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DETERMINATION OF OPTIMUM BOND THICKNESS OF REINFORCED CONCRETE BEAM STRENGTHENED EXTERNALLY BY BONDED STEEL PLATES

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ABSTRACT

Epoxy bonded steel plate (EBP) had been shown to be an effective structural strengthening method for degraded and old civil structures. A good number of research have been geared to study strengthening technique over the last two decades. However, the optimum bond thickness that would be structurally acceptable remains a gap in the literature. The intention of this study is to determine experimentally the optimum bond thickness of reinforced concrete (RC) beam strengthened externally by bonded steel plates. To achieve the aim, thirty-Nine (39) beams were tested. Each beam sample had 100 x 150 mm cross section and 1100mm length with a shear span to depth ratio (av/d) of 2.5 and were reinforced with 2ϕ10 mm and 2Φ8 mm reinforcements in the zone presumed to go into tension and compression respectively. The shear reinforcements were provided with Φ6mm links at 220mm centre to centre. Four bond layer thicknesses, 2 mm, 4mm 6 and 8mm, were chosen. For each bond layer thickness, three (3) levels of plate thickness were chosen-l.0 mm, 1.5 mm, and 2mm, all with constant breadth and length of 80mm and 1000mm respectively. The tension surfaces of the beams were prepared to remove all cement paste and were thoroughly cleaned of loose particles. Both side of the steel plates were totally cleaned and then kept safeguarded from contamination. The two-part structural epoxy resin was mixed thoroughly and bonded to the tension surfaces of the beams to the required thickness-2mm, 4mm, 6mm, and 8mm. the steel plate was placed at the right location, and kept in position for proper boding. At least 7-day was allowed between strengthening and loading of the beams. The beams were strengthened with 1, 1.5 and 2mm thick plates of four different levels of bond thickness-2mm, 4mm, 6mm, and 8mm respectively at the tension face. All the beams were instrumented as simply supported. According to the findings, there is a maximum bond thickness that would be structurally acceptable for RC beams strengthened or upgraded with structural steel plate. Results also confirmed that as the bond thickness increases, the ductility index reduces. Strengthening reinforced concrete beam with steel plate increases the stiffness of the beam. In order to maintain composite behavior up to the point of failure, steel plate thickness to bond thickness ratio should be kept within the range of 0.3 to 0.4 for beams strengthened while the thickness-to-width ratio of steel plates shall not be more than 0.015

KEYWORDS: *Optimum bond thickness; strengthening: Contribution to bending strength: Ductility index*

1. INTRODUCTION

Strengthening reinforced concrete by steel plate bonding started during the mid-60s (L'Hermite, 1967, Raithby, 1980, Bresson 1971, Klaiber et. al, 1987, Lerchental, 1967, Swamy *et al*, 1989, Ladner and Webber C., 1981, Täljsten, 1990,) in South Africa where a reinforced concrete (RC) beam element in an estate structure required to be strengthened as a result of omission of internal reinforcing bars during construction stage. According to Dussek, (1974), epoxy bonded steel plate was used to solve the omission. Steel plates as external reinforcement to strengthen existing concrete elements with epoxy adhesive is an effective means of improving their service loads and also increasing their ultimate strength. The technique's primary advantages are that the strengthening may be completed very fast and simple while the structure is still in use. Also, the consequent variations in member sizes are often minor. The approach has been widely applied in several nations for civil engineering structures in tension, compression and shear.

Anandhi *et al*., (2018) used galvanized steel sheets to improve the bending and shear properties of RC. The research results recorded that the strengthened beam had higher ductility and strength than the control beam and also, the encapsulated galvanized sheet can be effectively considered to repair the concrete beam.

Ashraf (2014) researched on RC members strengthened with steel plate sheet using mechanical tie approach. Study shows that the deformation of the beam is reduced by substituting the internal tension steel with an external steel plate under same load. According to the authors, “the reference beam uses 150 mm^2 of internally drawn steel without the outer plate showing maximum center deflection, while the inner steel beam with 150 mm^2 outer steel plate exhibit minimal deflection".

Khattab *et al*., (2017) investigated the possible use of steel plate openings with RC deep beams. The study parameters include the shape of the opening, steel plates and stud connectors. Compared to the reference solid beam, the construction of circular, rectangular and square openings, resulted in the reduction of ultimate capacity by approximately 20.5%, 18.3%, 24.7% and 31.7%, respectively.

Xiang *et al*., (2006) researched on the mechanical properties of RC beams reinforced with bonded steel plate and CFRP externally. The experimental and theoretical analysis findings revealed that strengthening with steel plate composite beam is more effective than with CFRP plate. The study results have been proved in the historical high-rise building project in Shanghai.

Ha and Mutsuyoshi (2008) studied the usefulness of various shear strengthening approaches using epoxy-bonded steel strips, steel sheets, external anchoring stirrups and carbon fiber reinforced plastic (CFRP) sheets and to improve the shear resistance of reinforced concrete beams. The results confirmed the usefulness of the external anchoring stirrups, bonded steel plate, and CFRP plate for shear strengthening of RC beams.

Kamal *et al*, (2019) studied various methods on upgrading of RC beams subjected to flexure and shear. The study revealed that "the bearing capacity of CFRP strengthened beams enhances by 27 and 24% in terms of bending and shear stress acceptance, whereas the beams upgraded with Steel Fiber Reinforced Concrete (SFRC) have the lowest and did not meet the purpose of the study".

Akinropo and Dundu, (2014) indicated that many studies have been carried out concerning the use of steel plates in strengthening using the External Bonded Retention (EBR) technique and the Near Surface Approach (NSM). These methods have shown to be extremely effective. Although near-surface mounting is a relatively new technology, its effectiveness may be hindered by insufficient concrete cover. Because strengthening practices are usually applied to older structures, data on concrete masking and reinforcement may not be available. Although concrete coverings are available, they may not be sufficient to accommodate the required grooves. The NSM can also damage the reinforcement bar during the preparation of the groove. Based on these challenges, external bonded reinforcing techniques have better practical applications than near surface mounting (NSM) techniques.

Alaa, (2013) evaluated experimentally the behaviour of reinforced concrete beams upgraded using effective reinforcement materials. The author uses plain and RC layers and steel plates. Study was carried out on beams (100 x 150 x 1100 mm). The beam was grouped into three A, B and C. The group A was strengthened with a 2 cm thick concrete layer. The group B was strengthened with a 2 cm thick concrete layer reinforced with a mesh. The group C was strengthened with steel plate. The results showed that for Group A and Group B, the ductility, ultimate strength, failure mode and stiffness, of RC beams will be influenced by the type of mesh and concrete layer when applying the same thickness of reinforcement layer.

The optimum bond thickness that would be structurally desirable by epoxy-bonded steel plates strengthening techniques is not thoroughly understood, although, the plate gluing method has been widely used in practice. There have been a number of investigations on the structural behavior of steel plated beams reported, however, there has been no systematic examination of the optimum bond thickness that would be desirable for the structural behavior of steel plated beams. In this work, experimental test data are presented on the optimum bond thickness of RC Beam strengthened externally by epoxy bonded steel plates. The key geometric and mechanical parameters study is; variations in steel plate thickness, variations in bond thickness and bending strength, ductility index, mode of failure, ultimate Load capacity respectively.

2. MATERIALS AND METHODS

Thirty-Nine (39) beams were tested. Each beam sample had 100 x 150 mm cross section and an effective span of 1100 mm with a shear span to depth ratio (a_v/d) of 2.5 and were reinforced with 2φ10 mm and 2Φ8 mm reinforcements in the zone presumed to go into tension and compression respectively. The shear reinforcements were provided with Φ6mm links at 220mm centre to centre. The beam samples were tested simply supported and subjected at one-third points load. Table 1.0 and Figure 1.0 list the various beam arrangements. Four bond layer thicknesses, 2 mm, 4mm 6 and 8mm, were chosen. For each bond layer thickness, three (3) levels of plate thickness were chosen-l.0 mm, 1.5 mm, and 2mm, all with constant breadth and length of 80mm and 1000mm respectively. Beams FA-0 (see Table 1) was used as a control. Beam PFA-2, PFA-4, PFA-6 and PFA-8 were strengthened with 1.0mm steel plate of four different levels of bond thickness-2mm, 4mm, 6mm, and 8mm respectively at the tension face. While Beam PFB-2, PFB-4, PFB-6 and PFB-8 were strengthened with 1.5mm steel plate of four different levels of bond thickness-2mm, 4mm, 6mm, and 8mm respectively at the tension face. Also, Beam PFC-2, PFC-4, PFC-6 and PFC-8 were strengthened with 2mm steel plate of four different levels of bond thickness-2mm, 4mm, 6mm, and 8mm respectively at the tension face.

2.1 Material Properties

The concrete used was produced in the structural laboratory, Niger Delta University, Nigeria. The mix composition was l: 2:4 with a water-cement ratio of 0.55. After 28-day of concrete curing, the compressive strength was tested by crushing three concrete cube samples. The average strength (f_m) was calculated to be 29MPa.

The main internal reinforcement for the study beams was of high yield stress bars with yield and ultimate tensile strength of 420MPa and of 500MPa respectively. The links chosen for this study were of mild yield stress materials with a yield stress of 245MPa and an ultimate tensile strength of 325MPa.

The steel plates used for strengthening were also of mild yield stress materials. Three steel plate thicknesses of 1.0 mm, 1.5mm and 2mm, were used with yield stress of 230MPa and ultimate strengths of 320MPa.

The adhesive used in the study was a structural two-part of Sikadur(R)-31 epoxy resin with a mortar-like consistency. The adhesive had a tensile strength, tensile modulus of elasticity, Bending Strength and Tensile Bond Strength of 15-20, 3300, 30-40 and 4-15MPa respectively.

Table 1 Beams details

Sample ID	Steel plate thickness (mm)	Bond thickness (mm)	Internal reinforcement		Tension reinforcement ratio	Strengthening configuration
			Tension zone	Compression zone		
FA-0	-	-	2φ10	2φ8	0.012	Control Beam
PFA-2	1.0	2.0	2φ10	2φ8	0.012	Flexure
PFA-4	1.0	4.0	2φ10	2φ8	0.012	Flexure
PFA-6	1.0	6.0	2φ10	2φ8	0.012	Flexure
PFA-8	1.0	8.0	2φ10	2φ8	0.012	Flexure
PFB-2	1.5	2.0	2φ10	2φ8	0.012	Flexure
PFB-4	1.5	4.0	2φ10	2φ8	0.012	Flexure
PFB-6	1.5	6.0	2φ10	2φ8	0.012	Flexure
PFB-8	1.5	8.0	2φ10	2φ8	0.012	Flexure
PFC-2	2.0	2.0	2φ10	2φ8	0.012	Flexure
PFC-4	2.0	4.0	2φ10	2φ8	0.012	Flexure
PFC-6	2.0	6.0	2φ10	2φ8	0.012	Flexure
PFC-8	2.0	8.0	2φ10	2φ8	0.012	Flexure

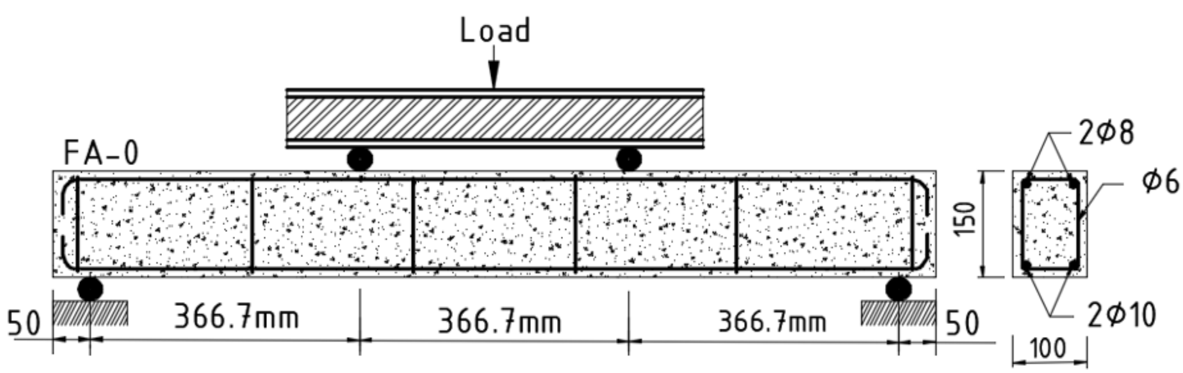

Figure 1: Beam configuration

2.2 Strengthening procedure
The tension surfaces of the beams were prepared to remove all cement paste and were thoroughly cleaned of loose particles. The steel plates were cut to the required sizes. Both sides of the steel plates were totally clean and then safeguards from contamination. The structural two-part epoxy resin was mixed thoroughly (Table 2) was applied to the tension surfaces of the beams to the required thickness-2mm, 4mm, 6mm, and 8mm. the steel plate was placed at the bottom face, and kept in position for proper boding. At least 7-day was allowed between strengthening and loading of the beams. All the study beams were instrumented as simply supported. The deformation at midspan was measured at every load-step through dial gauges. Furthermore, crack patterns and locations where these cracks were observed are also recorded regularly throughout the testing.

Figure. 2: Beam surface treatment and Epoxy Resin

3. RESULTS AND DISCUSSION
Only relevant data on the determination of optimum bond thickness of reinforced concrete beam strengthened externally by bonded steel plates are presented below.

3.1 Beams strengthened with 1.0mm-thick plates
Beam PFA-2, PFA-4, PFA-6, and PFA-8 were strengthened with 1.0mm-thick plates at the tension face with four different levels of bond thickness (2mm, 4mm, 6mm, and 8mm). Table 2 presents the experimental test results used to determine the optimum bond thickness of the strengthened reinforced concrete beams. Each beam was tested, examine, and compared to the reference beam against the deformation, ductility index, steel plate contribution to structural behavior, mode of failure, and ultimate failure load. Table 3, and Figure 3, 4 and 5 present 1.0mm steel plate contribution to bending capacity, failure load vs bond thickness, ductility index vs bond thickness, and load against deformation respectively.

Table 2: Test Results of Beams strengthened with 1.0mm-thick plates

Sample ID	Yield Load (kN	Deformation At Yield load (mm)	Failure Load (kN)	Deformation At Failure load (mm)	Mode of Failure
FA-0	28.74	3.85	37.33	4.05	Flexure
PFA-2	26.00	1.55	48.67	4.60	Shear
PFA-4	28.35	2.05	51.29	4.57	Shear
PFA-6	36.83	3.35	49.70	5.66	Shear
PFA-8	35.76	3.43	46.30	4.00	Shear

Table 3: 1.0mm Steel Plate Contribution to Bending Capacity

Sample ID	Failure Load (kN)	Bending Capacity M_{exp}, (kNm)	Percentile Contribution to Bending Capacity (%)
FA-0	37.33	6.84	-
PFA-2	48.67	8.92	30.41
PFA-4	51.29	9.40	37.43
PFA-6	49.70	9.11	33.18
PFA-8	46.30	8.49	24.12

3.1.1 Ultimate Load-Carrying

Beam FA-0 ((Without steel plate)

Beam FA-0 was used as reference beam (without steel plate) to compare the load-carrying and bending capacities of the strengthened beams. At a load of 11.0kN, the first crack appeared directly at the mid-span. Flexural stresses were noted to be the cause of the crack. The crack propagates to the web as the load increases. The load versus midspan graph for FA-0 is shown in Figure 5. The beam failed by the yielding of internal rebars. Beam FA-0 yielded at a load of 28.7kN and an ultimate load of 37.33kN as shown in Figure 5.

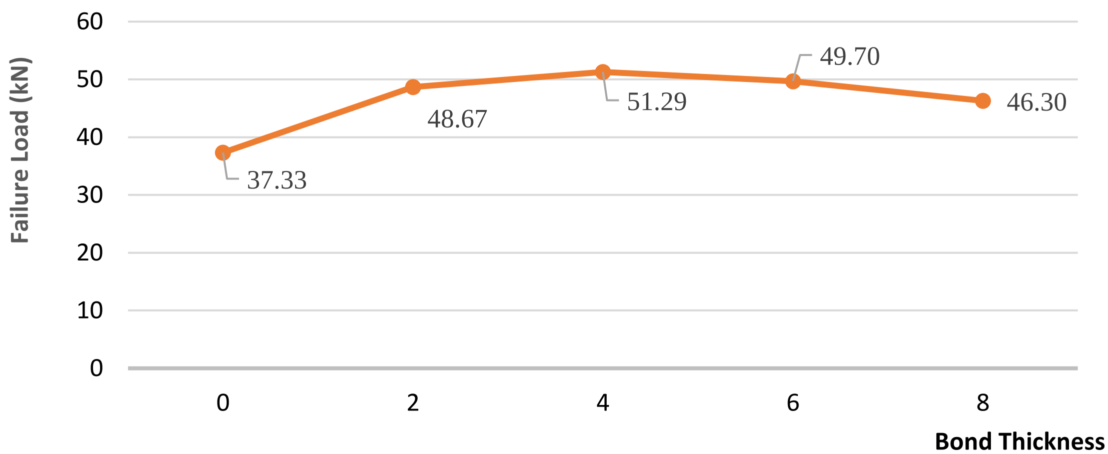

Fig. 3: Failure Load vs Bond Thickness FA-0, PFA-2, PFA-4, PFA-6, and PFA-8

Beam PFA-2 (Strengthened with 1.0mm-thick plates and 2mm bond thickness)

During loading, it was observed that the first flexural crack began to form at 16kN.The beam PFA-2 yielded at a load of 26.0kN. It was noted that the PFA-2 beam failed in shear, with cracks forming near the support. An ultimate load of 48.67 kN was observed for this beam. It can be notice from Figure 5, that the mid-span deformation increased about 4.6mm, while the load-carrying capacity increased by approximately 30%. Ductility index versus bond thickness is presented in Figure 4 and PFA-2 had ductility index of 3.0, however, only 13% increase in deformation at failure load was achieved. This indicates that steel plate strengthening of concrete beam increases the ductility of the structural element. The beam PFA-2 contributed 2.08kN to bending resistance, that is 30% higher than reference beam FA-0. The beam is stiffer compared to FA-0.

Beam PFA-4 (Strengthened with 1.0mm-thick plates and 4.0mm bond thickness)

In the course of loading, it was noted that the first cracking initiated due to stresses at a load of 10.9kN. The crack location was close to the support. Failure of beam PFA-4 took place as results of shear failure of beam but the load at failure observed was 51.29kN, 37% higher than reference beam FA-0. This happened due to the development of a critical shear crack propagated towards the loading points. The deformation at failure was 13% higher than that of the reference beam. A ductility index of 2.2 was realized. Figure 4 shows the performance of the beam based on ductility index. Figure 5 presented the load versus mid span deformation. From Table 3, the beam contributed 2.56kN to bending, which is 37% higher than reference beam FA-0. The beam is stiffer than FA-0 as shown in Figure 5.

Beam PFA-6 (Strengthened with 1.0mm-thick plates and 6.0mm bond thickness)
The load-carrying strength increased linearly during the test. This can be seen from the load versus mid span deformation graph. The initial shear crack was observed at 15.3kN load near the left-hand support. As the load steps increases, the cracks propagated towards the point load. Also, flexural cracks were observed as the loading increases. The beam PFA-6 yielded at 35.83kN and failed at 49.7kN due to shear. The PFA-6 is 33% higher in resistant than reference beam FA-0 at failure**.** PFA-6 show a ductility index of 1.7 at failure. The deformation at failure was 1.4 times the reference beam. Figure 5 depicted the load versus mid span deformation. The beam contributed 2.3kN to bending. The beam is also stiffer than FA-0.

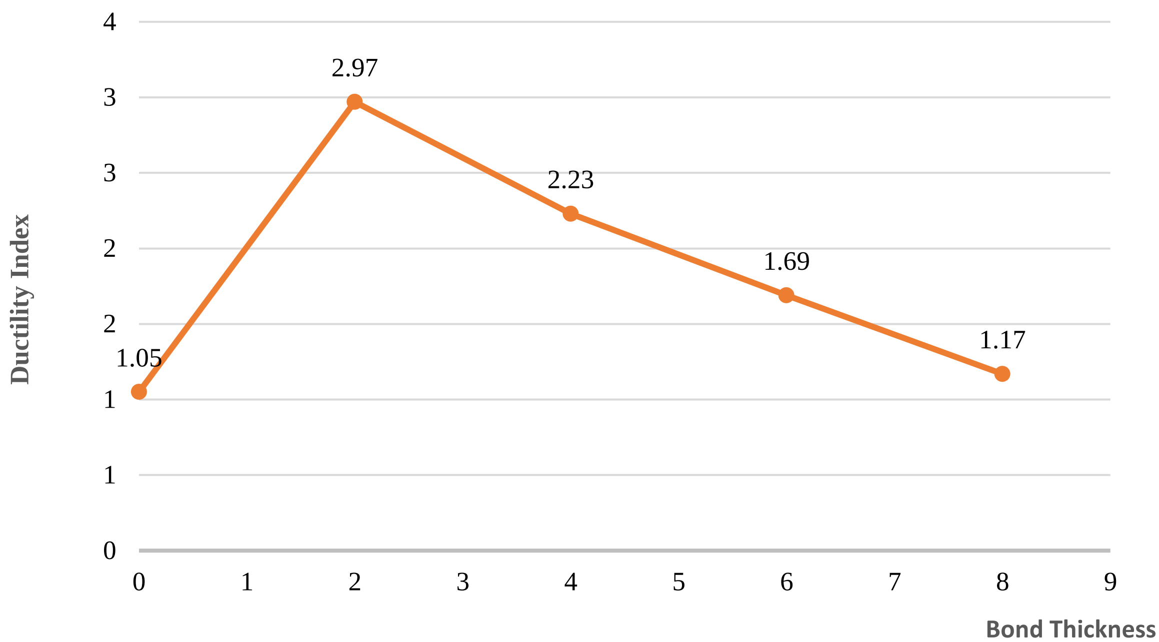

Fig. 4: Ductility Index vs Bond Thickness for FA-0, PFA-2, PFA-4, PFA-6, and PFA-8

Beam PFA-8(Strengthened with 1.0mm-thick plates and 8.0mm bond thickness)
First crack was observed to about 11.39kN within the constant moment region, followed by shear cracks developing toward the support. As the loading increases, the cracks became visible. The beam PFA-8 was observed to be yielded at a load of 35.76kN and failed at 46.3kN load due to shear cracks. The shear cracks were developed at about 45^0 to the longitudinal axis between the loading point and the support. Though, Beam PFA-8 shifts the behaviour toward brittleness which validates (Maghsoudi & Bengar, 2011). The Beam PFA-8 is 24% higher than the failure load of reference beam FA-0. Figure 5 depicted the load versus mid span deformation. The PFA-8 beam contributed 1.64kN to bending. The beam is also stiffer than FA-0 as shown in Figure 5.

3.1.2 Bending Capacity

Table 3 shows that the bending resistance of reinforced concrete beams can be significantly improve by strengthening with 1mm steel plate at the tension. Beam PFA-2, PFA-4, PFA-6, and PFA-8 had the same surface area (80 x 1000mm) of 1mm thick plate, however, the bending resistance contributed by PFA-2, PFA-4, PFA-6, and PFA-8 were 2.08kN, 2.56kN, 2.3kN and 1.64kN respectively. PFA-8 was observed to be little lower in terms of bending resistance due to sudden shear failure caused by the delay in transferring stresses to the steel plate.

3.1.3 Load–Deformation Behaviour

The test results presented in Figure 5 and Table 2 confirmed that all the beams strengthened with 1.0mm steel plate bonded to the tension face was significantly stiffer than the reference beam FA-0. The deformations of beam PFA-2, PFA-4, PFA-6, and PFA-8 at the failure load of reference beam FA-0 37.33kN were lower than the reference beam. The lowest deformation was recorded in beam PFA-8. The test results also confirmed the possibility of shifting from a ductile behaviour to brittle behaviour by using 1mm steel plate. As stated earlier, increased deformation in PFA-2, PFA-4, PFA-6 could be due to ductile behavior of the external reinforcement. This was actually expected because the transformed second area moment for the strengthened reinforced element has increased. The test beams PFA-2, PFA-4, PFA-6, and PFA-8 show very consistent load versus mid span deformation behaviour.

3.1.4 Effect of Bond Thickness

Results (Figure 3) from this study show that the bond thickness of the strengthening RC beam is the most important aspect that directly effects the behaviour and stiffness of the strengthening element. The findings reveal that there is a limiting bond thickness that would be structurally suitable for strengthening of reinforced concrete beams in terms of both bending capacity and ductility.

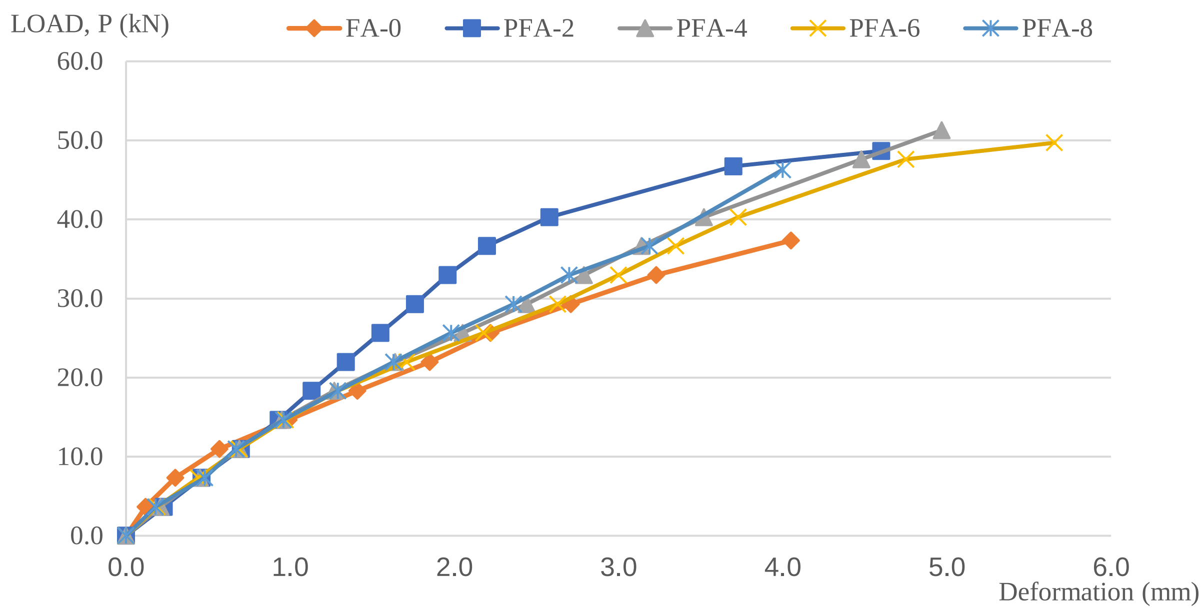

Fig. 5: Load vs Deformation for FA-0, PFA-2, PFA-4, PFA-6, and PFA-8

3.2 Beams strengthened with 1.5mm-thick plates

PFB-2, PFB-4, PFB-6, and PFB-8 beams were strengthened at the tension face with 1.5mm thick plates and four various levels of bond thickness -2mm, 4mm, 6mm, and 8mm. The results are presented in Table 4 and were used to estimate the optimum bond thickness of the reinforced concrete beams. The deformation, ductility index, steel plate contribution to structural behavior, mode of failure, and ultimate failure load of each beam were tested, examined, and compared to the reference beam.

Table 4: Test Results of 1.5mm Steel Plate Flexural Strengthening

Sample ID	Yield Load (kN)	Deformation at Yield load (mm)	Failure Load (kN)	Deformation at Failure load (mm)	Mode of Failure
FA-0	28.74	3.85	37.33	4.05	Flexure
PFB-2	29.31	3.05	44.22	5.10	Shear
PFB-4	32.97	1.69	47.63	3.90	Shear
PFB-6	43.96	2.73	51.29	3.79	Shear
PFB-8	40.30	3.24	42.00	3.83	Shear

Table 5: 1.5mm Steel Plate Contribution to Bending Capacity

Sample ID	Failure Load (kN)	Bending Capacity M_{exp}, (kNm)	Contribution to Bending Capacity (%)
PA-0	37.33	6.84	
PFB-2	44.22	8.11	18.57
PFB-4	47.63	8.73	27.63
PFB-6	51.29	9.40	37.43
PFB-8	42.00	7.70	12.57

3.2.1 Ultimate Load-Carrying

Beam PFB-2 (Strengthened with 1.5mm-thick plates and 2.0mm bond thickness)

During testing, it was observed that first shear crack was observed near the support at 9.3kN. The shear crack extended towards the point loads as load step increases. The beam yielded at a load of 29.3kN and failed suddenly at a load of 44.22kN as a result of shear cracks at the end of the 1.5mm steel plate. It was notice that the beam showed no yielding of external reinforcement. However, an enhancement of 18.5% was obtained relative to FA-0. The maximum deformation measured at failure load was 5.1mm with ductility index of 1.67 (Figure 7) and was 24% greater in the failure load compared with FA-0. Figure 8 shows load against deformation, which the beam exhibited a higher load carrying capacity relative to FA-0. From Table 5, it is observed that the bending capacity of reinforced concrete beams can be substantially increase by strengthening with 1.5mm steel plate. Beam PFB-2 contributed 18.5% to bending capacity.

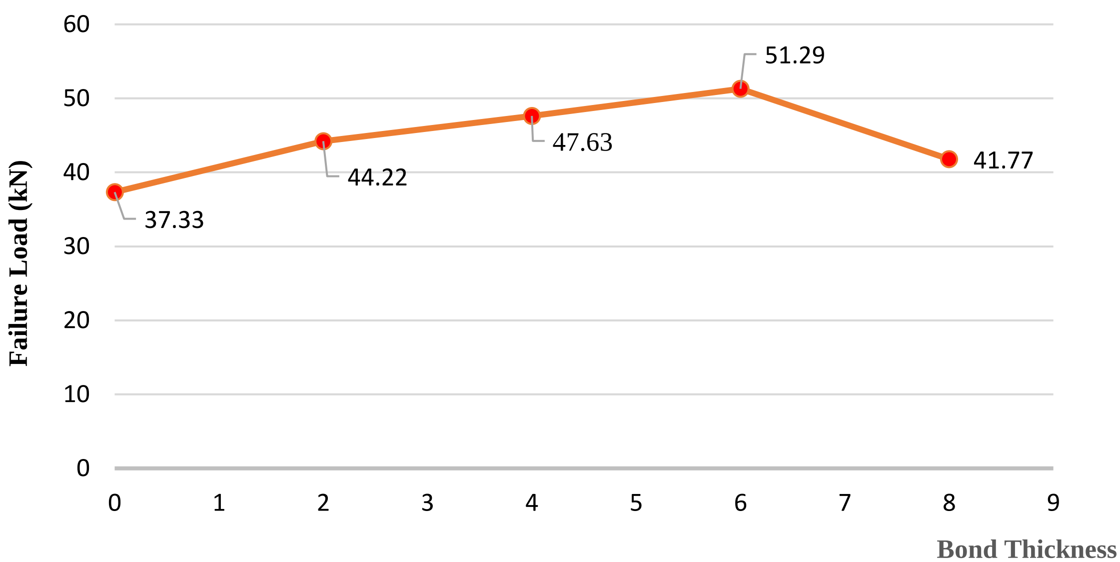

Fig. 6: Failure Load vs Bond Thickness FA-0, PFB-2, PFB-4, PFB-6, and PFB-8

Beam PFB-4 (Strengthened with 1.5mm-thick plates and 4.0mm bond thickness)

During the laboratory testing, it was observed that the first crack was recorded at a load of 7.6kN below the loading points. As loading progresses, flexural and shear cracks were also observed. The beam yielded at 33.0kN load and failed in shear at a load of 47.6kN which is 28% more efficient than reference beam FA-0. Figure 8 gives the load against deformation, the maximum deformation recorded at failure was 3.9mm with a ductility index of 2.3 was attained. Table 5 shows that the bending capacity of PFB-4 improved significantly and contributed 28% to bending capacity. Ductility index versus bond thickness is presented in Figure 7.

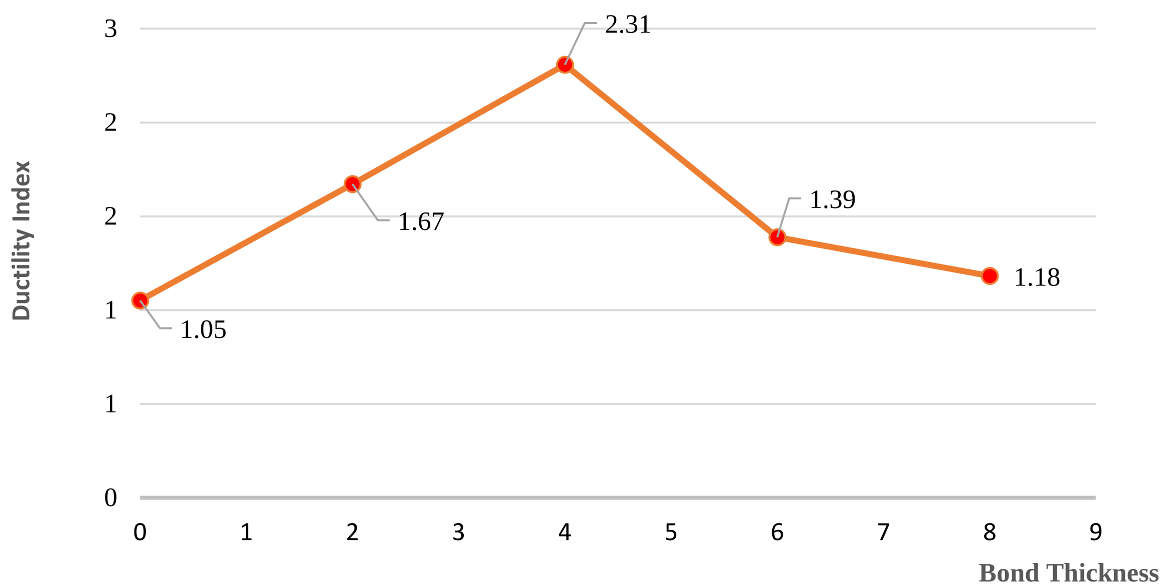

Fig. 7: Ductility Index vs Bond Thickness for FA-0, PFB-2, PFB-4, PFB-6, and PFB-8

Beam PFB-6 (Strengthened with 1.5mm-thick plates and 6.0mm bond thickness)
The initial crack of beam **PFB-6** was formed at a load of 8.5kN near the right support during load. The first crack was seen to be shear. As load step increases, other cracks were observed on the beam. The beam yielded at 44.0kN load and failed in shear at a load of 51kN. The beam is 37% higher than reference beam FA-0 which failed at 37.33kN. From Figure 8, it is observed that the maximum recorded deformation at failure was 3.8mm with a ductility index of 1.4. Results presented in Table 5 shows that the bending capacity was improved significantly and the beam contributed 37% to bending resistance.

Beam PFB-8 (Strengthened with 1.5mm-thick plates and 8.0mm bond thickness)
During loading, the first flexural crack was seen at 9.4kN load and was recorded at the constant moment region. As loading increases, more cracks were observed also. The beam yielded at a load of 40.3kN and completely failed in shear at 43.0kN load and it was sudden. The beam at failure is 13% higher than the failure load of reference beam FA-0 as shown in Table 4 and Figure 8 which shows the load versus deformation. The recorded deformation at failure load was 3.83mm. Table 5 shows that beam PFB-8 contributed 13% to bending strength. The reduction is due to increase in bond thickness.

3.2.2 Load Versus Deflection Behaviour

Deformation can also be considered as a measure of ductility to analyze the structural behaviour of strengthened RC beams as stated Mukhopadhyaya *et al*. (1998). Figure 8 shows that 1.5mm thick plate strengthened beams are stiffer than FA-0 beam. At 37.33kN (failure load for FA-0), the deformations of PFB-2, PFB-4, PFB-6, and PFB-8 beams were considerably lower than the reference beam. PFB-2, PFB-4, PFB-6, and PFB-8 all showed brittle failure during the loading process.

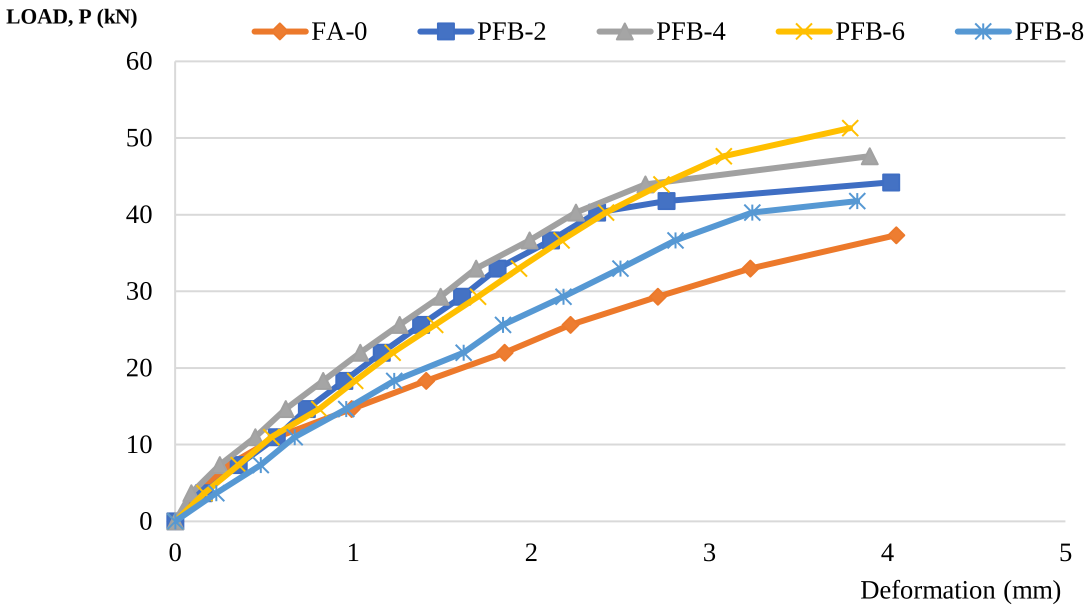

Fig. 8: Load vs Deformation for FA-0, PFB-2, PFB-4, PFB-6, and PFB-8

3.2.3 Bending Capacity

The results in Table 5 shows that strengthening reinforced concrete beams with 1.5mm steel plate at the bottom can significantly improve their bending capacity. Beams PFB-2, PFB-4, PFB-6, and PFB-8 all had the same surface area, but nevertheless their bending capacities were 18.5%, 28.0%, 37%, and 13%, respectively. Due to rapid shear failure, PFA-8 was found to have the lowest bending capability.

3.3 Beams strengthened with 2mm-thick plates

Laboratory test results from 2mm-thick plates were presented in Table 6. Each beam type was examined and compared to its reference beam against the ductility index, CFRP fabric contribution to bending, mode of failure, load-carrying capacity, crack patterns, and load-deflection behavior. Beams strengthened with 2mm-thick plates are FC-2, FC-4, FC-6, and FC-8 with varying bond thickness (2mm, 4mm, 6mm, and 8mm). The contribution of the 2.0mm thick plate to bending capacity, failure load against bond thickness, ductility index against bond thickness, and load against deformation were shown in Table 7, and Figure 8, 9 and 10 respectively.

3.3.1 Ultimate Load-Carrying

Beam PFC-2 (Strengthened with 2.0mm-thick plates and 2.0mm bond thickness)

During testing, it was observed that, PFC-2 beam showed an increase in load-carrying capacity of 27%. Figure 11 presents the load against deformation graph. The first crack observed was flexural and formed at the constant moment area. The first crack was recorded at a load of 9.9kN. As loading steps increases, cracks became visible. The Beam PFC-2 yielded at a load of 43kN with an increase in yield load of 50% relative to the reference beam and completely failed at 47.5kN load due to shear. A ductility index of 1.3 was attained as shown in Figure 10. From Table 7, it is observed that this beam contributed 27.23% to bending capacity.

Table 6: Test Results of 2mm Steel Plate Flexural Strengthening

Sample ID	Yield Load (kN)	Deformation at Yield load (mm)	Failure Load (kN)	Deformation at Failure load (mm)	Mode of Failure
FA-0	28.74	3.85	37.33	4.05	Flexure
PFC-2	43.00	2.78	47.50	3.50	Shear
PFC-4	36.64	2.27	48.36	3.75	Shear
PFC-6	43.96	2.73	47.23	3.20	Shear
PFC-8	40.30	2.16	43.96	3.04	Shear

Beam PFC-4 (Strengthened with 2.0mm-thick plates and 4.0mm bond thickness)
During testing, it was recorded that the mode of failure was similar to beam PFC-2. Figure 11 shows that the use of 2.0 thick plate with 4.0mm bond thickness increased the load resistance from 37.33kN to 48.36kNm, which is 30% higher than that of reference beam FA-0. The Cracks were observed at constant moment region and extended towards the loading points. The flexural cracks along the shear region became wider and visible as the applied load increases, The first crack formed at a load of 10.14 kN below the loading points. Web-shear cracks were also observed with an increase in load steps. The beam yielded at a load of 36.6kN and finally failed in shear at a load of 120.90kN with an increased in ultimate load of 30% compared to the reference beam. A ductility index of 1.7 was attained as presented in Figure 9. Table 7 clearly shows the Beam PFC-4 contribution to bending capacity.

Table 7: 2.0mm Steel Plate Contribution to Bending Capacity

Sample ID	Failure Load (kN)	Bending Capacity $M_{exp,}$ (kNm)	Contribution to Bending Capacity (%)
PA-0	37.32	6.84	-
PFC-2	47.50	8.71	27.34
PFC-4	48.36	8.87	29.68
PFC-6	47.23	8.66	26.61
PFC-8	43.96	8.06	17.84

Beam PFC-8 (Strengthened with 2.0mm-thick plates and 8.0mm bond thickness)
The graph of Load against deformation for samples PFA-8 is shown in Figure 11. First crack was formed as a result of flexural stresses at a load of 10.67kN and was observed at the constant moment area. From Figure 11 and Table 6, it was observed that the beam had a yield load of 35.8kN and failed at a load of 43.9kN by shear failure with an increase in maximum load-carrying capacity of 18%. The beam P**FA-8** showed a ductility index of 1.4.

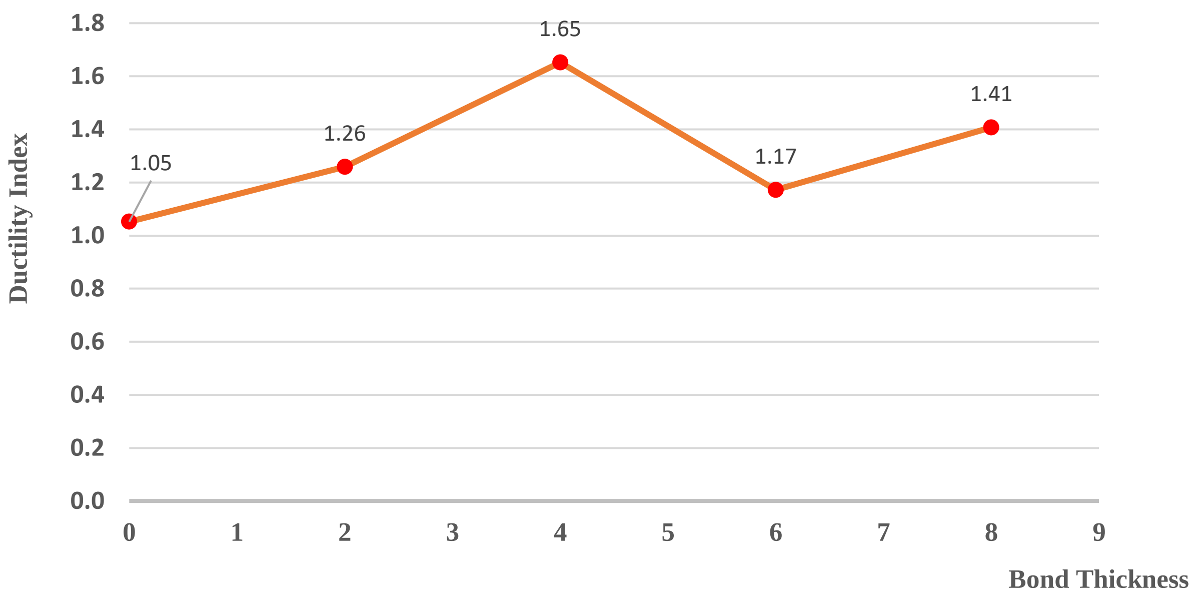

Fig. 9: Ductility Index vs Bond Thickness for FA-0, PFC-2, PFC-4, PFC-6, and PFC-8

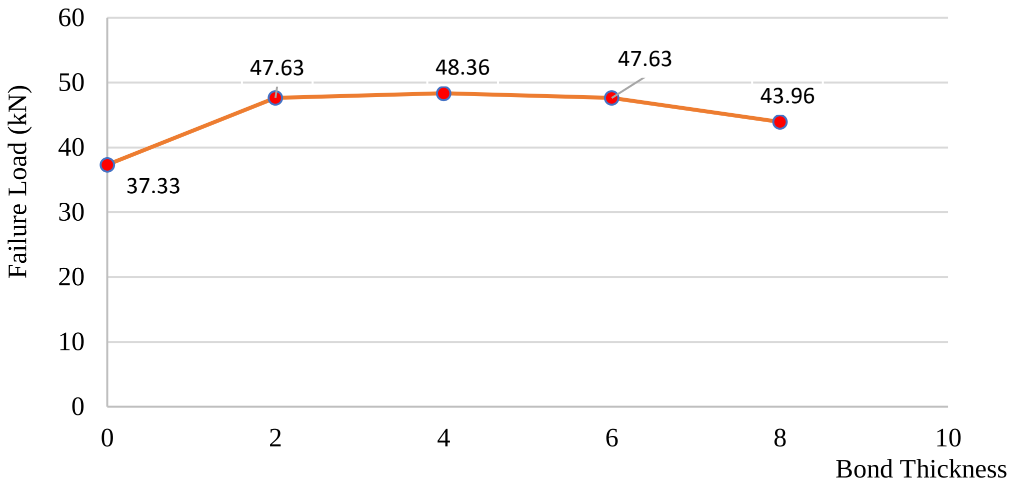

Fig. 10: Failure Load vs Sample Type FA-0, PFC-2, PFC-4, PFC-6, and PFC-8

3.3.2 Load-Deformation Behavior

The load against deformation behaviour of the structural elements through the loading history is of importance. Studies showed that the load against deformation behaviour is also used to understood the behaviour of strengthened reinforced concrete element (Mukhopadhyaya *et al*. (1998). Table 6 shows results of the deformations of beams strengthened with 2.0mm-thick plates at failure. From Figure 11, it can be confirmed that the PFC-2, PFC-4, PFC-6, and PFC-8 are much stiffer than FA-0. This was expected because the transformed second area moment for the strengthened reinforced element has increased. The studied showed that all the beams exhibited very consistent load-deformation response. Though, the deformation at failure for FA-0 is significantly higher than PFC-2, PFC-4, PFC-6, and PFC-8. The 2.0mm steel plate strengthened beams do not reflect ductility which is generally associated with reinforced concrete elements.

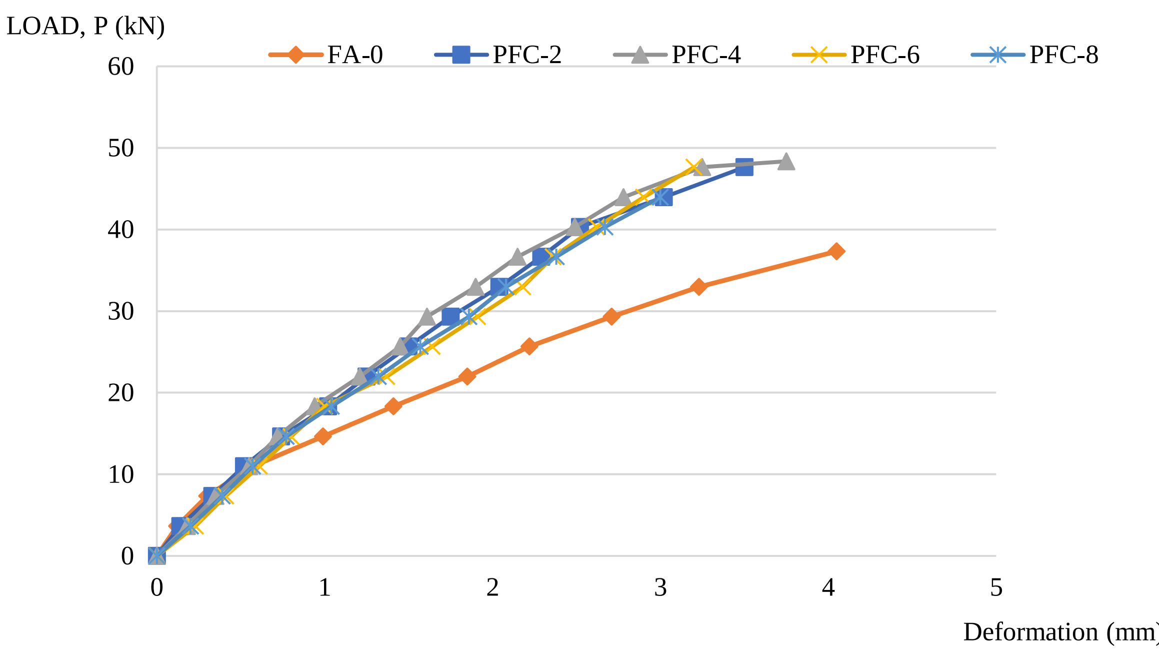

Fig. 11: Load vs Deformation for FA-0, PFC-2, PFC-4, PFC-6, and PFC-8

3.3.3 Bending Capacity

Table 7 presents results of bending capacity. The results confirmed that the application of steel plate improved the bending resistance of reinforced concrete elements. The bending capacity contribution of beams strengthened with 2.0mm-thick-PFC-2, PFC-4, PFC-6, and PFC-8 was approximately 27%, 30%, 27%, and 18% to bending respectively. The study evidently confirmed that the bond thickness has direct effect on the structural performance as graphical presented in Figure 10.

4. CONCLUSION

Experimental approach on the determination of optimum bond thickness of reinforced concrete beam strengthened externally by bonded steel plates. also, ductility index, bending capacity and deformation response were closely studied. the following deductions were drawn based on the results;

- According to the findings, there is a maximum bond thickness that would be structurally acceptable for RC beams Strengthened with steel plate.
- Increase in bond thickness leads to a reduction in ductility index
- Strengthening reinforced concrete beam with steel plate increases the stiffness of the beam.
- Steel plate thickness to bond thickness ratio should be kept within the range of 0.3 to 0.4 for beams strengthened.
- The thickness-to-width ratio of steel plates shall not be less than 0.015.

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