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Behaviour of Bonded and Unbonded Post-Tensioned Lightweight Concrete Beams

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الملخص:
هذا البحث يهدف الي دراسة سلوك الكمرات الخرسانية منخفضة الوزن سابقة الاجهاد باستخدام الكابلات المحاطة بمونة اسمنتية والغير محاطة عمليا من خلال استخدام حبيبات البوليسترين كحل بديل جزئي لخفض وزن وحدة الخرسانة الجافة من ٢٣ كيلو نيوتن/ متر٣ إلى 18.2 كيلو نيوتن / متر٣وتحقيق مقاومة ضغط 35 MPa ومقاومة شد 3.48 MPa. البرنامج العملي يتكون من خمس كمرات من الخرسانة خفيفة الوزن بابعاد ثابتة 150*350*4000 مم (عرض * ارتفاع* طول)علي التوالي مع تغير عرض الشفة ناحية الضغط لتصبح 150مم في حالة القطاع المستطيل و 350مم في حالة القطاع ذات الشفة من جهة واحدة و550مم في حالة القطاع ذات الشفة من الجهتين.العينات مقسمة الي مجموعتين المجموعة الاولي تتكون من ثلاث عينات (عينة مستطيلية القطاع و عينة ذات شفة من جهة واحدة وعينة ذات شفة من جهتين) تلك المجموعة مسبقة الاجهاد باستخدام كابلات غير محاطة بمونة اسمنتية اما المجموعة الثانية فتتكون من عينتين (عينة مستطيلية القطاع وعينة ذات شفة من جهتين) تلك المجموعة مسبقة الاجهاد باستخدام كابلات محاطة بمونة اسمنتية. تم تسليح جميع العينات باستخدام كابل سبق الاجهاد ناحية الشد مع وجود حديد تسليح سيخين قطر 12 مم. جميع الكمرات تحتوي علي كانات قطر 10 مم بمسافة توزيع 100 مم لاول واخر 1000 مم وبمسافة 200مم للجزء المتبقي من الكمرة المختبرة. قطر الكابلات المستخدمة لتطبيق قوي سبق الاجهاد 12.70مم. تم اختبار الكمرات تحت تاتير اربعة نقاط للتحميل لدراسة تاثير نوع القطاع الخرساني وخواصه (مستطل او ذات شفة واحدة او ذات شفتين) وايضا تاثير تغير نوع الكابلات المستخدمة (محاطة ام غير محاطة بمونة اسمنتية).

Abstract:
This paper presents an experimental program conducted to study the behavior of bonded and unbonded post-tensioned lightweight concrete beams (LWC) beams by partial aggregate replacement with polystyrene foam. the used mix have cubic compressive strength 35 MPa, tensile strength 3.48 MPa, and density 18.2 kN/m3. the experimental program consists five lightweight concrete tested beams divided to two groups, the overall dimensions of the beams are (150*350*4000) mm with different flange width: (150, 350 and 550) mm for (R, L and T) sections respectively. The first group consist of three unbonded prestressed beams with different cross section properties (R, L and T) section. The second group consist of two bonded prestressed beams with different cross section properties (R and T) section. All beams reinforced by one tendon and non-pre-stressed steel with diameter 2T12 mm as bottom reinforcement. All beams were reinforced using closed stirrups of 10 mm diameter with spacing 100mm for the first 1000 mm in the two ends and 200 mm for the rest of the beam. All the beams were also reinforced with two ordinary longitudinal reinforcements of 10mm diameter as a top reinforcement with 25 mm clear cover. The dimeter of used prestressing tendons was 12.7 mm. The beams were tested under four-point loading condition with constant moment zone up to failure to examine its flexural behavior. The main variables in this experimental program were the concrete cross sections properties (R, L and T) and prestressing tendon type (bonded and unbonded).

Keywords: Foamed concrete, Reduced weight concrete, Lightweight Concrete and prestressed concrete, bonded tendons, unbonded tendons.

1-Introuduction

The development of reliable prestressing techniques has certainly been an important innovation in the field of structural concrete. It enabled concrete construction to compete successfully within areas that had previously been dominated by steel constructions, including long span bridges, high rise buildings, pressure vessels and offshore structures. Today, prestressing and, in particular, post-tensioning with bonded and unbonded tendon with compression flange is a mature technology, providing efficient, economic and elegant structural solutions for a wide range of applications. The Effective flange width is one of the most important factors affecting the design and the serviceability behavior of concrete beams. According to many design codes the effective flange width depends on Slab thickness, Effective span length and Girder spacing. In case of using bonded prestressed beams, the stress changes in the prestressing steel can be determined from the strain compatibility between concrete and steel, which means that the analysis is section dependent. However, in case of beams with unbonded tendons, it is necessary to formulate the global deformation compatibility between the anchorages of tendons. The stress change in tendon is member dependent and is influenced by initial cable profile, span to depth ratio, deflected shape of the structure and beam end conditions. This makes the analysis of beams with unbonded tendons more complicated. A significant portion of the load carried by Pre-stressed concrete beams is the self-weight of the beams. Therefore, the used of reduced weight concrete (LWC) in this paper, which combines the advantages of normal density concrete by achieving the same strength and reduced self-weight by partially replacing the normal weight aggregates with polystyrene foam. The latter material can therefore be produced using standard methods familiar to the construction industry with a dry unit weight of 18.20 kN/m3, which in turn leads to dead load reduction by 15 – 20 % which additional benefits can then be realized in the form reduced crane capacity requirements, and lower shipping costs.

Lightweight Concrete (LWC) has been used in construction since the eighteenth century. It is very important in decreasing the cost of Reinforced Concrete (RC) structures. The weight and type of coarse aggregate and the ratio between fine and coarse aggregate are the main parameters used to reduce the density of concrete (less than 1800 kg/m3) [1 - 4]. Foam with different forms is used in the construction field and can be used in the mixed material of concrete.

Youssef, et. Al. 2018[5], presented the experimental result on the performance of structurally reinforced foam concrete flat slab exposed to fire under eccentric and concentric loads. results showed by comparing the performance of structural lightweight polystyrene foam concrete flat slabs and normal-weight concrete flat slabs, the ultimate load decreased in the foam concrete flat slab by approximately 7.0% for concentric load and 4% for eccentric load compared with those of normal-weight concrete. The number of cracks decreased and the crack width increased in foam concrete.

Hussein, et al. (2012) [6] examined the behavior of bonded and unbounded prestressed normal strength and high strength concrete beams. The program consisted of a total of nine beams; two specimens were reinforced with non-prestressed reinforcement, four specimens were reinforced with bonded tendons, and the remaining three specimens were reinforced with unbonded tendons. The overall dimensions of the beams were 160x340x4400 mm. The beams were tested under cyclic loading of four-point load configuration up to failure to examine its flexural behavior. The main variables in this experimental program were nominal concrete compressive strength (43, 72 and 97

MPa), bonded and unbonded tendons and prestressing index (0%, 70% and 100%). Some of the results of this study, which relates to our scope of work, are summarized as follows: a-Presence of non-prestressed reinforcement in partially prestressed beams enhanced the ductility up to 92% in comparison to that of fully prestressed concrete beams and controlled the crack formation and crack width. b- Increasing the nominal compressive strength from 72 to 97 MPa for bonded prestressed beams led to a slight increase in the ultimate and cracking loads by 4% and 18%, respectively.
Omar (2002) [7] investigated the performance of prestressed lightweight concrete beam made from clinker aggregate under two-point load and comparisons with normal weight prestressed concrete beam. The clinker is incorporated into the concrete as a direct replacement for both fine and coarse aggregates at 100% replacement level. The use of clinker lightweight concrete was found to save the amount of the total dead load up to 18.8%. The results of the study concluded that lightweight concrete using clinker exhibit an almost similar pattern in cracking behaviour and failure modes. The test results show that the prestressed lightweight concrete beams can resist loading up to 90% of the normal prestressed concrete beams. The study also shows that clinker lightweight concrete exhibit good performance and is suitable to be used in prestressed concrete beam. ACI 423.7-07 [8] presents recommendations for materials, design, and construction for concrete structures prestressed with unbonded tendons. Since the early 1950s, many experimental and analytical researches have been conducted to evaluate the stress at ultimate in unbonded tendons.

According to ACI 423.7-07 [9]:

$For\ L/d \leq 35$

$$f_{ps} = f_{pe} + \left(70 + \frac{f_c'}{100\rho_{ps}}\right) MPa$$

with the limitation that $f_{ps} < f_{pe} + 400$, and $f_{ps} < f_{py}$

$For\ L/d \geq 35$

$$f_{ps} = f_{pe} + \left(70 + \frac{f_c'}{300\rho_{ps}}\right)\ MPa$$

with the limitation that $f_{ps} < f_{pe} + 200$, and $f_{ps} < f_{py}$

where: $\rho_{ps} = ratio\ of\ prestressing\ reinforcemet\ \ A_{ps}/bd_p$

$f_{ps} = stress\ in\ prestressing\ reinforcemet\ at\ ultimate$

$f_{pe} = allowable\ \ prestressing\ stress\ at\ time\ of\ tranfer$

$f_c' = concrete\ compressive\ strength$

2-Experimental Program

The experimental program consists of five prestressed beams with overall depth, width and length of 350, 150 and 4000-mm, respectively with different flange width: (150, 350, 550) mm for (R, L, T) sections respectively. The beams were simply supported with a clear span of 3800-mm as shown in Fig. 1. Specimens consist of two groups, the first group consist of three unbonded prestressed beams with different cross section properties (R, L and T) section. The second group consist of two bonded prestressed beams with different cross section properties (R and T) section. All beams reinforced by one tendon and non-pre-stressed steel with diameter 2T12 mm as bottom reinforcement. All beams were reinforced using closed stirrups of 10 mm diameter with spacing 100mm for the first 1000 mm in the two ends and 200 mm for the rest of the beam. All the beams were also reinforced with two ordinary longitudinal reinforcements of 10mm diameter as a top reinforcement with 25 mm clear cover. The dimeter of used prestressing tendons was 12.7 mm. The flexural non-prestressed steel and steel stirrups were made of de-formed high tensile steel with yield stress of 360 MPa and ultimate strength of 520 MPa. The yield and ultimate stress of the prestressing steel strands were 1674 and 1860 MPa, respectively. The prestressing steel strand had a profile similar to the bending moment induced from the concentrated loads. The selection of mixture properties for normal and reduced weight concrete was based on several trail mixes and their dry cured 28-day compressive strength. The average dry cured 28-day compressive strengths of the selected mixes were 35 MPa.

2-1 Test specimens

The variables considered in this study, were the concrete cross sections (R, L and T) and tendon type (bonded and unbonded) as given in Table 1. The details of the tested specimens are as follows:

Specimen B3 and B10 with rectangular section and reinforced using one tendon (unbonded and bonded) respectively with diameter 12.7 mm in addition to 2T12 mm diameter non-prestressed bars. Specimen B5 and B11 with T- section and reinforced using one tendon (unbonded and bonded) respectively with diameter 12.7mm in addition to 2T12 mm diameter non-prestressed bars. Specimen B6 with L- section and reinforced using one unbonded tendon with diameter 12.7 mm in addition to 2T12 mm diameter non-prestressed bars as shown in Fig.2 and Fig. 3.

The prestressing force was applied at both ends of each beam using 250 kN jack capacity after the concrete reached an age of 28 days on four steps up to 1395 MPa stress level, which is equal to 75% of the ultimate stress for strands, as shown in Fig. 4.

The specimens (B10 and B11) with bonded strands were grouted under pressure using grout with 36 MPa compressive strength, as shown in Fig. 5.

2-2Test set-up

The specimens were tested under four-point loading condition with constant moment zone. This setup has to be achieved using a hydraulic jack with 3000 kN capacity and using 1000 kN load cell as shown in Fig. 6. To achieve the two acting loads, a rigid steel spreader beam of 1.00m length is used to divide the applied load into two-point loads. The rigid steel beam was borne on a 30mm steel plate which is rested on the top of the concrete beam. This 30mm steel plate is attached on the concrete surface using a mortar-based material. Then the steel plat is leveled using spirit level to insure its horizontality. The vertical deflection of the tested beam was recorded using dial gauge with accuracy 0.01 mm and also using linear variable deferential transducers, LVDT, which has length = 200mm. 3 LVDT and two dial gauges were used to measure the vertical deflection with spacing 630mm.

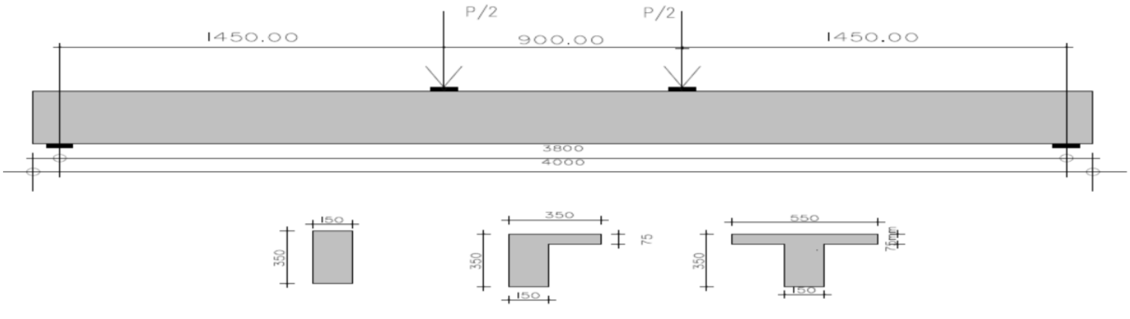

Fig. 1: Concrete dimensions of prestressed beams

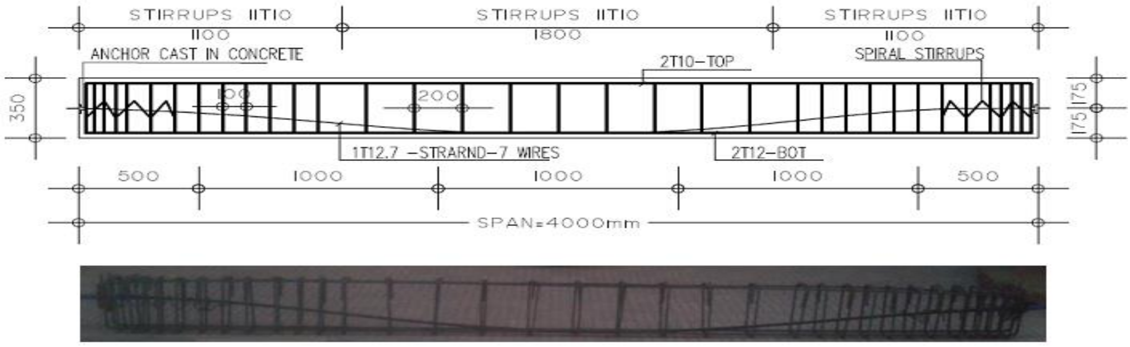

Fig 2: Typical Reinforcement Detailing and Tendon profile for Specimens

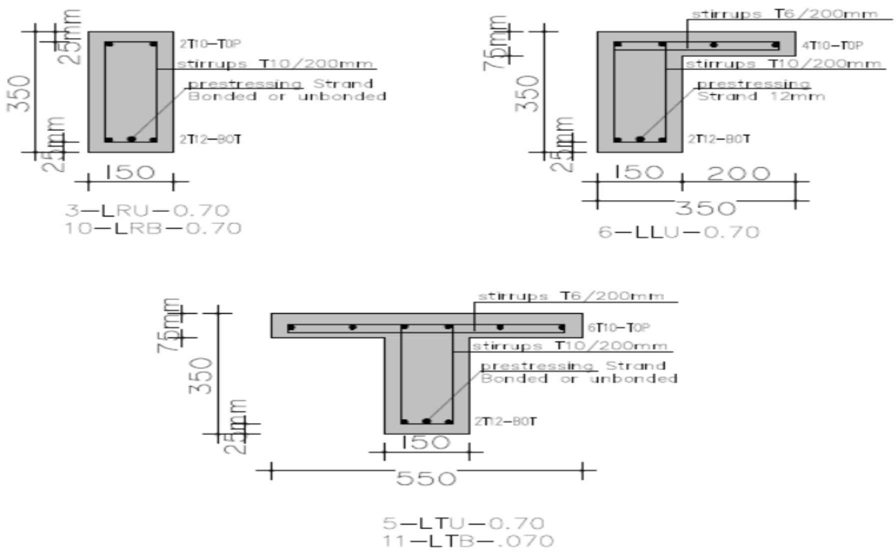

Fig 3: Shows the Cross Section for Various Beams.

Fig. 4: Application of Prestressing Force and Elongation After Tensioning the Tendon.

Fig. 5: Grouting Injection

Fig. 6: Experimental Setup

Table 1: The Experimental Specimens' Variable

Specimens code	***Type of concrete***	**Cross Section Type**	***Number of Tendon***	***Bottom RFT. A_s***	***Top FRT. $A_{s'}$***	**Bond**
B3-LRU-0.70	L	R	1T12.7	2T12	2T10	U
B5-LTU-.70	L	T	1T12.7	2T12	2T10	U
B6-LLU-0.70	L	L	1T12.7	2T12	2T10	U
B-10-LRB-0.70	L	R	1T12.7	2T12	2T10	B
B11-LTB-0.70	L	T	1T12.7	2T12	2T10	B

3- Discussion of the Experimental Results

The parameters used in this study are the concrete cross section and grout. Effect of the concrete cross section is presented by the specimens B3, B5 and B6 for (R, L, T) beams sections respectively. Effect of grout is presented by the specimens (B3and B5) for unbonded tendon and (B10 and B11) for bonded tendon. Table 2 summarized the cracking, failure and service loads for all tested beams as well as their relative vertical deflection, energy absorption capacity, initial stiffness and post-cracking stiffness for all specimens.

Table 2: Summarized the Test Result of All Specimens

Specimens no.	***P_{cr}*** *(kN)*	***p_{max}*** *(kN)*	*Δ_{max}* *(mm)*	***$P@\Delta all$*** *(kN)*	***E.A*** *(kN.mm)*	***D.M*** *(mm)*	***I.S*** *(kN/mm)*	***P.S*** *(kN/mm)*
B3-LRU-0.70	30.3	89.0	51.7	70.0	3393	15.0	8.9	2.6
B5-LTU-0.70	49.1	116.1	65.1	81.2	5539	15.8	16.0	3.2
B6-LLU-0.70	46.9	103.8	52.0	77.4	4240	15.8	10.2	3.1
B10-LRB-0.70	40.1	94.0	51.8	71.5	3817	16.1	9.0	3.0
B11-LTB-0.70	50.6	124.2	61.2	84.0	5936	16.3	17.8	3.4

Where:
P_{cr} : Cracking load, **P_{max}** : Failure load, **Δ_{max}** : The vertical deflection at mid span corresponding to maximum load, ***$P_{@\Delta all}$*** : The service load corresponding to deflection at mid span = L/250,
E.A : The Energy Absorption Capacity, **D.M** : The ductility measured was defined as the deflection at 70% of failure load, **I.S** : Initial stiffness, **P.**S : Post-cracking stiffness.

3-1 Effect of Concrete Cross Section with Different Properties

The effect of concrete cross section with different properties (rectangular section, T-section and L-section) was examined for two groups considering the effect of tendon type.

3-1-1 Crack Patterns and Modes of Failure

The crack Pattern and Failure for specimens with unbonded tendon (B3, B5 and B6) shown in Fig. 7, Fig. 8 and Fig. 9 respectively. Number of cracks at service load for B3, B5 and B6 was 20, 29 and 27 respectively. Fig. 10 and Fig. 11 show the crack Pattern and Failure for specimens with bonded tendon B10 and B11. Number of cracks at service load for B10 and B11 was 25 and 40 respectively. All beams B3, B5, B6, B10 and B11 had the same failure mode stared by crushing of concrete followed by sudden collapse of the beams due to rupture of the prestressing strand and the failure was at the section of maximum moment.

3-1-2 Load deflection curve and failure loads

The test results show that, by using the compression flange in concrete beams with unbonded tendon increased the cracking load by 62.04% and 54.78% for T and L section specimens respectively and the maximum load by 30.40% and 16.60% for T and L section specimens respectively. Also, the deflection at load equal 89 kN decreased by 48.50% and 55.60% for T and L section specimens respectively as shown in Fig.12 and

Fig.13. The initial stiffness increased by 79.70 % and 14.60% for T and L section specimens respectively, as well as post-cracking stiffness for increased by 23.07% and 19.20% for T and L section specimens respectively as shown in Fig.14. while the Area under load deflection curve increased by 63.20% and 24.96% for T and L section specimens respectively as shown in Fig.15.

By using compression flange in concrete beams with bonded tendon, increased the cracking load by average 47.8% and the maximum load by average 26.36%. Also, the deflection at load equal 94 kN increased by 59.05% as shown in Fig.16 and Fig. 17. The initial stiffness increased by 62.16% as shown in Fig.18 while the Area under load deflection curve increased by 55.51% as shown in Fig.19.

3-2 Effect of Grouting

The effect of grouting (bonded and unbonded) on the behavior of tested beams was examined for two groups beams specimens considering the effect of concrete cross section (R and T).

3-2-1 Crack Patterns and Modes of Failure

The crack Pattern and Failure for specimens with rectangular cross section (B3 and B10) shown in Fig. 7 and Fig. 10 respectively, number of cracks at service load for B3 and B10 was 20 and 25 respectively. Fig. 8 and Fig. 11 show the crack Pattern and Failure for specimens with T- cross section B5 and B11, number of cracks at service load for B5 and B11 was 29 and 40 respectively. All beams B3, B5, B10 and B11 had the same failure mode stared by crushing of concrete followed by sudden collapse of the beams due to rupture of the prestressing strand and the failure was at the section of maximum moment.

3-2-2 Load Deflection Curve and Failure Loads

The test results show that, by using bonded tendon in partially prestressed concrete beams with R-section, increased the cracking load by 32.2% and the maximum load by 5.60 %, while the deflection at load equal 89 kN decreased by 23.40% as shown in Fig. 20 and Fig. 21. Also noticed that, the initial stiffness and the post-cracking stiffness increased by 1.12% and 3.04% respectively as shown in Fig. 22, while the energy absorption capacity increased by 5.11% as shown in Fig.23.

In addition by using bonded tendon in partially prestressed concrete beams with T-section, increased the cracking load by 3.05% and the maximum load by 7.00%, while the deflection at load equal 116.1 kN decreased by 32.25% shown in Fig 24 and Fig. 25 Also noticed that, the post-cracking stiffness increased by 3.75% shown in Fig. 26, while the energy absorption capacity increased by 7.10% shown in Fig. 27.

Fig. 7: Crack Pattern and Failure for Specimen B3 (LRU-0.70)

Fig. 8: Crack Pattern and Failure for Specimen B5 (LTU-0.70)

Fig. 9: Crack Pattern and Failure for Specimen B6 (LLU-0.70)

Fig. 10: Crack Pattern and Failure for Specimen B10 (LRB-0.70)

Fig. 11 :Crack Pattern and Failure for Specimen B11 (LTB-0.70)

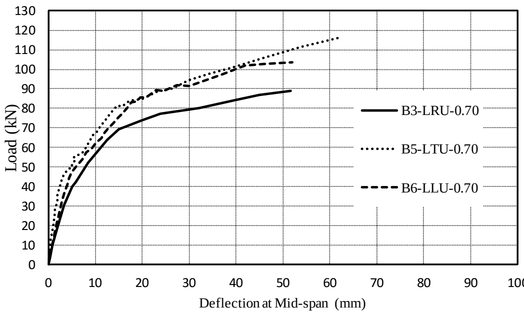

Fig. 12: Load-Deflection Relationship for SpecimensB3 LRU-0.70, B5-LTU-0.70 and B6-LLU-0.70

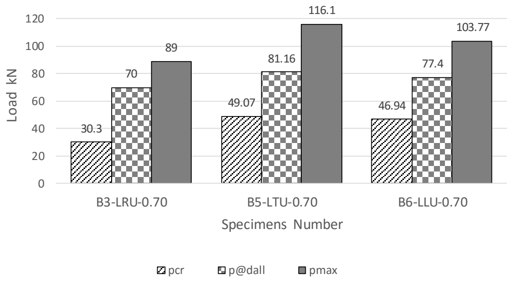

Fig. 13: Cracking, Service and Failure Load for Specimens B3 LRU-0.70, B5-LTU-0.70 and B6-LLU-0.70

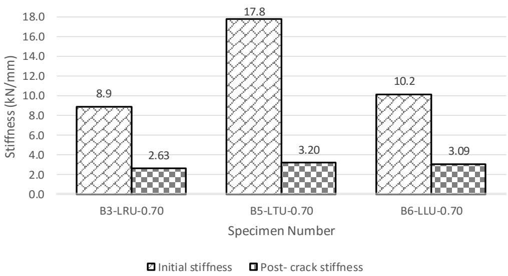

Fig. 14: Initial Stiffness and Post-Cracking Stiffness for Specimens B3 LRU-0.70, B5-LTU-0.70 and B6-LLU-0.70

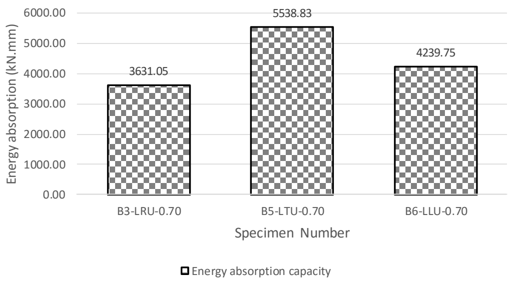

Fig.15: Energy Absorption Capacity for Specimens B3 LRU-0.70, B5-LTU-0.70 and B6-LLU-0.70

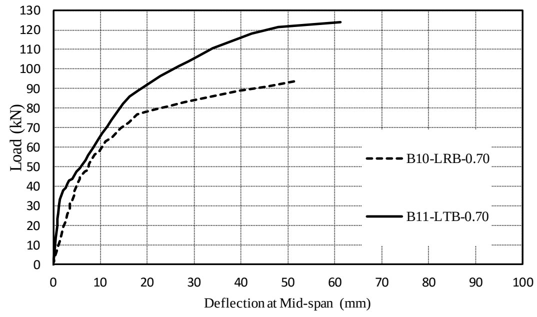

Fig. 16: Load-Deflection Relationship for Specimens B10 LRB-0.70 and B11-LTB-0.70

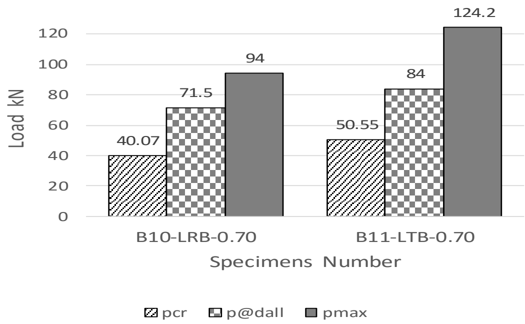

Fig. 17: Cracking, Service and Failure Load for Specimens B10 LRB-0.70 and B11-LTB-0.70

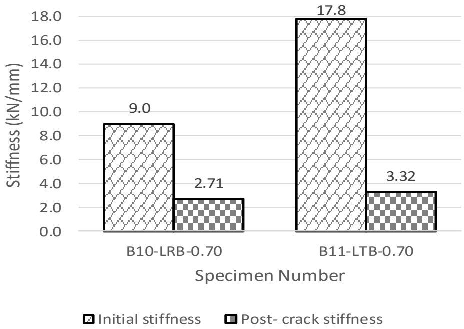

Fig. 18: Initial Stiffness and Post-Cracking Stiffness for Specimens B10 LRB-0.70 and B11-LTB-0.70

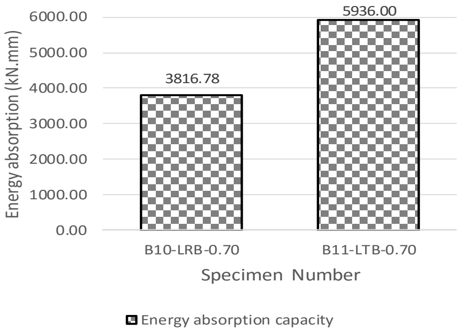

Fig. 19: Energy Absorption Capacity for Specimens B10 LRB-0.70 and B11-LTB-0.70

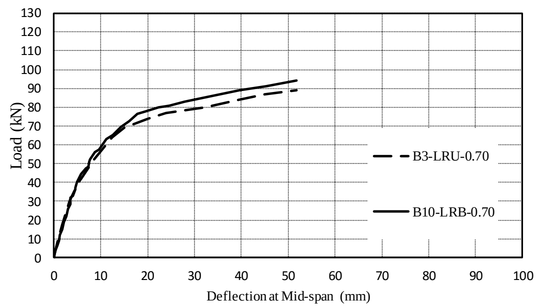

Fig. 20: Load-Deflection Relationship for Specimens B3 LRU-0.70 and B10-LRB-0.70

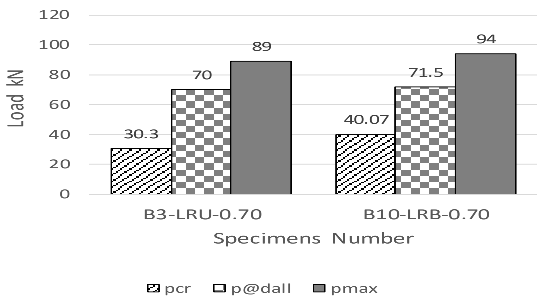

Fig. 21: Cracking, Service and Failure Load for Specimens B3 LRU-0.70 and B10-LRB-0.70

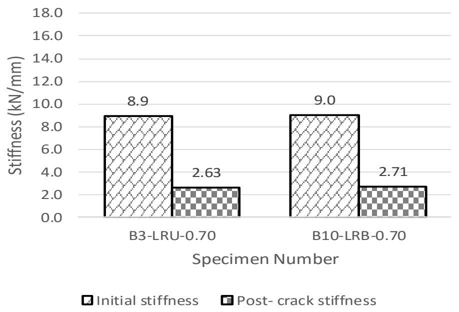

Fig. 22: Initial Stiffness and Post-Cracking Stiffness for Specimens B3 LRU-0.70 and B10-LRB-0.70

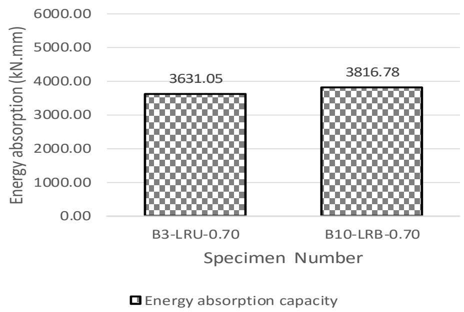

Fig. 23: Energy Absorption Capacity for SpecimensB3 LRU-0.70 and B10-LRB-0.70

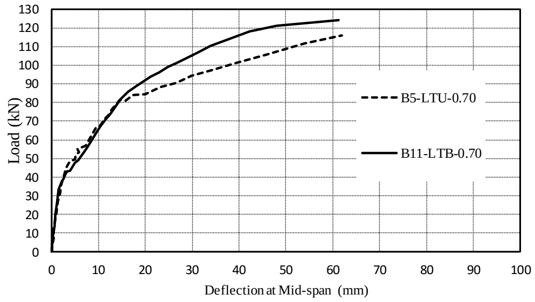

Fig. 24: Load-Deflection Relationship for Specimens B5 LTU-0.70 and B11-LTB-0.70

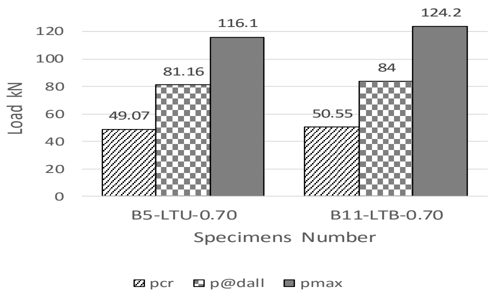

Fig. 25: Cracking, Service and Failure Load for Specimens B5 LTU-0.70 and B11-LTB-0.70

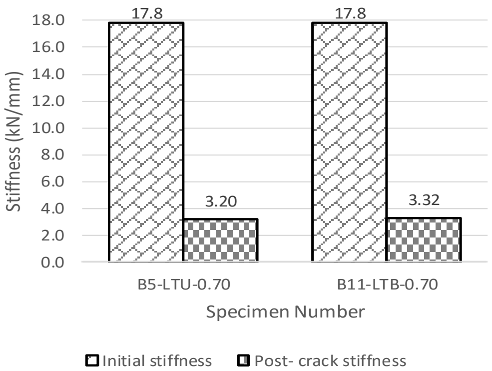

Fig. 26: Initial Stiffness and Post-Cracking Stiffness for Specimens B5 LTU-0.70 and B11-LTB-0.70

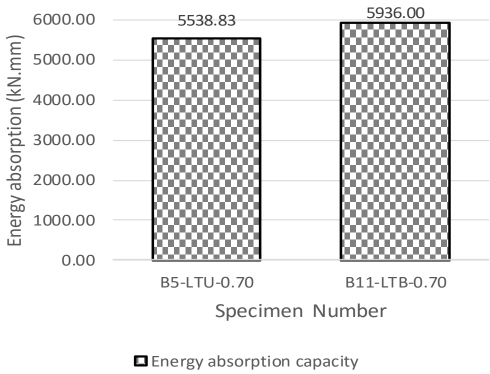

Fig. 27: Energy Absorption Capacity for Specimens B5 LTU-0.70 and B11-LTB-0.70

4- CONCLUSIONS

1- Using of compression flange in partially prestressed concrete beams with different section properties in case of unbonded tendon, increased the cracking load by 62.04% and 54.78% for T and L section specimens respectively, while the maximum load by 30.40% and 16.60% for T and L section specimens respectively.

2- Using of compression flange in partially prestressed concrete beams with different section properties in case of unbonded tendon increased the initial stiffness by 79.7 % and 14.60% for T and L section specimens respectively, as well as post-cracking stiffness for increased by 23.07% and 19.20% for T and L section specimens respectively. while the energy absorption capacity increased by 63.20% and 24.96% for T and L section specimens respectively.

3- By using grout (bonded tendon), increased the cracking load by 32.2% and 3.05% for R-section and T-section respectively. while the maximum load increased by 5.6% and 7.00% for R-section and T-section respectively.

4- By using grout (bonded tendon), increased the energy absorption capacity increased by 5.11% and 7.10% for R-section and T-section respectively.

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