Application of external prestressing on the rehabilitation of reinforced concrete beams

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Article Info	ABSTRACT
  	Concrete structure experiencing any form of distress due to multiple reasons; need remedial, strengthening, and rehabilitation measures, if the structure is to attain serviceability and strength requirements of different elements. Further, the external welding reinforcement and prestressing of the reinforced concrete members have been proven to provide an effective strengthening approach. The prestressed concrete describes a type of concrete where internal stresses are instituted to counteract the multiple tensile stresses that are characteristics of service loading. In these concrete structures, cables, hard-drawn wires or bars of high strength alloy steel are employed as tendons to generate the counteracting stresses. The prestressed concrete is made up of an active combination of steel and concrete as these materials are traditionally stressed before the application of external loads. The prestressing technique has been comprehensively reviewed in numerous articles showing that it is more effective than the RCC structures. External prestressing is emerging as an essential component of prestressing as it is structurally attractive and economical. In external prestressing, the tendons are placed outside the member to improve the load-bearing capacity of the structures and their members. In this study, a beam exposed to various loading condition and distress is strengthened using external prestressing. The ultimate deflection and failure characteristics were evaluated using different loading scenarios; beam weight, live weight, and dead weight. The results for the prestressing analysis was provided for 10 and 20 strands.

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1. Introduction

The external prestressing technique has been widely employed in the construction of urban, railway, and highway bridges [1]. In design and construction, the fundamental theory and formulas are used in the determination of the prestressing force. Durability elements such as shrinkage, temperature, and creep have been found to cause many changes in the prestressing force. Recently, there has been a surge in need for strengthened reinforced bridges due to the increase in the traffic loads, corrosion of steel reinforcement, and progressive structural aging [2]. External prestressing has been identified as a relatively new technique of strengthening these structures due to its speed and possibility of monitoring, replacing, and future tensioning of the tendons. External prestressing was initially used for strengthening of bridges, but it has since been utilized in the building of new structures and other strengthening needs [3]. Additionally, it has become a prevalent approach for external prestressing of concrete structures as it enhances the load-bearing capacity of a structural member. Steel, concrete, and timber have been utilized for external prestressing with steel and

fiber-reinforced polymer (FRP) being the most commonly used material for external prestressing [4]. In external prestressing the load is actively inducted by tendons imposing the stress on the concrete; thus, the behavior remains predominantly flexural. The external prestressing method has introduced an efficient solution for improving the rating capacity of existing bridges during the renewal of the infrastructure [5]. Furthermore, the use of external prestressing in the rehabilitation of structures as demonstrated an increase in life expectancy of the system and the individual member while simultaneously increasing the flexural strength significantly, thus reducing deflection and cracks widths.

Prestressing as a technique has been applied for stresses in the structural member whose values are known prior to the application of a full or live load [2]. The prestressed concrete describes reinforced concrete (RC) where the steel used for reinforcement is tensioned against the concrete. The stresses in these concrete structures are induced by the tensioning of the high tensile rods, strands, or wires which are completely anchored to the members that are under prestressing wire mechanical means [3]. Thus, in prestressing allowed applied to the prestressed reinforced concrete member containing bonded tendons causing equal strains on both adjacent tendon and the concrete. The compatibility of the concrete and tendon strains is a fundamental assumption in the computation for the strain and stress in prestressed sections [6]. The prestressing technique is vital for functionality and the stability of structures as it simplifies the connection and enhances the performance through limiting cracking and increasing stiffness. Prestressing can be applied in the following three areas, 1) In structural members with a greater length characterized by low rise and low structural height, 2) In building structures to attain lighter beams and slabs therefore considerably decreasing the dead load as compared to the RCC structures and 3) In Mega structures like in LNG storage Tanks, Dams, Containment walls in nuclear reactors, Chimneys, Rock Anchors and Cement Silos.

2. External prestressing

External prestressing defines post-tensioning technique where the tendons are placed outside the structure member [3]. This approach has been widely applied in the strengthening of bridges and buildings. The technique is attractive, especially in strengthening activities as it adds little weight to the initial structure making it easy to monitor, retrace, and replace tendons [2]. The technique is effective in both new and existing structures with the following advantages

1. Monitoring the profile of external tendons is easy both during and after installation, enhancing the inspection process.
2. Removal and replacement of external tendons during maintenance
3. Grouting is enhanced due to proper visualization
4. The technique reduces the dead load as the members can be made thinner.

In this research, we evaluate the applicability of external prestressing on rehabilitating reinforced concrete beams. The rehabilitation of the concrete beams is vital in the replacement and strengthening of structural members in construction. A comprehensive literature review was carried out to effectively provide a background on the emergence and use of external prestressing in strengthening structural members. Then a proposed approach is used for evaluation of prestressing and how it can be employed as a reliable and economical technique for rehabilitation of RC beams.

3. Literature Review

Demir et al. devised an alternative technique for straightening reinforced concrete beams using external steel members [1]. In this study, Demir et al., employed external steel members to improve both Shia and flexural capacities of the reinforced concrete beams (RC). The research considered two types of RC beams, i.e., ones without stirrups and those lacking the stirrups [1]. The beams were strengthened externally using steel clamps external longitudinal reinforcements. The use of steel clamps did not impact the load-bearing potential significantly of the test beams [1]. The ductility of the test beams increased significantly, and the failure characteristic changed from brittle to ductile. It was evident that the application of the clamps and longitudinal reinforcement did not considerably impact the ductility of test beams but increased the load capacities. Our research extends the analysis to create the viability of prestressing in rehabilitating RC beams.

Muthukumar et al. reports on an analytical and experimental study evaluating the use of the external prestressing technique in strengthening and rehabilitating distress RC beams. The beams in the experiment

were subjected to various degrees of distress and then strengthened using multiple levels of prestressing. The prestressed RC beams were tested for destruction [3]. The performance testing in this research investigated the beams with regards to stiffness characteristics, first crack load, failure load, crack propagation, ductility, failure mode, and the ultimate deflection. It was discovered that the trussed beam experienced delayed the first crack with improved stiffness characteristic [3]. The prestressing of the tie rod also improved the load-bearing capacity as well as stiffness features. Moreover, the load-bearing capacity of the rehabilitated beam was expanded considerably compared to the original RC beam [7]. This research dwelt on existing structures, whereas in our case, we evaluate the possibility of rehabilitating RC beams using external prestressing.

Ibrahim et al. investigated the parameters required for continuous concrete beam prestressed with external tendons. In this evaluation, he analyzes the behavior of members a different ultimate limit state. He used the ANSYS 10 computer program for dimensional finite element analysis of the model developed [8]. In comparing the flexural behavior at the ultimate capacity consider the following parameters; initial prestressing stress, concrete strength, loading arrangement, the resulting depth of the external filaments and the tendon profiles [8]. In this exercise, the final load capacity was improved as the comprehensive strength of the concrete increased. The results concluded that the surge in the effective strength led to the increase in the ultimate load effective prestressing [8]. The case of tendon profile demonstrated that the final load increased for the selected structure with different draped tendons when compared to the draped tendon profiles [9]. This analysis utilized finite element to analyze the parameters of continual concrete beam prestressed with external ligament while our research utilized the ConsiceBeam software investigate the effectiveness of external prestressing in rehabilitating RC beams.

Xue et al. acknowledge that the shear performance of a concrete beam is a vital mechanical feature; therefore, improved fear resistance is an essential component in the determination of a beams performance and its longevity [4]. This study evaluated the shear performance of concrete beams without web reinforcement by strengthening using external vertical prestressing rebars (EVPRs). Seven test beams were used for the collection of experimental data to characterize the factors influencing the shear behavior of concrete beams, i.e., stirrup ratio, comprehensive stress degree, arrangement spacing and prestressing force [4]. The results in this study showed that EVPRs substantially enhance the shear potentiality and ductility of concrete beams without the need for web reinforcement [10]. Additionally, the failure mode of these concrete beams changes from brittle diagonal tension tour mildly ductile shear compression. The shear and flexural cracks are entirely developed in these beams. The shear performance of the concrete beams become profound as the compressive stress degree and stirrup ratio are increased; the vertical compressive stress generated by the EVPRs would decrease the fundamental tensile stress of the concrete thus preventing share cracking while enhancing shear tolerance of the concrete structure [4]. The EVPRs can be utilized in the initial stages of the construction of the critical shear crack (CSC) to create stirrups during shear failure by sharing the shear load [7]. The research concludes that EVPR effectively improves the shear performance of concrete beams. This research dwells on the effect of EVPR on shear performance while ignoring the impact of external prestressing on the strengthening of RC beams. Our research will characterize the impact of external prestressing on RC beams providing the performance under ultimate deflection.

Yue-lin et al. studied the strengthening of RC beams utilizing prestressed glass fiber-reinforced polymer (PGFRP). The carbon fiber-reinforced polymer (CFRP) has gained popularity for employment in the repair of restoration material for the deteriorated RC structures [5]. The CFRP material is very stiff thus the distinction between the properties of the CFRP sheets and concrete will not favor the transfer of prestressing from the CFRP sheets to RC structure components [11]. Glass fiber-reinforcement polymer (GFRP) sheets have an elasticity Modulus that is close to that of concrete that is why it was selected in the study. In this study, Yue-lin et al. tested the deflection and the load-bearing capacity of the strengthened RC beams using the PGFRP and GFRP. The T-and Inverted-T shaped beams employed as the under-strengthened and over-strengthened beams. The GFRP sheets in the experiment were prestressed to one-half of their tensile potentiality prior to bonding with the T-and Inverted-T shaped RC beams [5]. The results illustrated that the prestressed tension in the PGFRP led to the cambers in the RC beams without the cracks in the tensile faces [5]. The PGFRP sheets significantly improved the load-carrying capacity. Similarly, the T-shaped beams combined with the GFRP sheet enhances the load-carrying capacity. Under external loads, the GFRP experienced a more significant deflection than the PGFRP [5]. This research utilizes glass in reinforcing the concrete beams, but in our study, we utilize steel strands for external prestressing to rehabilitate RC beams.

4.   The proposed system

This research applies the external prestressing to rehabilitate RC beams. The proposed system utilized Concise Beam 4.62i to simulate the various loading scenarios of the prestressed RC beams that are being rehabilitated. This system would accomplish a comprehensive evaluation of the effect of the tendons on the rehabilitation of the prestressed RC beams on shear capacity and crack distribution giving a detailed behavior of external prestressed RC beam. This process will seek to satisfy the following requirements;
The vertical components of the external prestressing resist shear force in the structural member.
The prestressing will flatten the inclination of the shear crack, therefore, enhancing the impact of the stirrups. The external prestressing increases the degree of shear compression zone thus improving the shear contribution of the concrete.
The prestressing of the diagonal shear crack is delayed; therefore, the propagation of the critical shear crack would be restrained by the prestressing, resulting in a relatively large shear crack load and shear strength.
The results of the research will be determined using the following shear strength formula. The formula would characterize the tendon distribution.

$$V_u = K(V_c + V_s) + V_p$$

Where

K is the increasing coefficient of the external prestressing given by $\sqrt{\dfrac{fpc}{ft}} + 1$

V_p is the external tendon shear contribution
Material Properties
The concrete strength is a significant parameter for the evaluation of the external prestressing used in the rehabilitation of the RC beams as it will affect the results in the simulation, especially in shear strength. Table 1 below illustrates the features of the concrete used in the numerical analysis.

Table 1. The properties of the concrete material used in the simulation.

Precast Beam	
Parameter	Value
Density (kgm3)	2400
Compressive strength (MPa)	40
Modulus of Elasticity (MPa)	29602
Cast-in-Place Pour	
Parameter	Value
Density (kgm3)	2400
Compressive strength (MPa)	30
Modulus of Elasticity (MPa)	26621
Prestressed beam at Transfer	
Parameters	Value
Compressive strength (MPa)	28
Modulus of Elasticity (MPa)	25968
During Initial Lifting	
Parameters	Value
Compressive strength (MPa)	30
Modulus of Elasticity (MPa)	26621

The experimental specimens consisted of different strands. The first scenario the prestressed concrete was made of ten strands and twenty for the second. Figure 1a demonstrates the cross-section of the specimen below and while figure 1b shows the length of the specimen that was selected for the deflection analysis.
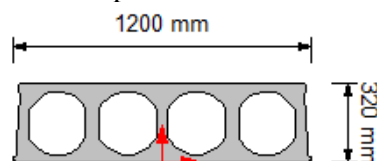

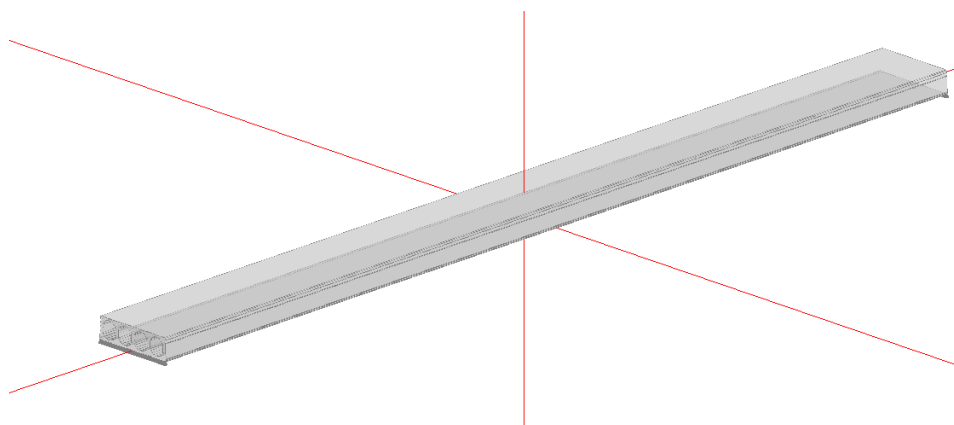Figure 1a. The cross-section of the specimen used for the simulation

Figure 1b. The length of the specimen used for the simulation

The section properties for the specimen selected in the experiment is illustrated in table 2. The parameters will define the loading behavior of the specimen.

Table 2: The parameters for the loading of the concrete

Parameters	Value
Cross-Sectional Areas, A	178514 mm3
Moment of Inertia, I	2373268012 mm4
Height of the Centroid, yb	158 mm
Volume to surface Ratio, V/S	59 mm
Shear Width, bw	251 mm
Height of Section	320 mm
Width of section	1200 mm

5. Results

The beam specimen was set up as illustrated in figure 2a, b, c for the various position. The beam will be support at both ends using the frames. The beams will be evaluated for three different scenarios i.e., initial load (FC), dead load (DL) and the Live Load (LL).

Figure 2a. The initial loading of the system setup for the 1.5 kN

Figure 2b. The set up for the dead load for 1.25 kN

Figure 2c. The set up for the Live load for 1.0 kN

The loading in figure 2a, b and c show the various loading scenarios that were used to evaluate the rehabilitation ability of external prestressing to rehabilitate the RC beams [12,16,17]. The beam is supported between two-point supports that will ensure the load is applied through the desired points to initiate deflection [1,18]. The loading on the beams was evenly distributed to be able to monitor the shear cracking and the deflection of the beams. The result in the simulation was recorded for the deflection.

Table 3. Deflection for 10 Strands in the Beam

FINAL LONG-TERM DEFLECTION ESTIMATE
(-ve = deflection down, +ve = camber up)

Design Code Used: CSA A23.3-14

Location x m	Primary P/S P mm	Beam Weight D mm	Dead Load D mm	Live Load L mm	Net Deflection mm
0.000	0.0	0.0	0.0	0.0	0.0
0.064	2.9	-1.3	-0.8	-0.3	0.5
0.280	12.7	-5.6	-3.6	-1.3	2.1
0.560	25.1	-11.2	-7.2	-2.6	4.1
0.840	37.1	-16.7	-10.8	-3.9	5.7
1.120	48.6	-22.2	-14.3	-5.2	6.9
1.400	59.5	-27.6	-17.7	-6.4	7.8
1.680	69.9	-32.8	-21.1	-7.7	8.4
1.960	79.8	-37.9	-24.3	-8.9	8.7
2.240	89.2	-42.9	-27.5	-10.0	8.8
2.520	98.0	-47.6	-30.6	-11.1	8.8
2.800	106.3	-52.2	-33.5	-12.2	8.5
3.080	114.1	-56.5	-36.3	-13.2	8.1
3.360	121.4	-60.6	-38.9	-14.2	7.7
3.640	128.1	-64.5	-41.4	-15.1	7.1
3.920	134.3	-68.1	-43.7	-15.9	6.6
4.200	139.9	-71.4	-45.9	-16.7	5.9
4.480	145.0	-74.5	-47.8	-17.4	5.3
4.760	149.6	-77.2	-49.6	-18.0	4.7
5.040	153.6	-79.7	-51.2	-18.6	4.2
5.320	157.1	-81.8	-52.5	-19.1	3.6
5.600	160.1	-83.6	-53.7	-19.5	3.2
5.880	162.5	-85.1	-54.7	-19.9	2.8
6.160	164.4	-86.3	-55.4	-20.2	2.5
6.440	165.7	-87.2	-56.0	-20.3	2.2
6.720	166.5	-87.7	-56.3	-20.5	2.1
7.000	166.8	-87.8	-56.4	-20.5	2.0
7.280	166.5	-87.7	-56.3	-20.5	2.1
7.560	165.7	-87.2	-56.0	-20.3	2.2
7.840	164.4	-86.3	-55.4	-20.2	2.5
8.120	162.5	-85.1	-54.7	-19.9	2.8
8.400	160.1	-83.6	-53.7	-19.5	3.2
8.680	157.1	-81.8	-52.5	-19.1	3.6
8.960	153.6	-79.7	-51.2	-18.6	4.2
9.240	149.6	-77.2	-49.6	-18.0	4.7
9.520	145.0	-74.5	-47.8	-17.4	5.3
9.800	139.9	-71.4	-45.9	-16.7	5.9
10.080	134.3	-68.1	-43.7	-15.9	6.6
10.360	128.1	-64.5	-41.4	-15.1	7.1
10.640	121.4	-60.6	-38.9	-14.2	7.7
10.920	114.1	-56.5	-36.3	-13.2	8.1
11.200	106.3	-52.2	-33.5	-12.2	8.5
11.480	98.0	-47.6	-30.6	-11.1	8.8
11.760	89.2	-42.9	-27.5	-10.0	8.8
12.040	79.8	-37.9	-24.3	-8.9	8.7
12.320	69.9	-32.8	-21.1	-7.7	8.4
12.600	59.5	-27.6	-17.7	-6.4	7.8
12.880	48.6	-22.2	-14.3	-5.2	6.9
13.160	37.1	-16.7	-10.8	-3.9	5.7
13.440	25.1	-11.2	-7.2	-2.6	4.1
13.720	12.7	-5.6	-3.6	-1.3	2.1
13.936	2.9	-1.3	-0.8	-0.3	0.5
14.000	0.0	0.0	0.0	0.0	0.0

Table 3 above illustrates the ConsiceBeam results for ten strands used for external prestressing to rehabilitate the RC beams [13]. The results illustrate that the greatest deflection of 8.8 mm was recorded near the end of the bar close to the support. The bulk of the deflection was caused by the weight of the beam, which was considerable [14]. The value for loading is recorded as negative from the normal as it shows the direction against gravity to cause deflection.

Table 4. Deflection for 20 Strands in the Beam

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FINAL LONG-TERM DEFLECTION ESTIMATE
(-ve = deflection down, +ve = camber up)

Design Code Used: CSA A23.3-14
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Location x m	Primary P/S P mm	Dead Load D mm	Beam Weight D mm	Live Load L mm	Net Deflection mm
0.000	0.0	0.0	0.0	0.0	0.0
0.064	5.4	-0.8	-1.3	-0.3	3.0
0.280	23.7	-3.7	-5.8	-1.3	12.9
0.560	46.9	-7.3	-11.4	-2.7	25.5
0.840	69.1	-10.8	-16.8	-3.9	37.6
1.120	90.4	-14.2	-22.0	-5.2	49.0
1.400	110.7	-17.5	-27.2	-6.4	59.6
1.680	130.0	-20.8	-32.2	-7.6	69.5
1.960	148.4	-23.9	-37.1	-8.7	78.6
2.240	165.7	-27.0	-41.8	-9.8	87.1
2.520	182.1	-29.9	-46.4	-10.9	94.9
2.800	197.5	-32.8	-50.8	-11.9	102.1
3.080	211.9	-35.4	-54.9	-12.9	108.7
3.360	225.3	-38.0	-58.9	-13.8	114.7
3.640	237.8	-40.4	-62.6	-14.7	120.1
3.920	249.2	-42.6	-66.0	-15.5	125.1
4.200	259.7	-44.7	-69.2	-16.2	129.5
4.480	269.1	-46.6	-72.2	-16.9	133.5
4.760	277.6	-48.3	-74.8	-17.6	137.0
5.040	285.1	-49.8	-77.2	-18.1	140.0
5.320	291.6	-51.1	-79.2	-18.6	142.6
5.600	297.0	-52.2	-81.0	-19.0	144.8
5.880	301.5	-53.2	-82.4	-19.3	146.6
6.160	305.0	-53.9	-83.5	-19.6	148.0
6.440	307.5	-54.4	-84.4	-19.8	149.0
6.720	309.0	-54.7	-84.8	-19.9	149.5
7.000	309.5	-54.8	-85.0	-19.9	149.7
7.280	309.0	-54.7	-84.8	-19.9	149.5
7.560	307.5	-54.4	-84.4	-19.8	149.0
7.840	305.0	-53.9	-83.5	-19.6	148.0
8.120	301.5	-53.2	-82.4	-19.3	146.6
8.400	297.0	-52.2	-81.0	-19.0	144.8
8.680	291.6	-51.1	-79.2	-18.6	142.6
8.960	285.1	-49.8	-77.2	-18.1	140.0
9.240	277.6	-48.3	-74.8	-17.6	137.0
9.520	269.1	-46.6	-72.2	-16.9	133.5
9.800	259.7	-44.7	-69.2	-16.2	129.5
10.080	249.2	-42.6	-66.0	-15.5	125.1
10.360	237.8	-40.4	-62.6	-14.7	120.1
10.640	225.3	-38.0	-58.9	-13.8	114.7
10.920	211.9	-35.4	-54.9	-12.9	108.7
11.200	197.5	-32.8	-50.8	-11.9	102.1
11.480	182.1	-29.9	-46.4	-10.9	94.9
11.760	165.7	-27.0	-41.8	-9.8	87.1
12.040	148.4	-23.9	-37.1	-8.7	78.6
12.320	130.0	-20.8	-32.2	-7.6	69.5
12.600	110.7	-17.5	-27.2	-6.4	59.6
12.880	90.4	-14.2	-22.0	-5.2	49.0
13.160	69.1	-10.8	-16.8	-3.9	37.6
13.440	46.9	-7.3	-11.4	-2.7	25.5
13.720	23.7	-3.7	-5.8	-1.3	12.9
13.936	5.4	-0.8	-1.3	-0.3	3.0
14.000	0.0	0.0	0.0	0.0	0.0

Table 4 above illustrates the ConsiceBeam results for 20 strands used for external prestressing to rehabilitate the RC beams [15,19]. The results demonstrate that the greatest deflection of 149 mm was at the center of the bar in between the supports. The depression was caused by the loading as the effect of the loads could be observed easily.
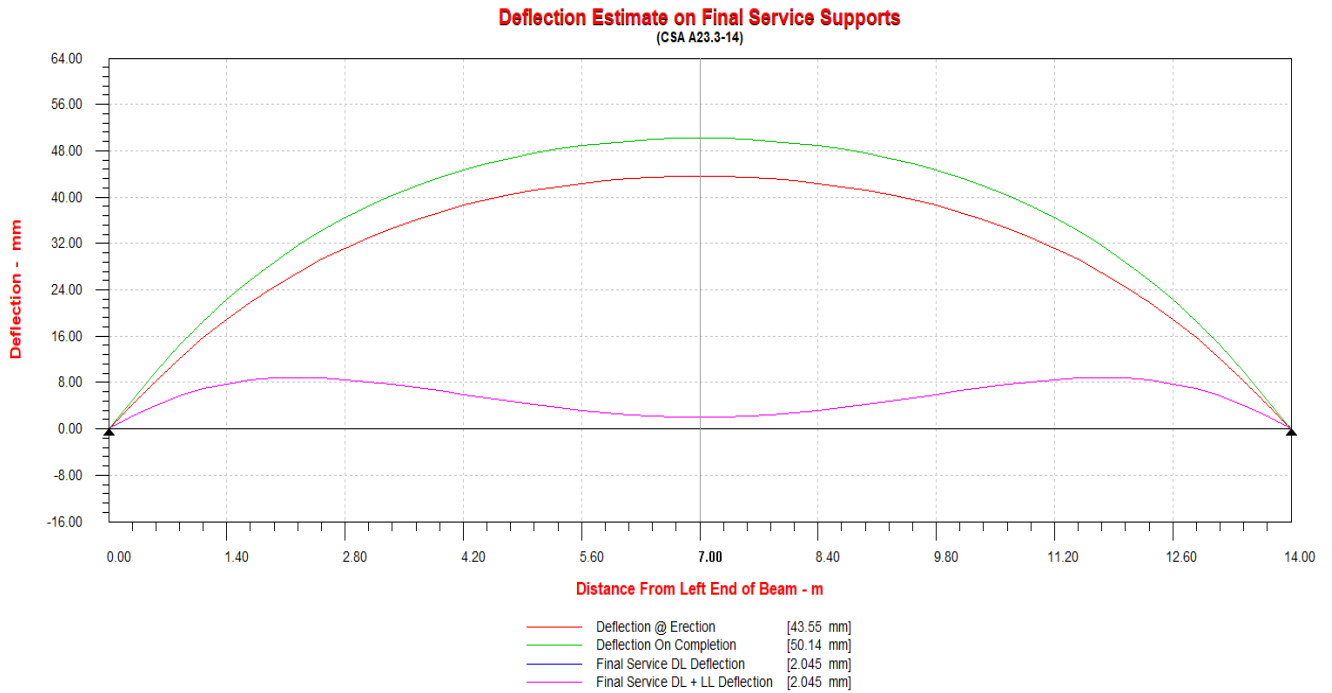
Figure 3. The deflection profile for the ten strands and the limits allowable for the structure member.

The deflection in the specimen with ten strands had a profile outlined in the graph above. The deflection was 8.8 mm on the two crests, whereas the allowable deflection for the structural member was within the range 43.55-50.14 mm [15]. It is evident the loading on the member did not significantly affect the properties and the operation of the beam.
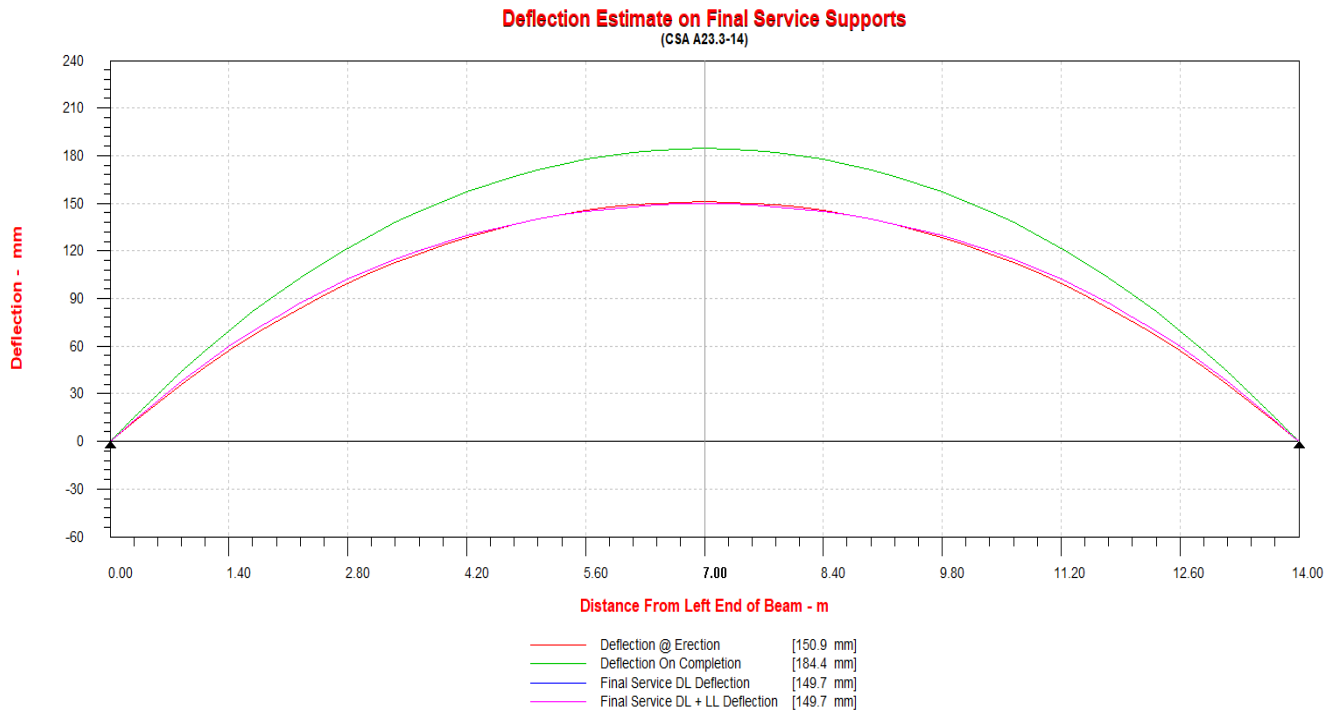

Figure 4: The deflection profile for the 20 strands and the limits allowable for the structure member.

The 20 strand specimen described a deflection formation illustrated in the figure above. The RC beam was considerably deflected at the center [13]. The deflection for this section was 149 mm, which was close to the

range in the allowable limit of 150.9-184.4 mm. The loading in this scenario led to increased stress on the beam.
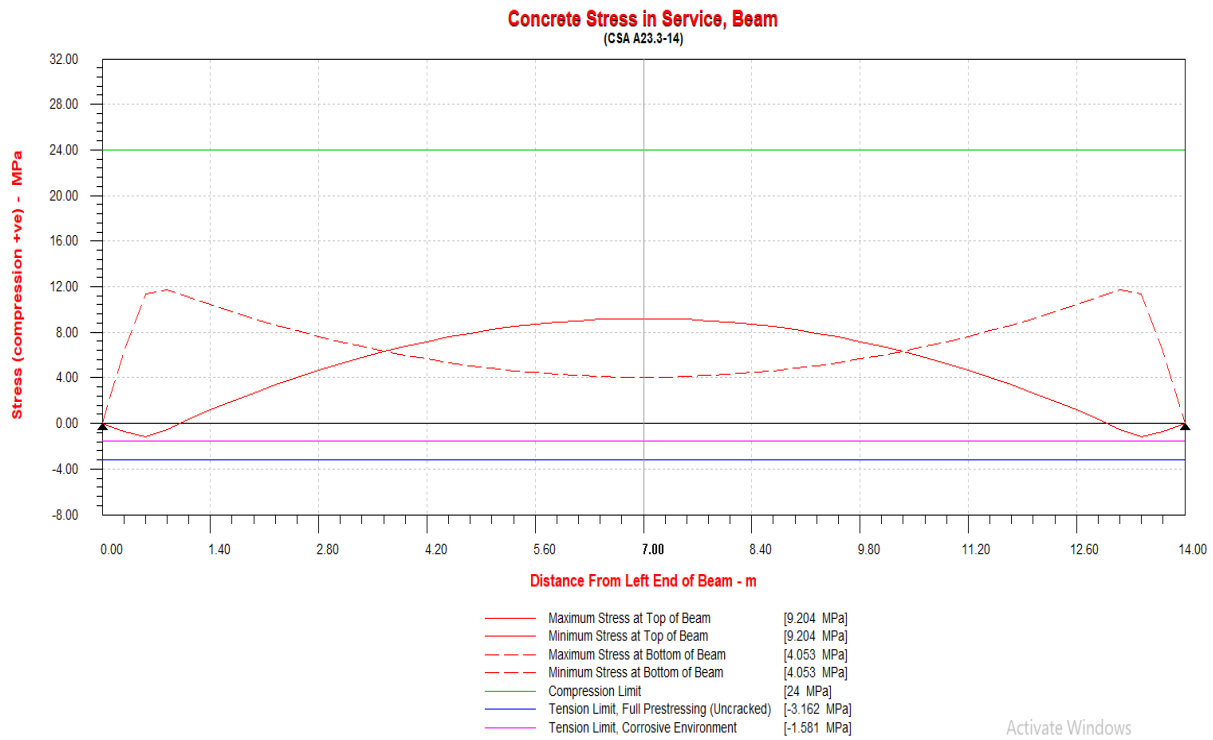

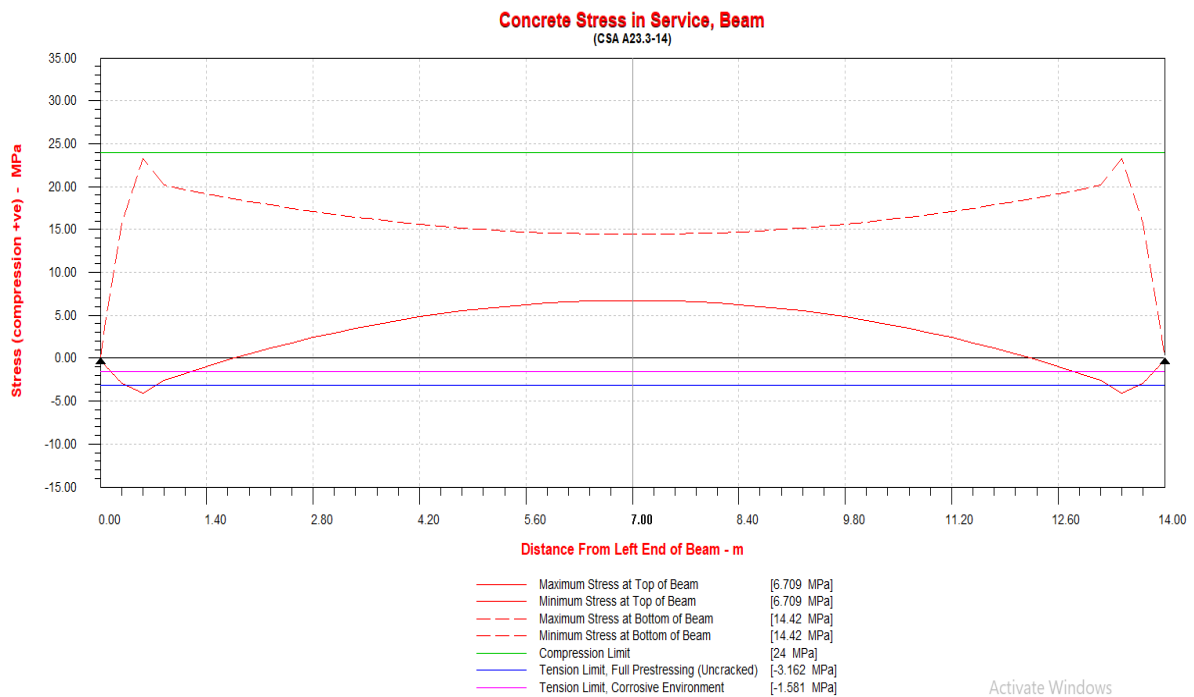Figure 5: The stress profile for the RC beam for the 10 strand scenario

Figure 6: The stress profile for the RC beam for the 20 strand scenario

The specimen in this research were tested using compressive strength on the deflection and cracking properties [1]. The results have shown that external prestressing can be used to rehabilitate RC beams. Further, the results in figure 5 and 6 demonstrate that external prestressing increases the shear strength and the loading capacity of the rehabilitated RC beams.

6.   Conclusion

Conclusively, the study has evaluated the application of external prestressing in rehabilitating reinforced concrete beams. The external prestressing techniques strengthened the restored RC beams by increasing the loading carrying capacity and the shear strength. The results in this evaluation can be used to recommend the future application of external prestressing, especially in urban bridges. The ability to monitor, remove, and replace the structural members in a bridge makes it easy to maintain the structure. It is now evident that external prestressing can be used for rehabilitation of the structures.

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