Behavior of Non-Coarse Aggregate Polymer Concrete Simply Supported Deep Beams with and without Web Openings

Mohamed Salem, Ahmed Mourad, Amira Shehata

Abstract: This study is aimed to focus the problems of using non-coarse aggregate polymer concrete, which had weak shear strength, on the behavior of structural elements subjected mainly to shear, especially the simply supported deep beams with and without square web openings, casted using non-coarse aggregate polymer concrete, experimentally and numerically. The polymer concrete consists of two parts; the first part is powder without coarse aggregate, while the second part is liquid polymer. The experimental analysis divided into two groups A without web openings and group B with web openings, each group consists of four specimens, one casted using normal concrete, while the other three specimens casted using polymer concrete with non-coarse aggregate. The parameters used in this study were, concrete type, web reinforcement ratio, and web openings. The results from both experimental and numerical show that the polymer concrete failed before web reinforcement reached its yield strain due to the effect of absence of coarse aggregate, which had a significant effect on shear strength, also increasing the percentage of either horizontal or vertical web reinforcement ratio lead to increase the ultimate capacity of polymer concrete specimens. In addition, the FEM gives a good agreement with experimental results. Finally, simplified Strut-and-Tie model is developed for each simply supported deep beam with and without web openings.

Keywords: Deep beams (DB), Polymer Concrete, non-coarse aggregate, Web Openings

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1. Introduction

THE reinforced concrete simply supported deep beams are widely used in most special structures that carry high loads like bridges, pile caps, folded plates, and high-rise buildings. Several researches carried out to investigate the behavior of normal concrete deep beams with and without web openings [1- 10]. Recently, Polymer concrete was used for some structural elements and roads because of its high workability, light weight, good strength, self-compacted, low permeability, and fast curing time. The polymer concrete usually consists of two components, the first component is powder which can be made from recycling building materials. While the second component was a liquid polymer resin. The both mechanical and chemical properties of many types of polymer concrete were studied, while the using of polymer concrete in casting structural elements still needs much researches. For simply supported deep beams, the main important property of polymer concrete is the shear strength because the most failure mode of deep beams was due to shear. For reinforced concrete shallow beams, the shear transfer mechanisms include; the shear in the uncracked compression zone, the dowel action, the interface shear transfer due to the aggregate interlock or the surface roughness of the cracks, and the residual tensile stresses across the cracks, as shown in figure (1)

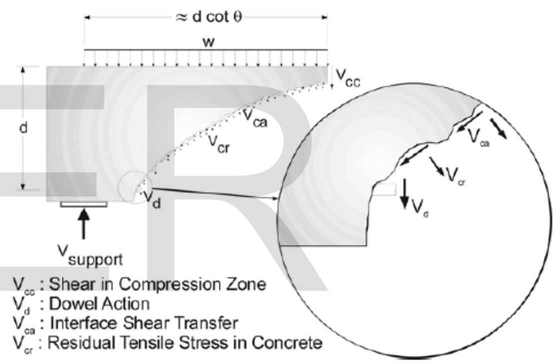

Fig. 1. Shear transfer mechanisms of RC beams

Previous studies of concrete showed that, coarse aggregate produced rough surface at failure, otherwise the fine aggregate produced smooth crack surface. In addition, the ability of rough crack surfaces to transfer shear due to the aggregate interlock. While the absence of coarse aggregate lead to decrease the ultimate shear strength of polymer concrete and suggesting alternative material added to polymer concrete like fiber steel to improve the ultimate shear strength [11- 16].

This study presents the effect of absence coarse aggregate on the behavior of simply supported deep beams with and without web openings casted using polymer concrete. An experimental and numerical study were carried out for this investigation.

2. Experimental Program

2.1. Details of test specimens

Eight simply supported deep beams were casted using polymer concrete without coarse aggregate. The specimens were divided into two groups; A, and B to investigate the behavior of polymer concrete deep beams with and without

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web openings. Etch group consists of four deep beams, one of them was casting using normal concrete and the other three DB were casting using polymer concrete. The main studied parameters are the type of concrete, vertical and horizontal web reinforcement ratio, and web openings.

The first group A includes four deep beams without web openings (DB), while the second group B includes four deep beams with square web opening (DBO), as shown in table (1).

All specimens were reinforced with 10 mm and 12 mm high tensile steel (fy = 460 MPa.) at top and bottom of the DB respectively. While the vertical and horizontal web reinforcement were mild steel ((fy = 240 MPa.) of 6 mm and 8 mm respectively. Both normal concrete and polymer concrete have a compressive strength of 25 MPa. Figure (2) shows Stress-strain curve of Polymer Concrete.

Concrete blocks at the supports with embedded steel plates were casted at both supports to avoid any local failure; The dimensions of tested specimens are 90 mm in breadth, 800 mm in height, and overall length of deep beams is 1350 mm, while the clear span length was 975 mm. as shown in figures (3&4).

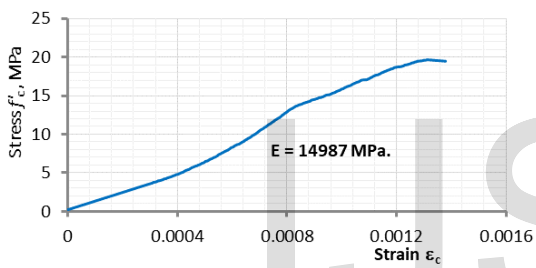
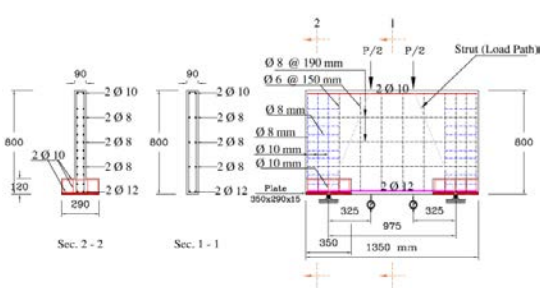


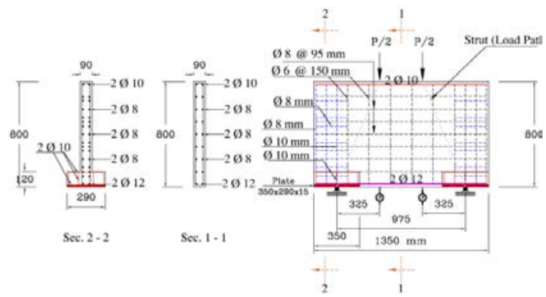
Fig. 2. Stress-strain Curve for Polymer Concrete with non-coarse Aggregate

TABLE (1): DETAILS OF TEST SPECIMENS.

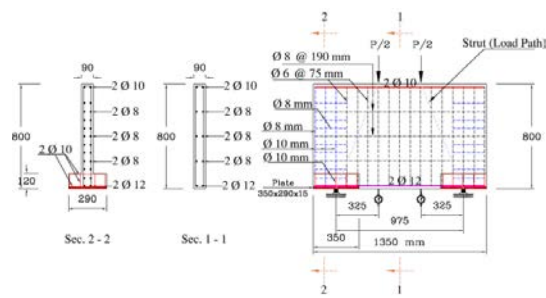
Group	Spec. No.	Conc. type	Opening position	Opening dimensions, mm	F_{cu} MPa	Long. Bottom RFT		Long. Top RFT		Vl. Web RFT			Hz. Web RFT		
						A_s, mm^2	$\rho\% = \frac{A_s}{bd}$	A_s, mm^2	$\rho\% = \frac{A_s}{bd}$	A_{sv}, mm^2	SV	$\rho\% = \frac{A_{sv}}{bS_v}$	A_{sh}, mm^2	Sh, mm	$\rho\% = \frac{A_{sh}}{bS_h}$
A	DB1	normal	--	--	25	226	0.33	157	0.23	56	150	0.41	100	190	0.58
	DB2	Polymer	--	--	25	226	0.33	157	0.23	56	150	0.41	100	190	0.58
	DB3	Polymer	--	--	25	226	0.33	157	0.23	56	150	0.41	100	95	1.16
	DB4	Polymer	--	--	25	226	0.33	157	0.23	56	75	0.82	100	190	0.58
B	DBO1	normal	center	200 x 200	25	226	0.33	157	0.23	56	150	0.41	100	190	0.58
	DBO2	Polymer	center	200 x 200	25	226	0.33	157	0.23	56	150	0.41	100	190	0.58
	DBO3	Polymer	center	200 x 200	25	226	0.33	157	0.23	56	150	0.41	100	95	1.16
	DBO4	Polymer	center	200 x 200	25	226	0.[illegible]	157	0.23	56	75	0.82	100	190	0.58



Details of deep beams DB1 and DB2

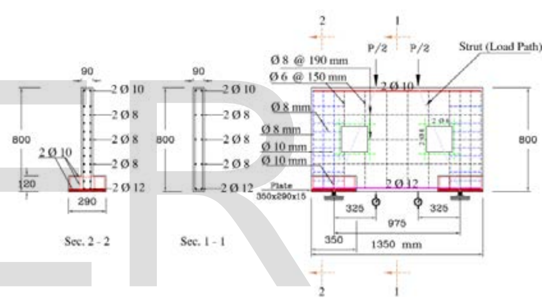


Details of deep beams DB3

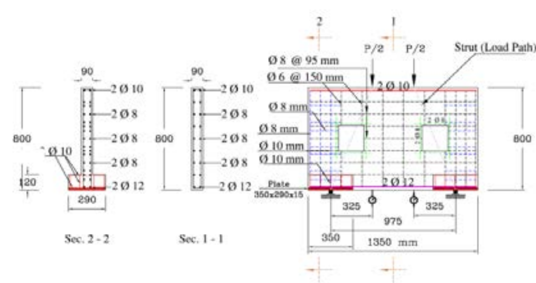


Details of deep beams DB4

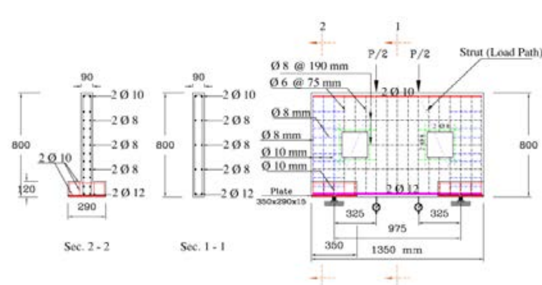
Fig. 3. Details of group A deep beams without web openings



Details of deep beams DBO1 and DBO2



Details of deep beams DBO3



Details of deep beams DBO4

Fig. 4. Details of group B deep beams with web openings

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2.2. Test Setup and measurements

The tested beams were simply supported over two rigid steel girders as shown in Figure (4). The load was applied vertically at the center of a rigid steel beam which, distributed equally on two bearing placed directly on the beam. All tested beams were loaded gradually up to failure. The deflection was measured at two points by using +100 mm linear variable differential transducer (LVDT). While, the crack width was measured by diagonals LVDT's. The strain of steel bars, were recorded using electrical strain gages (S.G.). The beams were applied to a displacement central test performed by using data acquisition online computer system programmed using Lab View software, as shown in Figure (5).

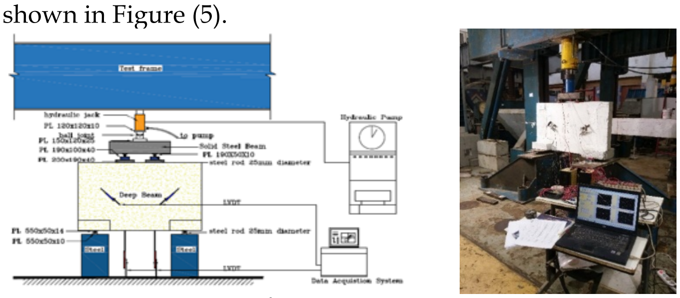


Fig. 5. Test Setup

3. Test Results

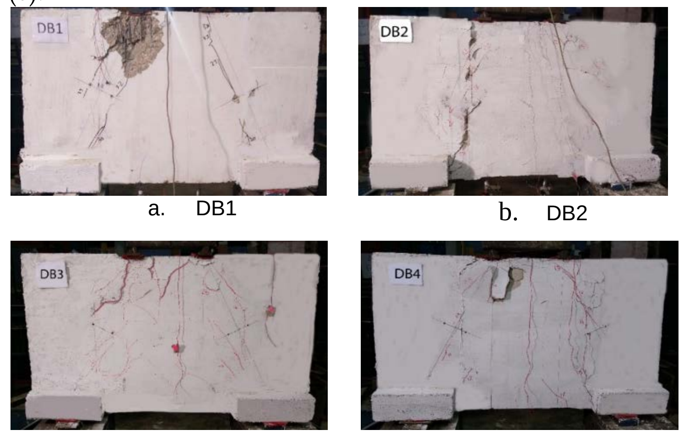
In the following, the results of mode of failure, applied loads versus specimens' deflections will be presented for each group of the experimental program.

3.1. Group A

3.1.1. Mode of failure and cracking patterns

From the results it can be observed that the mode of failure for all specimens was shear failure. The cracks started near the support then became diagonal and extended to the point of applied load at the top also some crushing of concrete under the load points of specimens occurred. The cracks for DB1 nearly parallel to load path (the path from point of applied load to the support), The cracks of polymer concrete specimen DB2 started diagonally near the support then became nearly vertical and extended to the point of applied loads due to the absent of coarse aggregate in polymer concrete. For the DB3 with increasing horizontal web reinforcement ratios the cracks were started diagonally near the supports and extended also diagonally to the point of applied loads. On the other hand, the cracks of DB4 started diagonally near the support then extended vertically at the middle area of the specimens then extended diagonally to the point of applied loads. This different in cracking patterns was due to the effect of web reinforcement ratios in the behavior of specimens which also decreasing the cracking width.

`It can be concluded that the absent of coarse aggregate in polymer concrete lead to decrease the shear friction along the cracked surface because there is no aggregate interlock. In addition, ultimate shear strength of polymer concrete is smaller than the corresponding ultimate shear strength of normal concrete. The cracking patterns are shown in figure (6).



a. DB1 b. DB2

c. DB3 d. DB4

Fig. 6. Cracks Patterns of Group A Tested Beams.

3.1.2. Load – deflection characteristics

The ultimate capacity of tested specimens measured using load cell used for the data acquisition system for each specimen as mentioned in Table (2). The ultimate load for normal concrete specimen DB1 is greater than the ultimate load for all polymer concrete specimens as shown in figure (7). Comparing the ultimate capacity of normal concrete DB1 and polymer concrete with non-coarse aggregate DB2 it can be observed that normal concrete increased the ultimate capacity of specimens by about 70% and decreased the deflection at ultimate due to the high stiffness of normal concrete, as shown in figure (8) On the other hand, the increasing percentage of both horizontal and vertical web reinforcement ratio to the double ratio values lead to increase the ultimate capacity of both DB3 and DB4 by 24% and 21% respectively, as shown in figures (9).

Table (2): Experimental results of group A tested specimens

Spec. No.	Experimental results		% of increasing in $P_u = (P_u - P_{u,DB1}) / P_{u,DB1}$	horizontal web RFT strain %	vertical web RFT strain %
	P_u kN	Deflection at ultimate load, mm			
DB1	653	4.26	70	0.129	0.12
DB2	385	7.8	0	0.054	0.048
DB3	477	6.77	24	0.097	0.085
DB4	465	7.09	21	0.0921	0.084

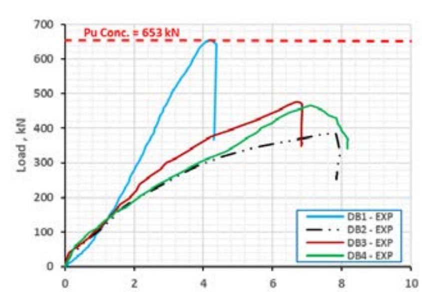


Fig. 7. Ultimate load – Deflection of all Group A Tested Specimens

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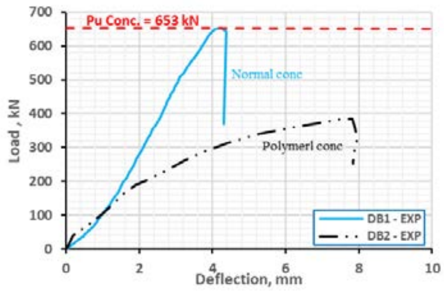
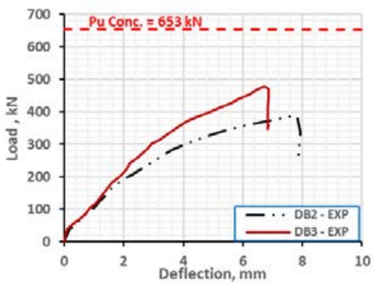
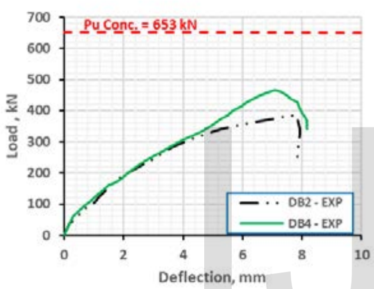


Fig. 8. Effect of Concrete type



a. Horizontal Web Reinforcement Ratio



b. Vertical Web Reinforcement Ratio

Fig. 9. Effect of Web Reinforcement Ratios on ultimate load of Group A

3.1.3. Web reinforcement strain characteristics

Table (2) shows the percentage of web reinforcement strain at ultimate load for each tested specimen. From the results it can be showed that for polymer concrete specimens DB2, DB3, and DB4, the strain in both horizontal and vertical web reinforcement did not reach the yield value of mild steel (0.12%). This means the bond between polymer concrete and web reinforcement is weak, and the shear along the cracks surfaces is also low due to the absence of coarse aggregate. While for normal concrete specimen DB1 the bond between concrete and web reinforcement is perfect. Also, the strain in horizontal web reinforcement is more than the strain in vertical web reinforcement by insignificant value. For this case it is important to use added material to the polymer concrete to improve the bond stress between polymer concrete and reinforcement.

3.2. Group B

3.2.1. Mode of failure and cracking patterns

From the results it can be observed that the mode of failure for all specimens was shear failure and the cracking patterns of all specimens nearly the same. The cracks started near the support then became diagonal to the web opening corners and then extended to the point of applied load at the top around the web openings. Two main cracks were propagated, first main crack started from the support to the interior bottom corner of web opening and the second main crack started from the exterior top corner of web openings to the points of applied loads.

Simply supported deep beams with web openings have a significant problem in shear behavior due to openings effect in overall shear behavior of deep beams. In addition, the absent of coarse aggregate in polymer concrete increased the shear problem of deep beams with web openings because of the decreasing on the shear friction along the cracked surface because there is no aggregate interlock. In addition, the web openings decrease the shear resistance of deep beams and the effect of polymer concrete on shear behavior of deep beam with web opening is observed. It is suggested to add alternative material to polymer concrete to improve the shear strength. as shown in figure (10).

a. DBO1

b. DBO2

c. DBO3

d. DBO4

Fig. 10. Cracks Patterns of group B Tested Beams.

3.2.2. Load – deflection characteristics

The ultimate capacity of tested specimens measured using load cell used for the data acquisition system for each specimen as mentioned in Table (3). The ultimate load for normal concrete specimen with web openings DBO1 is greater than the ultimate load for all corresponding polymer concrete specimens as shown in figure (11). The percentage of increasing in ultimate capacity of normal concrete DBO1 was 87.5% when comparing to the corresponding polymer concrete deep beam with web openings DBO2 due to the effect of concrete type, also the deflection at ultimate capacity of DBO1 is smaller than polymer specimens deflection at ultimate load due to the high stiffness of normal concrete, also the ultimate shear strength of polymer concrete with non-coarse aggregate is smaller than the ultimate shear strength of normal concrete, as shown in figure (12). On the other hand, the increasing in both horizontal and vertical web reinforcement increased the ultimate capacity for both DB3 and DB4 by 18% and 15.6% respectively. As shown in figures (13).

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TABLE (3): EXPERIMENTAL RESULTS OF GROUP B TESTED SPECIMENS

Spec. No.	Experimental results		% of increasing in $P_u = (P_u - P_{u,\ DBO1}) / P_{u,\ DBO1}$	horizontal web RFT strain %	vertical web RFT strain %
	P_u, kN	Deflection at ultimate load, mm			
DBO1	480	5.1	87.5	0.132	0.122
DBO2	256	6.06	0	0.052	0.048
DBO3	302	5.99	18	0.081	0.073
DBO4	296	5.13	15.6	0.076	0.065

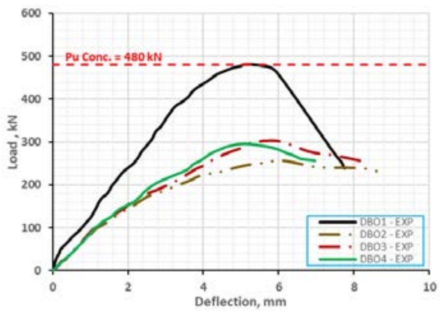


Fig. 11. Ultimate load – Deflection of all Group B Tested Specimens

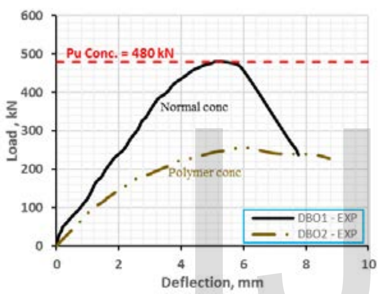
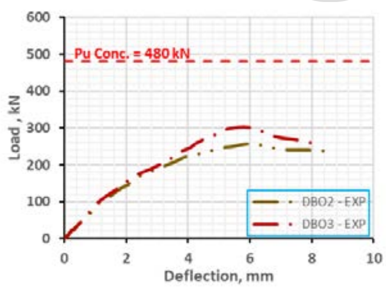
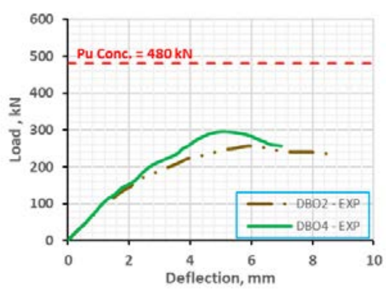


Fig. 12. Effect of Concrete type



a. Horizontal Web Reinforcement Ratio



b. Vertical Web Reinforcement Ratio

Fig. 13.: Effect of Web Reinforcement Ratios on ultimate capacity of Group B

3.2.3. Web reinforcement strain characteristics

Table (3) shows the percentage of web reinforcement strain at ultimate load for each tested specimen. From the results it can be showed that for polymer concrete specimens DBO2, DBO3, and DBO4, the strain in both horizontal and vertical web reinforcement did not reach the yield value of mild steel (0.12%). This means the bond between polymer concrete and web reinforcement is weak and the shear along the cracks surfaces is also small due to the absence of coarse aggregate and there is no aggregate interlock. While for normal concrete specimen DB1 the bond between concrete and web reinforcement is perfect. Also, the strain in horizontal web reinforcement is more than the strain in vertical web reinforcement by insignificant value. For this case it is important to use added material to the polymer concrete to improve the bond stress between polymer concrete and reinforcement.

3.2.4. Effect of web openings

Comparing the results obtained from group A and group B, as shown in table (4), it can be concluded that the ultimate capacity for normal concrete specimen without web openings was more than the ultimate capacity of corresponding normal concrete with web openings by 36%, while this ratio increased to 50% for polymer concrete specimens due to the weak bond and weak shear strength of polymer concrete and also effect of web openings on the load bath direction.

TABLE (4): EXPERIMENTAL RESULTS OF GROUP A VS GROUP B TESTED SPECIMENS

Spec. No.	Conc. type	opening	P_u, kN	% of increasing in $P_u = (P_{u,\ DB} - P_{u,\ DBO}) / P_{u,\ DBO}$
DB1	**Normal**	without	653	36
DBO1	**Normal**	With	480	0
DB2	**Polymer**	Without	385	50
DBO2	**Polymer**	with	256	0

4. NUMERICAL ANALYSIS

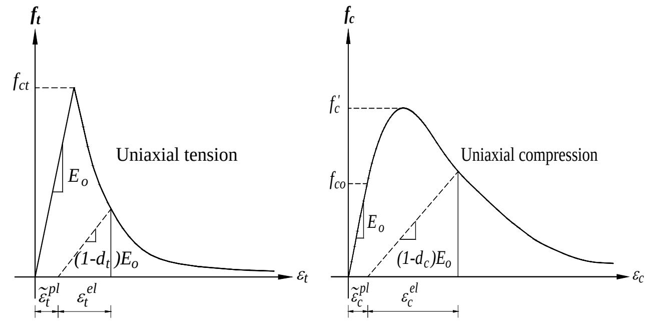
The finite element program ABAQUS [17] was used to study the behavior of reinforced concrete deep beams. The provided model was used to validate the results of experimental analysis of tested specimens with and without web openings.

5. MATERIAL MODELING OF TESTED SPECIMENS

5.1. Concrete

The concrete damage plasticity in ABAQUS software [17] can be used for defining the material properties of concrete material of deep beams. The concrete damaged plasticity model assumes that the two main failure mechanisms in concrete are the tensile cracking and the compressive crushing. The evolution of the yield (or failure) surface is determined by two hardening variables, tension and compression equivalent plastic strains, respectively. Each of them is linked to degradation mechanisms under tensile or compressive stress conditions, as shown in figure (14).

5.2. Steel



(a) (b)

Fig. 14. Response of Concrete Due To (A) Uniaxial Tension, (B) Uniaxial Compression.

The constitutive behavior of steel can be predicted using an elastic perfectly plastic model, as described in (ABAQUS /CAE 2017) [17]. In this approach, the steel behavior is elastic up to the yield stress. At this point, the material yields under constant load, as shown in Figure (15). The steel reinforcement embedded to the concrete assuming that there is a perfect bond between the concrete and the steel reinforcement.

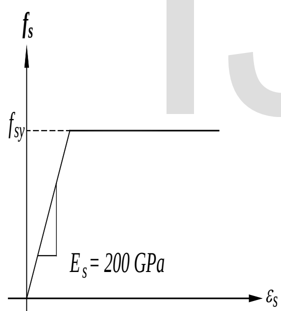
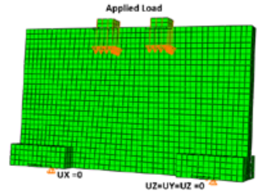


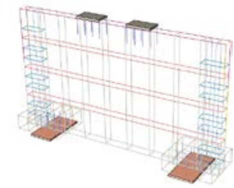
Fig. 15. Stress-Strain Relationship for Steel Reinforcement.

6. Model Validation

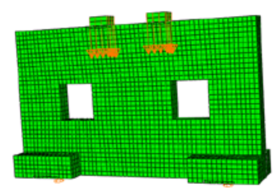
A three-dimensional finite element (FE) program 'ABAQUS' is used for the numerical analysis of all tested specimens. In reinforced concrete deep beams to model the concrete in ABAQUS and steel plates under applied load, an 8-node solid element, C3D8R was used. While longitudinal reinforcement, horizontal, and vertical reinforcement are model by using element T3D2.The load was applied at load-plates over the top of specimen, while the hinged supports were used. The details of FE model used in this validation is shown in Figure (16).



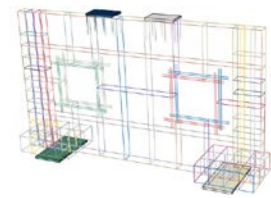
a. Mesh Used in Validation of Group A



b. Steel Reinforcement of Group A



c. Mesh Used in Validation of Group B



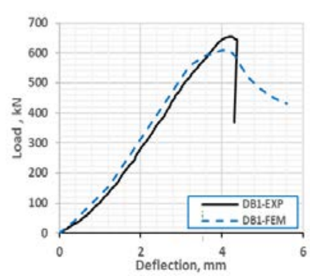
d. Steel Reinforcement of Group B

Fig. 16. Details of FE model used in this validation

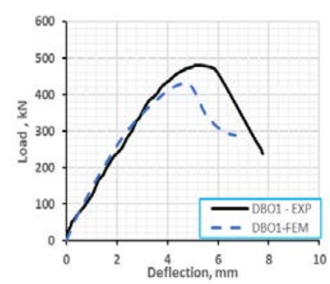
The ultimate load obtained from FE model was compared with the results obtained from the experimental results. The modeled response verifies the ability of the selected model to capture the whole beam's behavior up to failure and shows a good agreement to the experimental results. The results of the model can be used in validating and guiding experimental work. Table (5) and figure (17 & 18) show the FE model results compared to experimental results

TABLE (5): COMPARISON OF FEM RESULTS AND EXPERIMENTAL RESULTS ALL TESTED SPECIMENS

Group	Spec. No.	Experimental results		FEM results		% P FEM/ P EXP	% Def. FEM/Def. EXP
		P_u, kN	Deflection at ultimate load, mm	P_u, kN	Deflection at ultimate load, mm		
A	DB1	653	4.26	610	4.09	93	96
	DB2	385	7.8	391	7.18	101	92
	DB3	477	6.77	457	7.35	96	108
	DB4	465	7.09	438	7.3	94	103
B	DBO1	480	5.1	432	4.62	90	91
	DBO2	256	6.06	244	5.73	95	95
	DBO3	302	5.99	290	5.1	96	85
	DBO4	296	5.13	283	5.0	96	97



DB1



DBO1

Fig. 17. FEM vs. Experimental results for Normal Concrete specimens

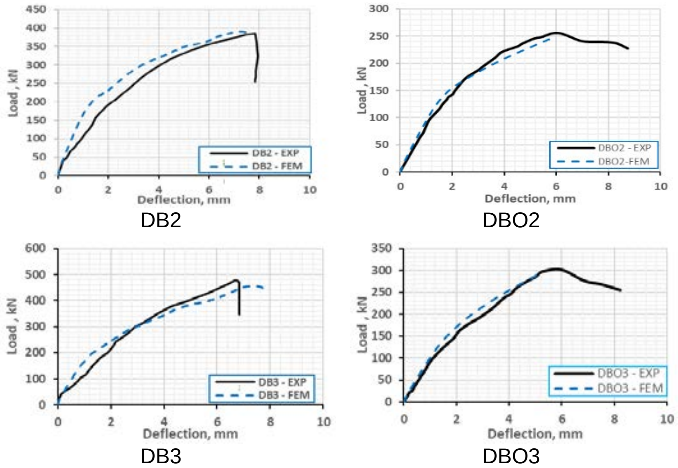


Fig. 18. FEM vs. Experimental results for Polymer Concrete specimens

7. Strut-and-Tie Model Prediction for Polymer Concrete Deep Beams

Figures (19 & 20) present the Strut-and-Tie model obtained from the validating model for non-coarse aggregate polymer concrete deep beams with and without web openings for different cases and parameters.

a) Strut-and-Tie Model Prediction for Polymer Concrete Deep Beams without web openings

Approximately same simplified Strut-and-tie model for all deep beams without web openings can be obtained and used to predict the ultimate capacity for both normal and polymer concrete specimens without web openings., as shown in figure (19).

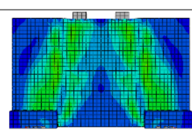
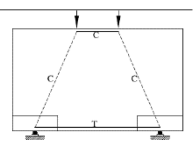
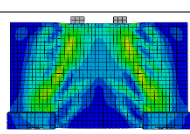
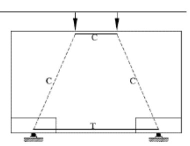
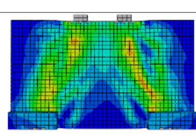
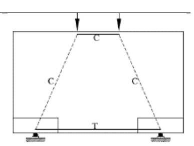
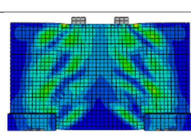
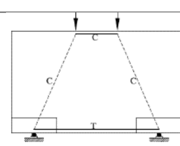
Spec . No.	Experimental	FEM	Simplified
DB1			
DB2			
DB3			
DB4			

Fig. 19. Simplified Strut-and-Tie Model Developed for Specimens without web openings (Group A)

b) Strut-and-Tie Model Prediction for Polymer Concrete Deep Beams with web openings

For specimens with web openings, a simplified Strut-and-tie model was obtained and used to predict the ultimate capacity for both normal and polymer concrete specimens, as shown in figure (20).

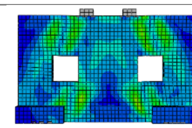
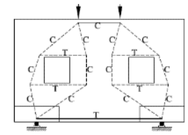
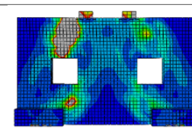
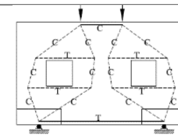
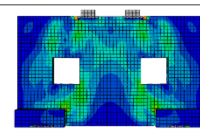
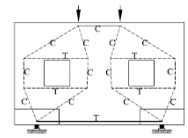
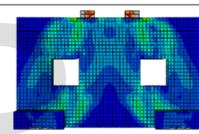
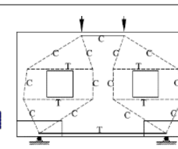
Spec . No.	Experimental	FEM	Simplified
DBO 1			
DBO 2			
DBO 3			
DBO 4			

Fig. 20. Simplified Strut-and-Tie Model Developed for Specimens with web openings (Group B)

8. Conclusions

his research presents an investigation of behavior of non-Coarse aggregate polymer concrete simply supported deep beams with and without web openings using both experimental and finite element model developed by ABAQUS software program. And also focusing to explain the shear strength problem of polymer concrete specially when used to cast deep beams with web openings. Based on the results obtained from Experimental and FEM, the next conclusions observed:

- Polymer concrete with absence coarse aggregate has significant problem with shear strength and can't be used for casting structural element exposed to shear without adding special alternative material like steel fiber or any other light weight material to improve ultimate shear strength of polymer concrete.
- The results obtained from FEM model had good agreement with experimental results and the model can be used for investigation the behavior of normal and polymer concrete deep beams with or without web openings.

- The ultimate capacity of deep beams casted with polymer concrete with or without web openings improved when increasing web reinforcement ratio.
- The bond between polymer concrete and web reinforcement is weak. In addition, the polymer concrete failed before web reinforcement reaches yielding, it is important to carry out more researches for improving both the bond and shear strength of polymer concrete.
- By increasing either horizontal or vertical web reinforcement ratio, the ultimate capacity of CDB increased.
- Increasing either vertical or horizontal web reinforcement ratio lead to increase the ultimate capacity for polymer concrete specimens.
- Generated simplified Strut-and-Tie model based on both Experimental FEM result for different case of studies in this research can be used to investigate the ultimate capacity of simply supported deep beams with and without web openings analytically.
- The web openings had a great effect on the stiffness and ultimate capacity of the specimens.
- The ultimate capacity for normal concrete specimen without web openings improved by 36% than the corresponding specimen with web openings, while this ratio increased to 50% for polymer concrete specimens due to the weak bond of polymer concrete and also the effect of web openings on the load bath direction.
- The deflection at ultimate load of normal concrete specimens with or without web openings is smaller than the corresponding polymer specimens due to the high stiffness of normal concrete.

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