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Behavior of Tapered Self-Compacting Reinforced Concrete Beams Strengthened by CFRP

Abstract- *This study presents an experimental investigation on the behavior of fourteen reinforced self-compacting concrete tapered beams with or without strengthening. The strengthening was applied by using carbon fiber reinforced polymer (CFRP) to beams with simply supported span and subjected to two points loading. Those beams have an overall length of 2000 mm, a width of 150 mm and a height of 250 mm at supports (hs) and a mid-span depth (hm) varies between 150 mm and 200 mm and with different strengthening scheme, they are investigated to evaluate the behavior at experimental test and to study the effect of the parameters which include haunch angle α, shear-span to effective depth ratio a/d and strengthening strips number and locations on beams behavior. The experimental results show that decreasing the value of haunch angle α increased the load capacity by about 56% and decreased the corresponding deflection while when tapered beams are strengthened by CFRP the ultimate load is increased up to 39% with decrease of deflection. On the other hand, increasing a/d ratio leads to a decrement in load capacity and increment in deflection.*

Keywords- *Carbon Fiber Reinforced Polymer (CFRP), Self-compacting concrete, Shear strength, Tapered beams.*

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1. Introduction

Self-compacting concrete (SCC) is highly flowable nonsegregating concrete that can spread into place, fill the formwork, and cover the reinforcement without any vibration. Generally, SCC is concrete made with common concrete materials. SCC is also named as self-compacting, self-placing and self-leveling concrete [1]. Reinforced concrete tapered beams are generally used in simply supported or continuous bridges and in midrise framed buildings in worldwide. Some advantages are gained by using these elements, such as improving stiffness or moment capacity to self-weight ratio and providing a smaller mid-span depth that makes the placement of different facilities like air conditioning and piping easier. However, in some countries such beams are not a common structural solution in buildings because of the higher costs that their construction demands, where this increase is attributed to hiring skilled for the formwork and reinforcing steel purposes [2]. Generally, beams are deepened by haunches near the supports to increase the support moment, which cause a significant reduction in the span moment. Thus, mid-span height can be diminished in order to obtain more clearance [3]. Despite the fact that reinforced concrete haunched beams are commonly used, there are no specific recommendations, in state – of the art codes, like ACI (American Concrete Institutes) or BS (British Standard Institutes).Although the German and Russian codes cover the design of reinforced concrete haunched beams in some details, these codes are not available to engineer in Iraq and many countries [4]. Fiber-reinforced polymer reinforcement is increasingly becoming significant in the strengthening and repairing of reinforced concrete structures, where it is commonly used as external strengthening for concrete slabs, beams and columns. Advantages of these techniques are common and keep growing, because of the easy installation, low cost, negligible losses, and high strength to weight ratio that these FRP materials can provide [5].

2. Experimental Program

The experimental program consists of constructing fourteen tapered simply supported beams by using SCC with designed fc' equals 35 MPa and tested with two point loads. All beams have dimensions shown in Figure 1. All beams are longitudinally reinforced with two bars of 16 mm and one bar of 8 mm diameter at bottom. At the top face, two deformed bars of 8 mm diameter

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have been provided. For vertical shear reinforcement, deformed bars of 4 mm diameter are used and provided at a spacing of 150 mm center to center. The beams were divided into three groups as summarized in Table 1.

3. Strengthening Scheme

Two groups, G2 and G3, each group has five beams were strengthen by CFRP. The numbers of strips and their spacings were designed according to ACI 440.2R-08 [6] while the location was chosen according to failure mode of the tested reference beams. U-shaped CFRP strips that have inclination of 45°**,** 50 mm width and different lengths were used to strengthen these two groups. The spacing center to center of all strips used was taken as 145 mm, Figures 2 and 3 show strengthening schemes for beam groups G2 and G3.

4. Concrete mix design

Many trail mixes were made according to the recommendations of EFNARC [7] to accomplish both fresh and hardened properties of SCC. Mix design of SCC must satisfy the standards of filling ability and segregation resistance. The mixes were designed to achieve cylinder strength *fc'* of 35 MPa at 28 days. In order to produce SCC, a superplasticizer based on polycarboxylic ether commercially named as GLENIUM 54 produced by BASF chemical company, Dubai-UAE was used throughout this work. Details of the adopted SCC mixture are shown in Table 2.

5. Load Measurement and Testing Procedure

All beams were tested at the structural laboratory of the University of Technology using a hydraulically AVERY testing machine of 125 ton capacity, the tests of beams were carried out at age of approximately 56 days. Before the day of testing, each beam was cleaned and the surfaces of the specimens were white painted to facilitate the detection of the first crack and crack patterns. All the beams were labeled and the location of supports, loading points and the dial gauges were located on the beams to facilitate the accurate setup of testing equipment as shown in Figures 4 and 5. All beams have been tested under monotonic loading, up to failure, with two concentrated loads. Initially each beam was loaded with small load then reduced to zero to make sure that the dial gauge is in touch with the bottom faces of beams and to seat the support and the loading system. After that, Loading was applied at regular increments of 10 kN. At each load stage, deflection and the concrete surface strains were recorded.

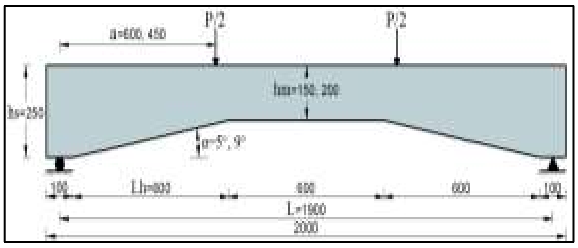


Figure 1: Geometry of the specimens
Note: All dimensions in mm

Table 1: Geometry and parametric study of experimental work

No.	Group No.	Specimen symbols	α deg.	a/d	Strengthening details
1	1	B1R	9	2.75	No strengthening
2		B2R	5	2.75	No strengthening
3		B1Ŕ	9	2.064	No strengthening
4		B2Ŕ	5	2.064	No strengthening
5	2	B1S2	9	2.75	Two inclined U-shape strips
6		B1S3		2.75	Three inclined U-shape strips
7		B1S3*		2.75	three inclined U-shape strips with different distribution
8		B1Ś2		2.064	Two inclined U-shape strips
9		B1Ś3		2.064	Thee inclined U-shape strips
10	3	B2S2	5	2.75	Two inclined U-shape strips
11		B2S3		2.75	Three inclined U-shape strips
12		B2S4		2.75	Four inclined U-shape strips
13		B2Ś2		2.064	Two inclined U-shape strips
14		B2Ś3		2.06	Three inclined U-shape strips

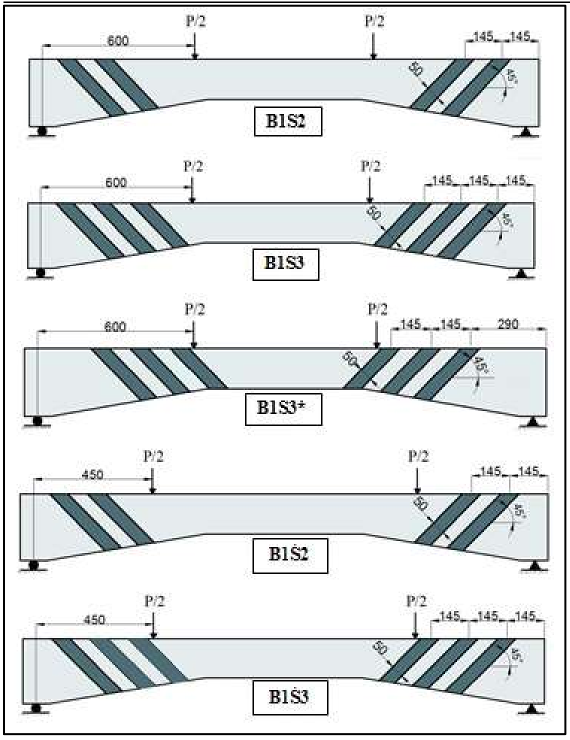


Figure 2: Strengthening scheme for G2(α=9°, hm=150 mm)

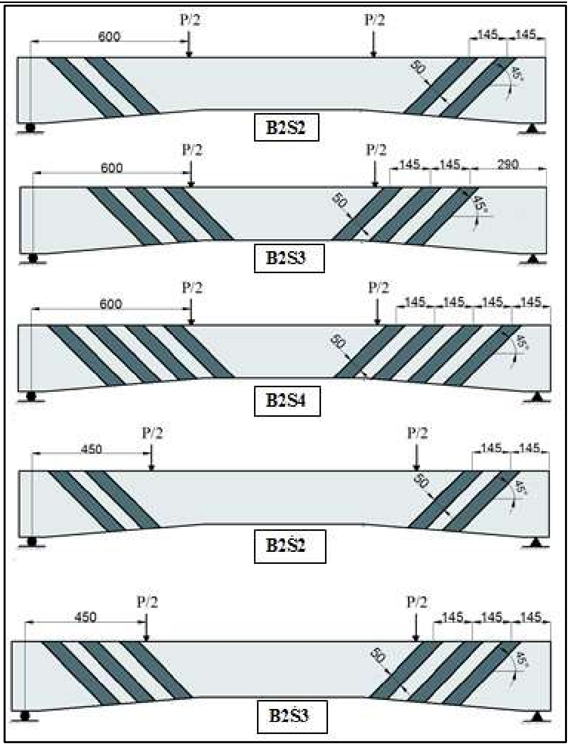


Figure 3: Strengthening scheme forG3(α=5°,hm=200 mm)

Table 2: SCC mix proportions

Cement (Kg/m^3)	Limestone Powder (kg/m^3)	Water (Kg/m^3)	W/p By weight	Coarse aggregate (Kg/m^3)	Fine aggregate (Kg/m^3)	Super plasticizer (L/m^3)
350	175	180	0.34	767*	797	4.9**

* Crushed gravel with a maximum size of 12 mm.

** 1.4 liter/100 Kg cement.

Figure 4: Beam test setup

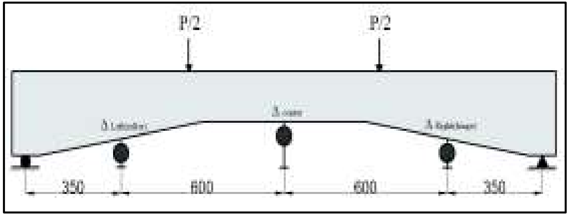


Figure 5: Positions of dial gauges

6. Test Results of Hardened SCC (control specimens)

In this experimental work, one type of normal SCC was used and all the tests and results were accomplished according to ASTM. Three cylinders (100 × 200) mm were tested at ages of 7days, 28days and beam test age to determine the average of the samples and get the compressive strength of the concrete. Splitting tensile strength was done by testing three cylinders (100 × 200) mm at ages of 7 and 28 days and the average of the three samples has been taken. The results of testing four (100 × 100 × 400) mm prisms were used to determine the flexural strength of SCC at ages of 7 and 28 days while static modulus of elasticity was obtained by testing two cylinders (150 × 300) mm at ages of 28 days and at beam test age. Table 3 illustrates the results of hardened SCC.

The experimental results of splitting tensile strength (f_{ct}) are compared with theoretical data adopted using the following equation adopted by ACI 318M-14, article 19.2.4:

$$f_{ct} = 0.56\sqrt{f_c'} \quad (1)$$

Where f_c' is the compressive strength of concrete (MPa) for cylinder.

As for flexural strength, the results obtained experimentally are compared with theoretical data using the ACI 318M-14 equation:

$$f_r = 0.62 \sqrt{f_c} \quad (2)$$

Table 3 offers the values of modulus of elasticity of concrete. Measurement of static modulus of elasticity of SCC concrete (E_c) is accomplished in accordance with ASTM C469-02 using (150×300) mm concrete cylinders tested in compression. These values are compared with data adopted by ACI 318M-14 equation:

$$E_c = 4700\sqrt{f'_c} \qquad (3)$$

The comparison revealed that the experimental and theoretical results of splitting tensile strength (f_{ct}) are approximately the same. On the other hand, flexural strength results are significantly higher than the values obtained using the ACI equations. Meanwhile, the results of modulus of elasticity were experimentally lower than that obtained theoretically.

7. Experimental Results

I. Behavior and Strength of Beams in Group G1

This group contains four reference beams that are free of any strengthening strips, the parameters adopted in this group are haunch angle α and a/d ratio. Test results of group specimens are listed in Table 4 while Cracks patterns and failure modes of reference beams are shown in Figure 6.

II. Behavior and Strength of Beams in Group G2

All the five beams included in this group are strengthened by CFRP strips and have the same dimensions where α = 9°; each beam has its own amount and distribution of external strengthening. The parameters of this group are strips number and location and a/d ratio. Test results are illustrated in Table 5 while Cracks patterns and failure modes of beams are shown in Figure 7.

III. Behavior and Strength of Beams in Group G3

This group contains five specimens all of them are strengthened by CFRP strips and have the same dimensions where α=5°; the parameters of this group are strips number and location and a/d ratio. Test results are illustrated in Table 6 while Cracks patterns and failure modes of beams are shown in Figure 8.

Table 3: Test result of hardened SC

Type of test	**Compressive strength f'_c (MPa)**			**Splitting tensile strength f_{ct} (MPa)**		**Flexural strength f_r (MPa)**		**Static modulus of elasticity E_c (GPa)**	
Age	**7 days**	**28 days**	**56 days**	**7 days**	**28 days**	**7 days**	**28 days**	**28 days**	**56 days**
Experimental results	24.8	34.3	39.75	2.7	3	4	6.3	26.42	27.84
Results according to ACI equations				2.78	3.27	3	3.6	27.5	29.6

Table 4: Test results of group G1 specimens

Specimens symbols	**α deg.**	**a/d**	**P_{cr} kN**	**$\Delta_{cr(center)}$ mm**	**P_u kN**	**$\Delta_{u(center)}$ mm**	**θ_L deg.**	**θ_R deg.**	**$P_{cr/shear}$ kN**
B1R	9	2.75	20	4.89	90	20.8	44	33	35
B2R	5	2.75	30	4.4	140	29.1	40	45	40
B1Ŕ	9	2.064	20	3.71	160	34.6	35	38	40
B2Ŕ	5	2.064	30	3.65	250	37	45	49	45

where: $\mathbf{P_u}$: Ultimate load capacity (kN), $\mathbf{P_{cr}}$: First flexural crack load (kN); $\mathbf{P_{cr/shear}}$: First shear crack load (kN),
$\mathbf{\Delta_{cr}}$; $\mathbf{\Delta_u}$: Deflection at mid-span associated with first cracking and ultimate load respectively (mm),
$\mathbf{\theta_L}$, $\mathbf{\theta_R}$: Angle of inclination of diagonal tension crack with respect to horizontal axes at the left and rightsides of beams.

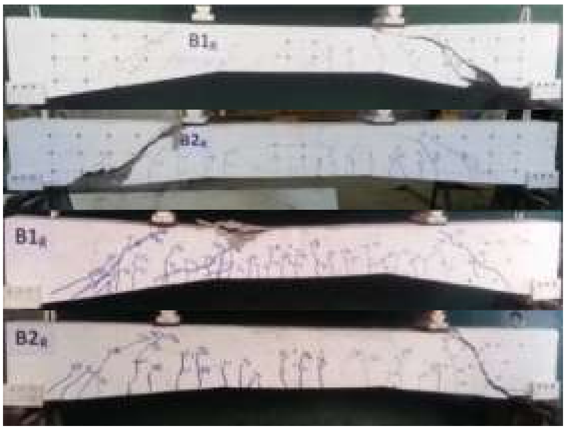


Figure 6: Cracks pattern of group G1

Figure 7: cracks pattern of group G2

8. The Effect of Haunch Angle α on Beams Behavior

Haunch angle effect appeared mainly on the deflection and load capacity of the tested tapered beams, where deflection undergoes a noticeable increment as the value of α increase as shown in Figures 9 to 12. On the other hand, increasing α leads to a decrement in the first inclined shear cracking (P_{cr}) and ultimate shear load (P_u) values as they considered a function of haunch angle “when the haunch angle increases, the volume of concrete diminishes, therefore, the shear strength also diminishes” [8].

Table 5: Test results of group G2 specimens

Specimens symbols	α deg.	a/d	P_{cr} kN	$\Delta_{cr(center)}$ mm	P_u kN	Δ_u mm	θ_L deg.	θ_R deg.	$P_{cr/shear}$ kN
B1S2	9	2.75	20	4.2	100	19.13	29	35	40
B1S3	9	2.75	20	3.4	110	19.6	39	32	45
B1S3*	9	2.75	20	2.1	125	19.1	43	45	40
B1Ś2	9	2.064	20	3.2	175	37.5	44	45	45
B1Ś3	9	2.064	20	1.8	188	38.1	53	45	50

Table 6: Test results of group G3 specimens

Specimens symbols	α deg.	a/d	P_{cr} kN	$\Delta_{cr(center)}$ mm	P_u kN	Δ_u mm	θ_L deg.	θ_R deg.	$P_{cr/shear}$ kN
B2S2	5	2.75	25	2.85	155	25.7	40	45	45
B2S3*	5	2.75	25	2.5	168	24.5	35	44	50
B2S4	5	2.75	30	2.5	175	24	45	43	55
B2Ś2	5	2.064	30	3.1	260	35.7	40	35	50
B2Ś3	5	2.064	30	2.5	270	33	45	44	55

Figure 8: Crack pattern of G3

Figure 9: Effect of α on deflection of unstrengthened beams (a/d=2.75)

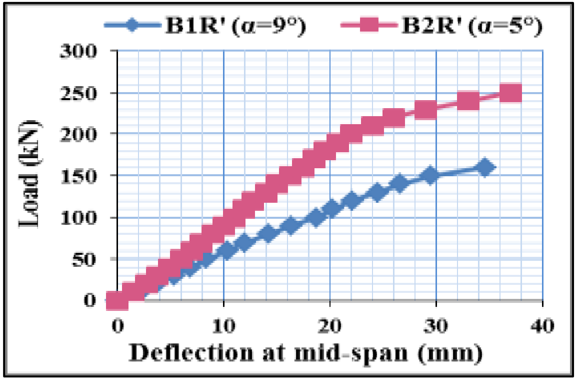
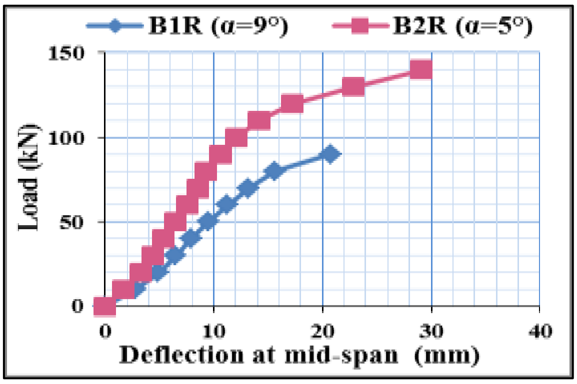


Figure 10: Effect of α on deflection of unstrengthened beams (a/d=2.064)



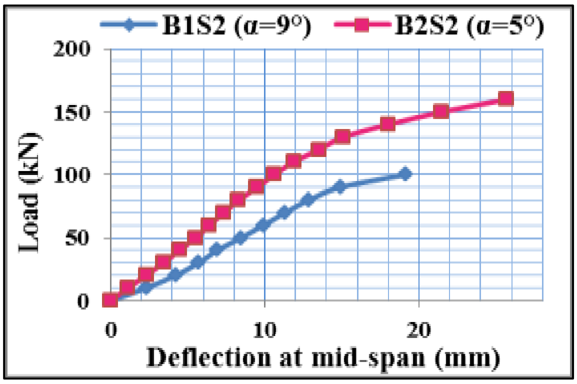


Figure 11: Effect of α on deflection of strengthened beams (a/d=2.75)

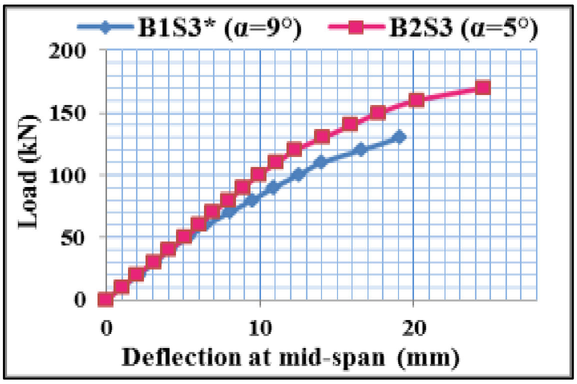


Figure 12: Effect of α on deflection of strengthened beams (a/d=2.064)

9. Effect of Shear Span to Effective Depth Ratio (a/d) on Beams Behavior

By observing test results, it was clear that the increment in a/d ratio from 2.064 to 2.75 caused a reduction in cracking load and ultimate load for most cases; this may be due to the increase of the bending moment at middle of shear span and increasing the tension stresses. The increment in the ultimate load due to reduction of a/d ratio in control beams was about 78% and 79% respectively. Moreover, the ratio of a/d had an impact on deflection value that a reduction in a/d ratio caused a little drop on deflection value at mid-span of the tapered beams; such reduction could be because of increasing the stiffness, which caused a loss in ductility. Figures 13 to 16 represent the effect of a/d ratio on the deflection.

10. Effect of Strengthening Scheme on Beams Behavior

According to test results, it is obvious that the increment in quantity of CFRP strips leads to some improvement in first shear crack load and ultimate load capacity for most cases. By increasing the strips number, the ultimate load increased by 11%, 22%, 39%, 9% and 18% respectively for G2 and 11%, 20%, 25%, 4% and 8% respectively for G3. This increment in load capacity is caused by the participation of CFRP strips in resisting the diagonal tension stresses, which often governed the failure. Figures 17 and 18 show the effects of strengthening on ultimate load of each beam.

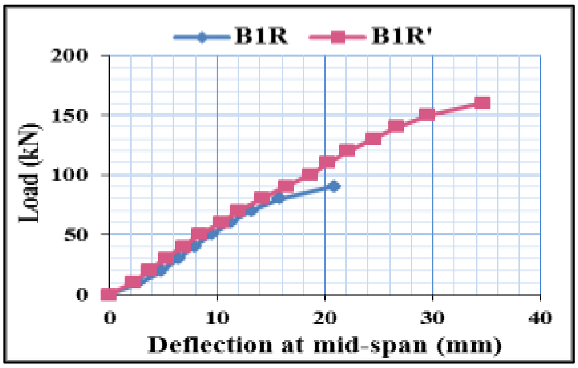


Figure13: Effect of a/d ratio on mid-span deflection of unstrengthened beams (α = 9°)

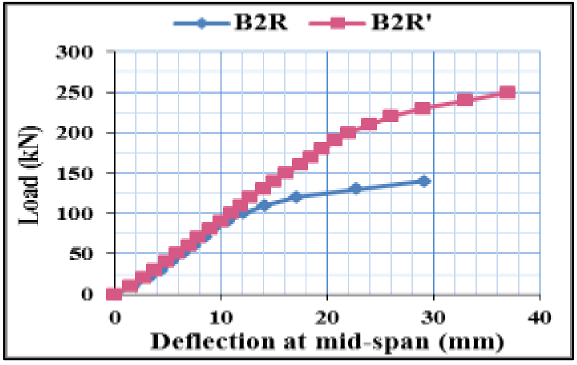


Figure 14: Effect of a/d ratio on mid-span deflection of unstrengthened beams (α = 5°)

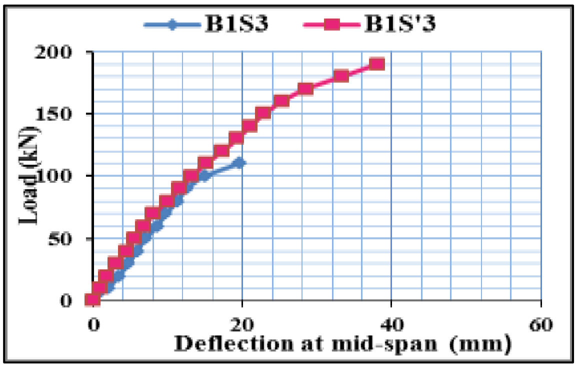


Figure 15: Effect of a/d ratio on mid-span deflection of strengthened beams (α = 9°)

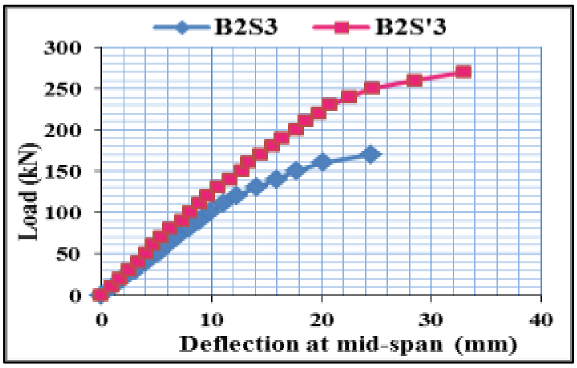


Figure 16: Effect of a/d ratio on mid-span deflection of strengthened beams (α = 5°)

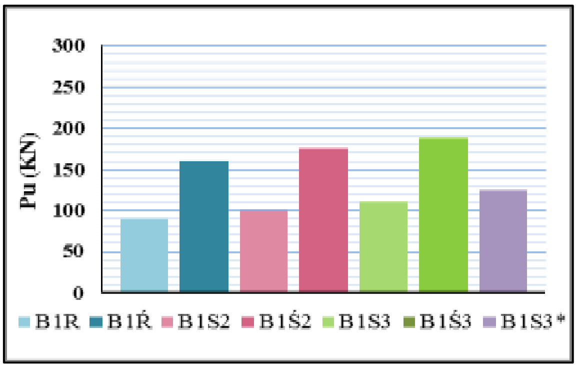


Figure 17: Effect of strengthening on the ultimate load (α = 9°)

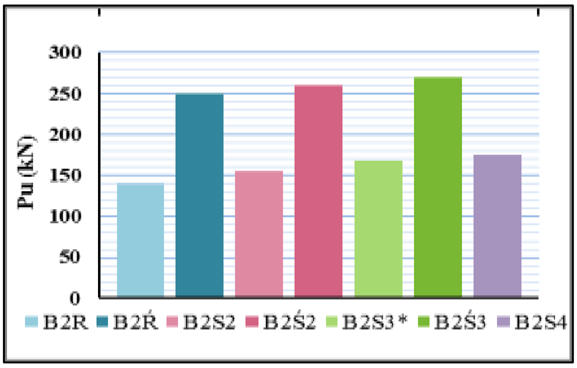


Figure 18: Effect of strengthening on the ultimate load (α = 5°)

11. Conclusions

By testing fourteen SCC tapered beams and by comparing test results it can be concluded that:

1. The first inclined shear cracking ($P_{cr/shear}$) and ultimate shear strength (P_u) of a tapered beam is considered as a function of the haunch angle α for all tested beams, where increasing haunch angle α leads to a reduction in ultimate load capacity by 56% and such increment in haunch angle α value produced a higher deflection values .

2. The presence of CFRP in the tapered beams at shear span increased the ultimate load up to 39% while a reduction in deflection is recognized (where Δ_{cr} = 4.89mm for beam B1R and Δ_{cr} = 4.2 for beam B1S2) when compared with beams without strengthening.

3. Using CFRP as external strengthening decreases the crack width and increases number of cracks.

4. Regarding the influence of a/d ratio on the behavior of SCC tapered beams that, it is concluded that the reduction of a/d ratio from 2.75 to 2.06 increases the failure load by 77% and 78% respectively as the haunch angle decreases.

5. The deflection at mid-span of the beam decreased as compared with beams of higher a/d ratio where the value of deflection is reduced from 4.89 mm to reach 3.71 mm at first crack load when a/d value reduced for beams B1R and B1Ŕ respectively.

6. Moving strengthening strips near loading points location (toward weaker part) prevents the major shear crack from initiating in the weaker section of the haunch part which has effect on load capacity where ultimate load increased by 14 % with respect to beams with same amount of CFRP.

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