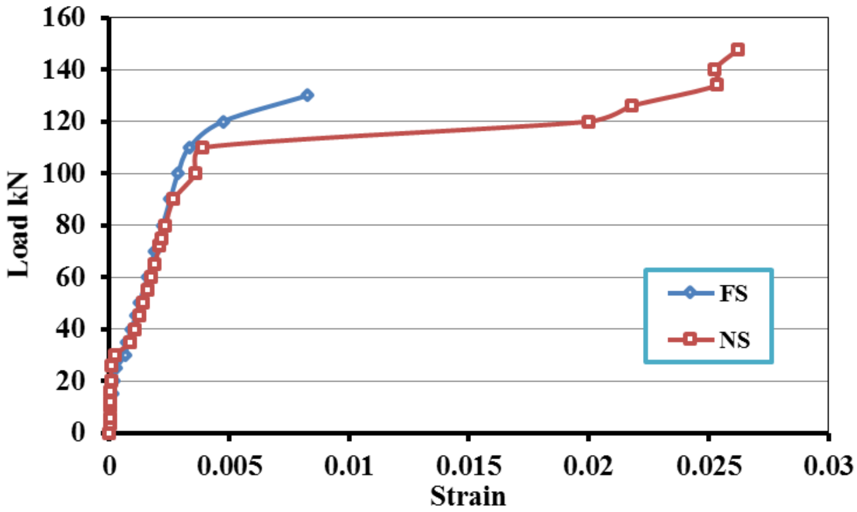
(a) Load–Strain for FS and FG beams



(b) Load–Strain for FG and NG beams



(c) Load–Strain for NS and NG beams

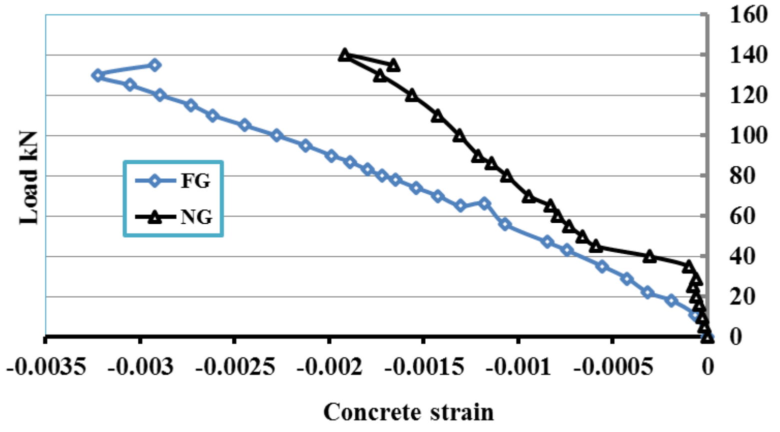


d) Load–Strain for FS and NS beams

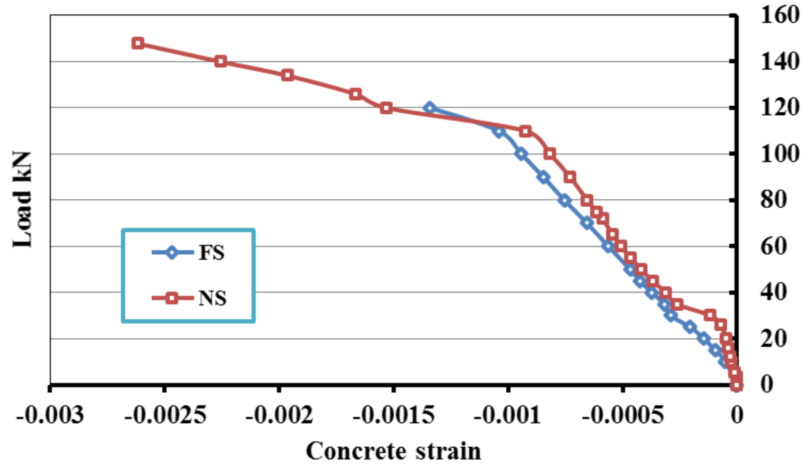
Figure 8. Load–Strain of main reinforcement bars

3.5. Concrete Strain

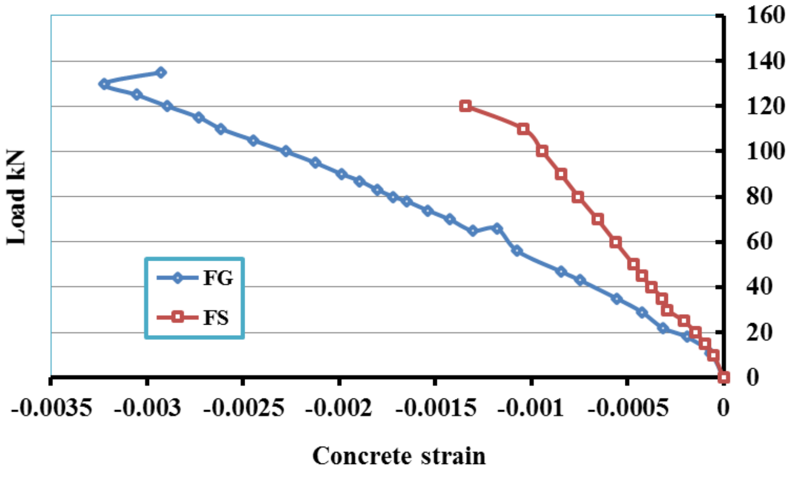
For beams reinforced with GFRP bars, as shown in Figure 9a the lightweight foamed concrete strain was linear and higher than the normal concrete strain. This because the low elastic modulus of lightweight foamed concrete which caused a high deformability, and the addition of fiber make to distribute the stress on a regular basis in lightweight foamed concrete that leads to linear concrete strain. For beams reinforced with steel bars, the lightweight foamed concrete strain was closely similar to the normal concrete strain as seen in Figure 9b below. The concrete strain in the beams reinforced with GFRP bars is greater than the concrete strain in beams reinforced with steel bars as shown in Figure 9c and 9d. Similar to the development of strains in the rebar, the concrete strain is negligible before cracking. With the formation of the first crack at midspan, the concrete strain increases considerably.



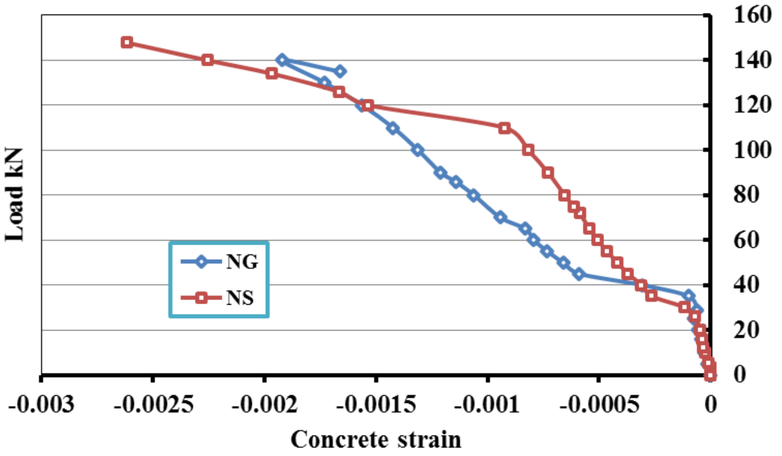
(a) Load-concrete strain curve of GFRP reinforced beams



(b) Load-concrete strain curve of steel reinforced beams



(c) Load-concrete strain curve of LWFC beams



(d) Load-concrete strain curve of normal concrete beams

Figure 9. Load-concrete strain curves

3.6. Ductility and Ductility Index

Ductility is a structural design demand in most design codes. The concept of ductility of a beam is related to its ability to sustain inelastic deformations without loss of its load capacity before failure. The ductility is important in the concrete structure in providing an advanced warning before failure. In steel reinforced concrete beam ductility is defined as the ratio of the deformation at the yield of steel to the deformation at the ultimate capacity of the beam. FRP bars have a linear elastic behavior up to the failure so that the general definition of ductility applied to the stee1 reinforced structures cannot be directly applied to the structures reinforced with FRP bars. Several methods such as the energy-based method or the deformation-based methods have been proposed to estimate the ductility index for FRP reinforced member [15]. ACI 440.1R- 06 recommends that the FRP reinforced concrete beams must be over-reinforced so that they fail by concrete crushing rather than by bar rupture. Therefore, the ductility of the systems is strongly dependent on the properties of the concrete [16].

3.6.1. Energy-Based Method:

Based on the definition of the energy based approach, ductility can be expressed as the ratio of the total energy to the elastic energy. Table 5 shows the ductility index of all tested beams based on the energy method. Naaman and Jeong (1995) suggested the following Equation 1 to estimate the ductility index [17]:

$$\mu_E = \frac{1}{2}\left[\frac{E_t}{E_e} + 1\right] \ldots\ldots \tag{1}$$

Where E_t is the total energy computed as the area under the load-deflection curve; and E_e is the elastic energy computed as the area of the triangle formed below line S, up to the point of failure load of Figure 10.

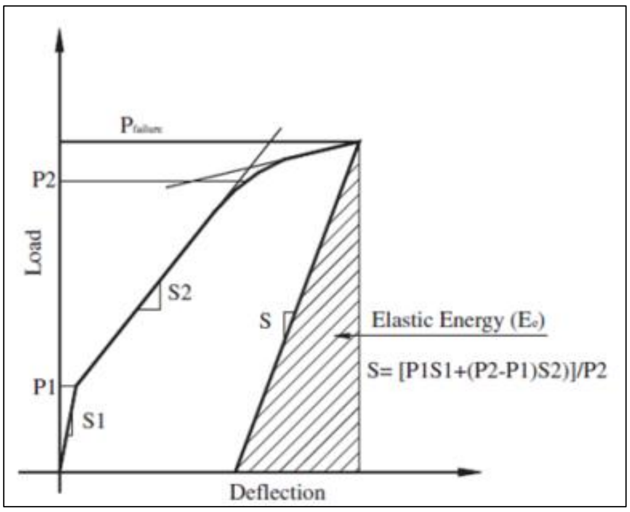


Figure 10. Energy Based Approach [17]

Table 5. Ductility Index of Tested Beams Based on Energy Method

Beams	E_t total energy N.mm	E elastic energy N.mm	μ_E Ductility Index
FG	1488.3	551.6	1.85
FS	592.25	951.95	0.81
NG	999.2	698.14	1.21
NS	417.68	1359.3	0.65

3.6.2. Deformation-based Method:

The deformability based approach takes into account the strength effect as well as the deflection effect on the ductility. It was first introduced by Jaeger et al. (1997) the strength factor and deflection factor are computed in the Equation 2 and 3 [18].

$$Deformability\ factor = strength\ factor \times deflection\ factor$$

$$Strength\ Factor = \frac{Load\ at\ ultimate}{Load\ at\ concrete\ strain\ 0.001} = \frac{P_u}{P_{0.001}} \tag{2}$$

$$Deflection\ Factor = \frac{Deflection\ at\ ultimate}{Deflection\ at\ concrete\ strain\ 0.001} = \frac{D_u}{D_{0.001}} \tag{3}$$

Table 6. The deformability factor of tested beams

Beams	P_u	$P_{0.001}$	D_u	$D_{0.001}$	Strength Factor	Deflection factor	Deformability factor
FG	145	56	22.4	6.61	2.58	3.38	8.774
FS	130	110	32.48	7	1.18	4.64	5.48
NG	140	70	17.1	7.4	2	2.310	4.621
NS	147	110	22	6.2	1.33	3.548	4.741

As shown in the Table 6 the results showed that the deformability factor of lightweight foamed concrete beam reinforced with GFRP bars is more than the deformability factor of normal concrete beams. That can attributed to the addition of steel fiber to the foam concrete which improve the low ductility of foamed concrete reinforced with GFRP bars

4. Prediction of Mid-Span Deflection

ACI-440.1R-06 concluded a modified expression for the effective moment of inertia for the concrete beams reinforced with FRP bars that account the reduction in the tension stiffening by entering the factor β_d in the Equation 4 to 7 above as:

$$I_e = \left(\frac{M_{cr}}{M_a}\right)^3 \beta_d\, I_g + \left[1 - \left(\frac{M_{cr}}{M_a}\right)^3\right] I_{cr} \leq I_g \tag{4}$$

Where β_d is the reduction coefficient for the reduction in the tension stiffening of concrete beams reinforced with FRP bars, the ACI-440.1R committee recommended the relationship for reduction coefficient β_d as:

$$\beta_d = \frac{1}{5}\left(\frac{\rho_f}{\rho_{fb}}\right) \leq 1.0 \tag{5}$$

The mid-span deflection for simply supported beams tested under four-point flexural load as following:

$$\Delta_{mid-span} = \frac{P_a a}{48 E_c I_e}(3L^2 - 4a^2) \tag{6}$$

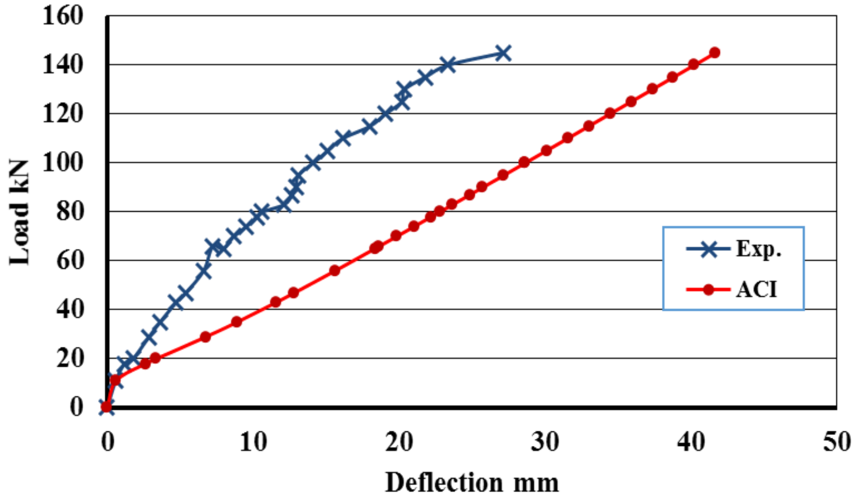


Figure 11. Mid-span deflection of FG beam

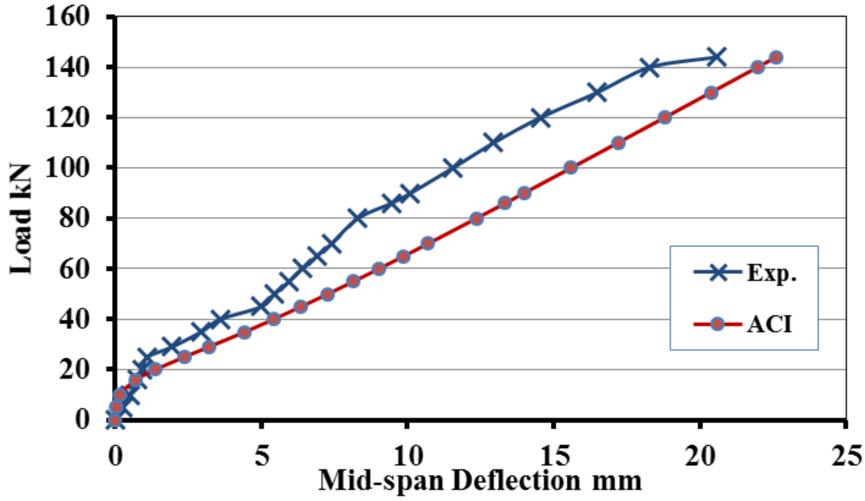


Figure 12. Mid-span deflection of NG beam

Figure 11 and 12. Show the comparison between the predicted model mid-span deflection by ACI-440.1R model and experimental test deflection for beams reinforced with GFRP bars. The experimental mid-span deflection of beam FG and NG is lower than the estimate deflection predict by ACI-440.1R-06 model.

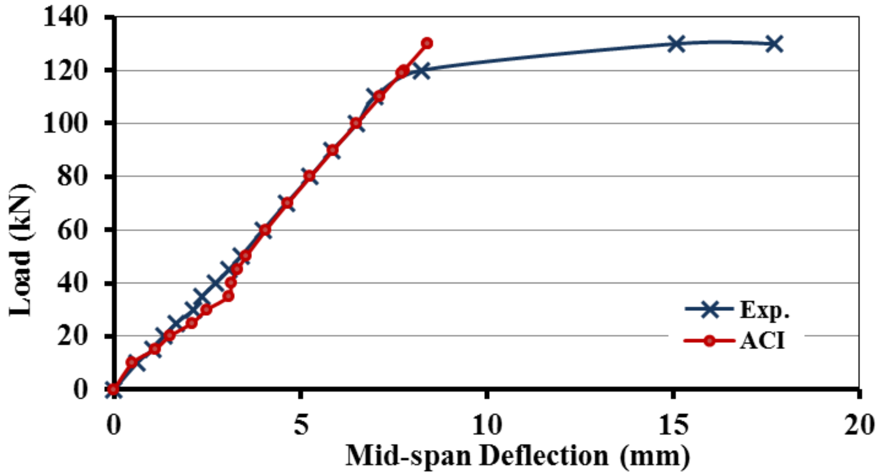


Figure 13. Mid-span deflection of FS beam

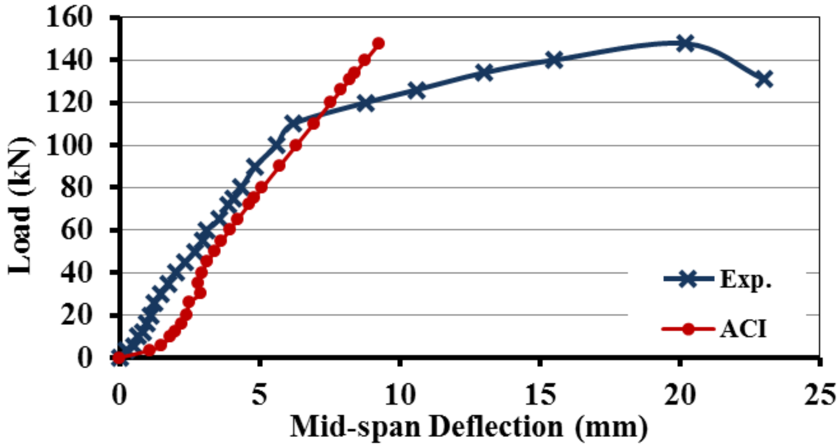


Figure 14. Mid-span deflection of NS beam

Figure 13 and 14. Show the comparison between the predicted model mid-span deflection by ACI-318 equation and experimental test deflection for beams reinforced with steel bars. The prediction model of beams FS and NS shows an estimate mid-span deflection correspond to the deflection of experimental test up to the load at yielding point of steel bar, and after that the prediction model shows an estimate mid-span deflection lower than the experimental test deflection.

Table 7 show that the ratio of the deflection predicted by ACI-440.1R-06 model to the experimental deflection for all tested beams at two load level, at 15% of ultimate load (close to the crack load) and at 35% of ultimate load (service load). After the first crack, the predicted deflection by ACI-440.1R-06 model was lower than the experimental test deflection

5. Prediction of Crack Width

The ACI-440.1R committee derived the formula for calculate the maximum crack width of concrete beams reinforced with FRP bars or steel bars modified by the bond quality coefficient k_b as:

$$w = 2\frac{f_f}{E_f}\beta k_b\sqrt{{d_c}^2 + \left(\frac{s}{2}\right)^2} \tag{7}$$

The k_b coefficient is the degree of the bind between the FRP bars and surrounding concrete. For the case with unknown k_b, the ACI-440.1R committee assumed a conservative value of 1.4.

Table 7. Mid-span deflection at service loads 15% and 35% of ultimate load of all tested beams

Beams	Deflection at 15% Ultimate load			Deflection at 35% Ultimate load		
	Exp.	ACI-440	ACI/Exp.	Exp.	ACI-440	ACI/Exp.
FG	1.77	3.35	1.88	6.1	10.58	1.74
FS	0.62	0.5	0.8	3.09	3.3	1.06
NG1	1.94	1.36	0.7	7.3	7.45	1.02
NS	1.26	2.5	1.98	2.95	3.65	1.24

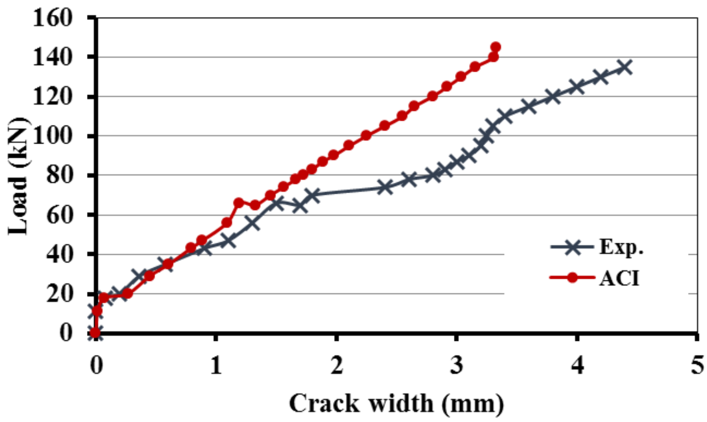


Figure 15. Crack width of beam FG

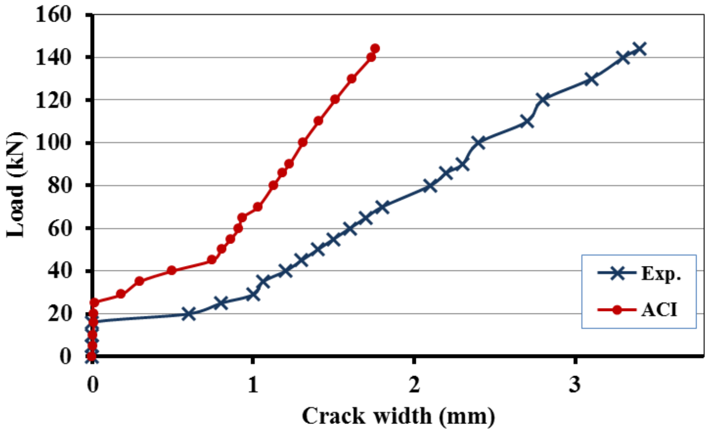


Figure 16. Crack width of beam NG

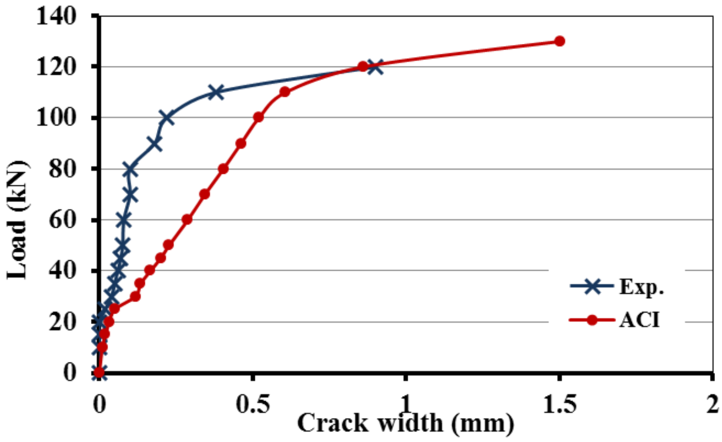


Figure 17. Crack width of FS beam

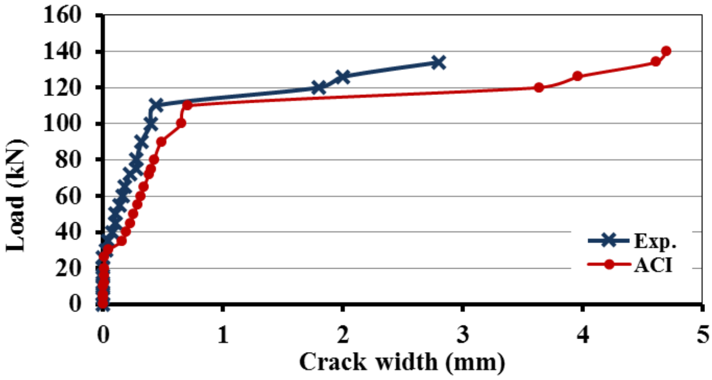


Figure 18. Crack width of NS beam

As shown in the Figures 15 and 16 the measured crack width of lightweight foamed concrete beams reinforced with GFRP bars was closer to the predicted crack width by ACI 440.1R-06 than the normal concrete beams reinforced with GFRP bars. This is due to the presence of steel and polypropylene fibers into the LWFC which play a vital role to control and decrease the cracks.

In the Figure 17 the measured crack width from the experimental test of lightweight foamed concrete beams reinforced with steel bars was less than the predicted crack width by ACI 318-14. This is because the adding of steel and polypropylene fibers into the light weight foamed concrete control the cracks width. In Figure 18. The measured crack width from the experimental test of normal concrete beams reinforced with steel bars was less than the predicted crack width by ACI 318-14.

6. Conclusion

By comparing lightweight foamed concrete reinforced with GFRP bars to normal concrete beams it was found that the increase in the load capacity for lightweight foamed concrete is 3.6% of the load capacity for normal concrete beams. By comparing lightweight foamed concrete beams reinforced with GFRP bars, it was found that the increase in the load capacity for beam reinforced with GFRP is 11.54% of the load capacity for beams reinforced with steel bars. The load-deflection behavior of all the tested beams reinforced with GFRP bars was elastic linear up to the cracking load.

The deflection in beams reinforced with GFRP bars is greater than in the beams reinforced with steel bars. The cracks width of lightweight foamed concrete beams reinforced with GFRP bars is smaller than the cracks width of normal beams reinforced with GFRP bars, due to the presence of steel and polypropylene fiber which control the cracks in LWFC beams. The experimental test of deflection and crack width for all tested beams show a good correspond with ACI model.

7. References

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