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Unidirectional Carbon Fibre Anchorage Length Effect on Flexural Strength Capacity For Concrete Beams

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***Abstract*:** *Concrete structures often require rehabilitation after years of service. The recent rapid developments in fibre reinforced polymers (FRP) opened the doors for a new era of rehabilitation, low production costs, light weight and durability of these products were the main properties that allowed to use it in many structural retrofitting and strengthening areas. Many studies focused on strength gain performance of the concrete elements when using different types and FRP formation. In addition to that, this study examined strength and pre-failure behaviour with three lengths categories, and constant moment zone loading application. Three categories of different carbon fibres strengthen length (Full, intermediate and short) along with a control beam were prepared and tested. The full length category showed an average of 24% strength gain, on the other hand, the intermediate category achieved similar strength gain 24%, and finally, short length category preformed poor in terms of strength gain and failed similarly to the control element. It was concluded that reducing the anchorage length up to a point before the concrete will tear-off will improve the strength performance comparing will extended anchorage lengths.*

Keywords: *Carbon fibre, reinforced polymers, Adhesive, Anchorage length*.

1. Introduction

Concrete structures are known to have a certain service life, which limits the use of it and usually determine the feasibility of the structure existence. Often deterioration in the structure performance is due to gradual concrete creep, steel corrosion, freeze-thaw action, change in use and initial under design. The action taken in many cases is demolition and rebuilding the structure, however this option is not considered to be sustainable, cost efficient and environmental friendly. As it involves more use waste production and significant use of raw materials. Due to that, alternatives to upgrade structures to co-op with the required performance are more preferable. Since the most common failure mode in concrete bridges and structures occurs in the tension side, therefore in the 1960s techniques of strengthening concrete structures by bonding steel plates to the surface of the tension zone with adhesives and bolts. The first application of this repair conducted in the UK was the strengthening of four cracked bridges at the M5 Worcestershire, England in 1975 [1], but using steel plates was not possible in all situations such as in low clearance spaces, fixes subjected to corrosion and formation difficulties. Whereas the recent developed fibre polymers are far easier to apply on the structure as it can be formed flexibly around curves and can be wrapped over the concrete elements when required. In addition, most of these fibre polymers are unaffected by moisture and can be more durable than the steel in many cases.

This study focused on examining concrete beams elements modes of failure and performance for three carbon fibre (FRP) strengthening lengths. Elements were tested under four-point loading system to produce constant moment zone (CMZ), this system was necessary in this study to set a constant effective strengthening length (L eff) for all category regardless to the difference of failure loads, the anchorage length (L a) was constant for each category which is load application dependent (see Fig. 1).

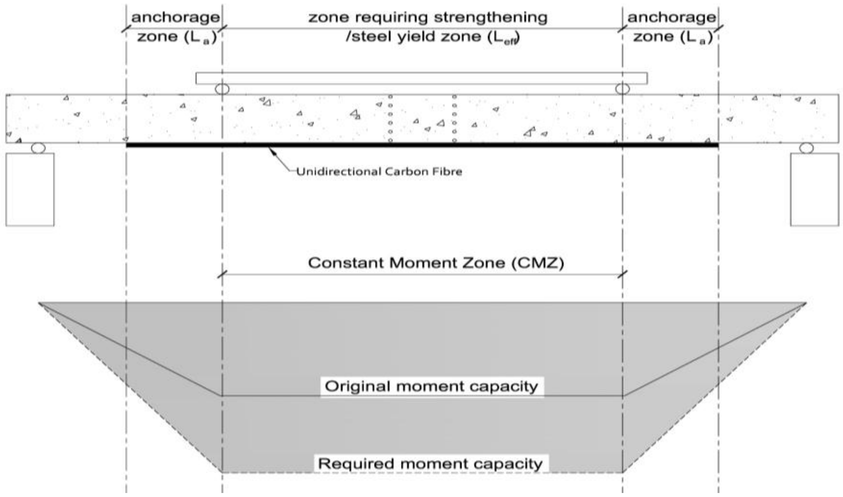


Fig. 1: Testing setup, constant moment zone and anchorage length.

2. Related Studies

A study of the rehabilitation of concrete chimneys, done by Kobatake, Kimura and Katsumata [2], considered the length of (FRP) needed to provide sufficient anchorage. Carbon fibre tape was fixed to a concrete block where the tensile load was applied via the internal rebar in the block. The composite debonded away from the concrete when the anchorage length was low, but the failure mode changed to composite tensile failure above a certain bonded length. The anchorage length required to reach composite failure was unique to the particular specimen geometry used, however, test results showed that an undesirable premature failure occurs if the bonded length of plate is insufficient. Obaidat and others [3] Investigated the behaviour of structurally damaged full-scale reinforced concrete beams retrofitted with CFRP laminates in shear or in flexure with main variables considered were the internal reinforcement ratio, position of retrofitting and the length of CFRP. The results concluded that the shorter the CFRP was the more shear concentration will occur on the ends, yet, only one failure mode was experienced which is fibre debonding.

3. Methodology

Specimen Categories: Ten beams were prepared, divided into three categories of FRP length; each category consist of three beams, in addition, a control beam which provides a comparison reference; these categories are illustrated in Fig. 2.

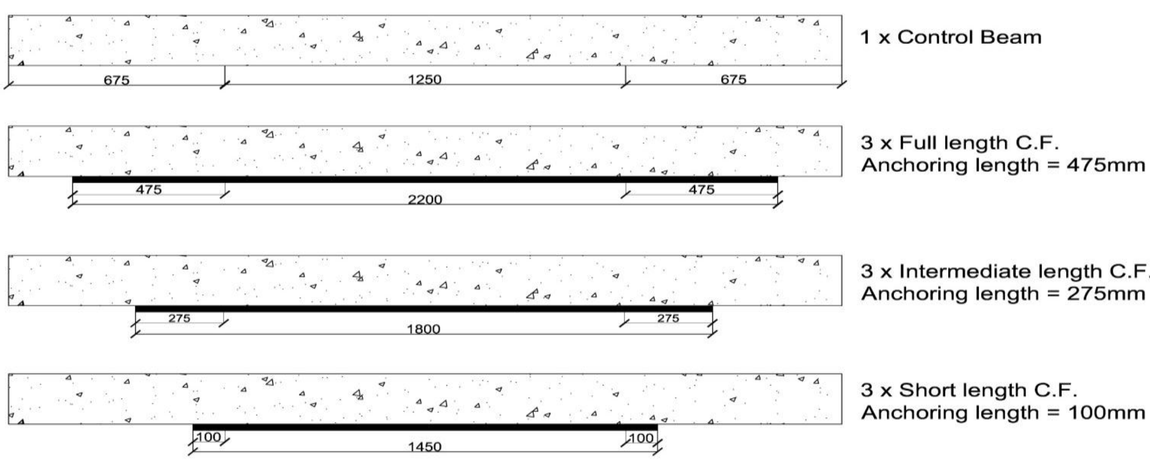


Fig. 2: Carbon fibre and anchorage length for each category.

3.2. Materials

Concrete: Specimens were 1:2:3 cement, sand and aggregates respectively. Water cement ratio W/C of 0.5 used as it is a widely used ratio in the industry. The cement used in the study was general purpose Portland-fly ash cement that complies with the British standard [4] with CEM II/B-V notation. Sea-dredged sand and Crushed the limestone aggregates were used as shown in Fig. 3. Portable mixing water which complies with the British standard [5] was used.

Reinforcement Steel: Steel cages were assembled as in Fig. 3, where six shear links (Ø 6mm) from each side of the beam were presented in the shear zones (to prevent shear failure) and two main tensile bars (Ø 10mm) along the beam length.

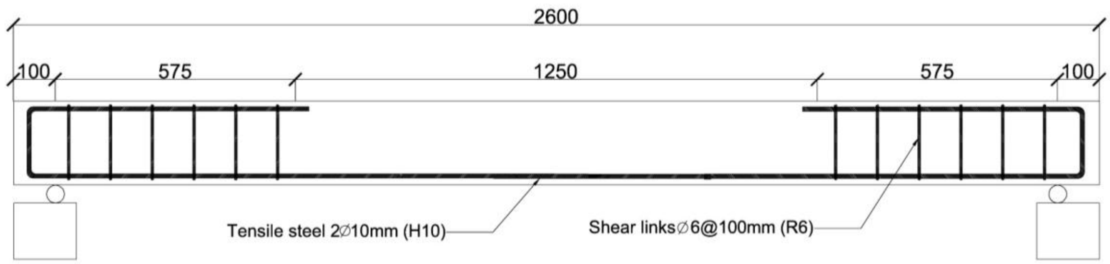


Fig. 3: Beams reinforcement details

3.3. Instrumentation

Vertical Deflection: Ten Linear Variable Displacement Transducers (LVDT) were positioned below the beam to record the deflection values in the critical locations.

Concrete Surface Strain: At the beam centre, two columns each consist of six rows of Demountable mechanical strain gauges (DEMEC) were glued on the beam surface on both sides to record the concrete strain values during loading process.

Carbon Fibre Surface Strain: 20mm stain gauges were placed on the carbon fibre outer layer in two places; under loading point and the beam centre. The aim of these strain gauges was to record the strain values within the carbon fibre layer against each load.

4. Results

4.1 Deflection Results: The maximum deflection reading from the two traducers placed under the beam centre was used to prepare the load/deflection figure. Categories (FCF, ICF and SCF) showed less deflection value compared to the control element (CON) as it can be seen in Fig. 4. On the other hand, the short strengthened category (SCF) showed earlier failure due to concrete tear-off. The figure also shows significant decrease of slope after 10kN as the load was being stored in the compression side as will be seen in figure (neutral axis), further drop in the slopes occurred after 15mm deflection as a result of the steel yielding (see Fig. 4).

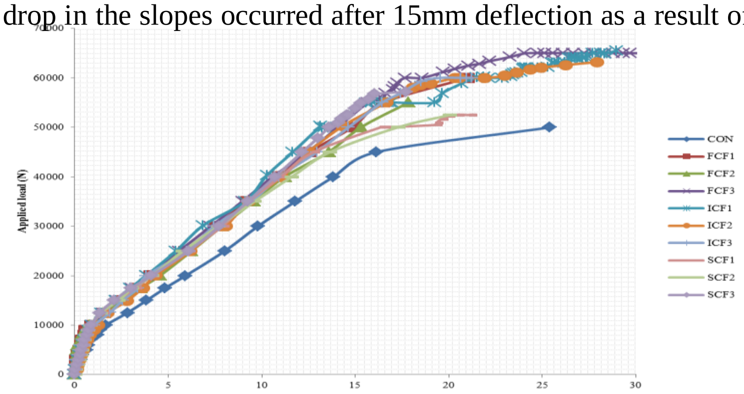
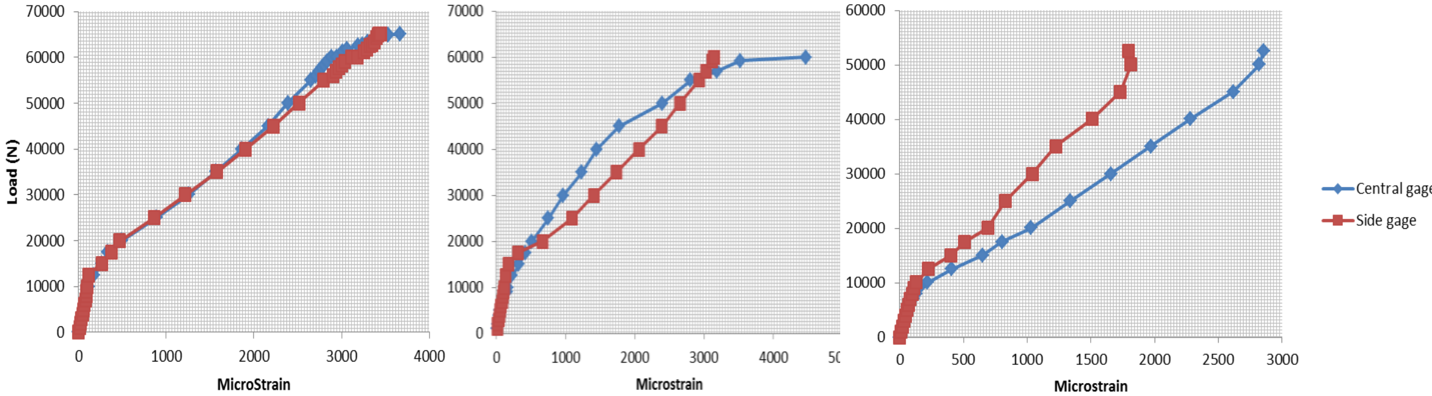


Fig. 4: Load against deflection for all beams.

4.2 Carbon Fibre Surface Strain Results: Strain gauges readings recorded consistent low strain gain rate; similar to both deflection and neutral axis depth (from concrete surface strain readings) up to 10kN as can be seen in Fig. 5. That represents an average carbon fibre surface strain gauges reading for each category.



(a) (b) (c)

Fig. 5: Fibre strain against load for: (a) FCF, (b) ICF, (c) SCF.

Strain readings indicated that for the (FCF) beams both centre and support side gauges follows the same pattern. As for the (ICF) beams in Fig. 5 (b), the side strain is higher than the central, up to a point before minor cover cracks start to initiate at the carbon fibre anchoring end, after these cracks start to propagate a reduction in the side strain occurred due to losing anchorage strength, which urged the central fibre area to carry more strain up to failure. The (SCF) category maintained higher central strain, whereas the side stain showed almost constant reading close to failure which indicates anchorage failure as illustrated in Fig. 5 (c).

4.3 Failure Modes

4.3.1 Control Beam (CON): showed steel yielding (SY) and shallow/local concrete crushing (LCC) of 30 mm in depth due to bending. Energy dissipation was moderate. The failure occurred within the maximum moment zone (see Fig. 6).

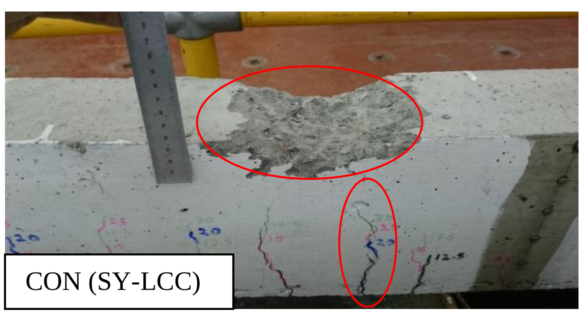
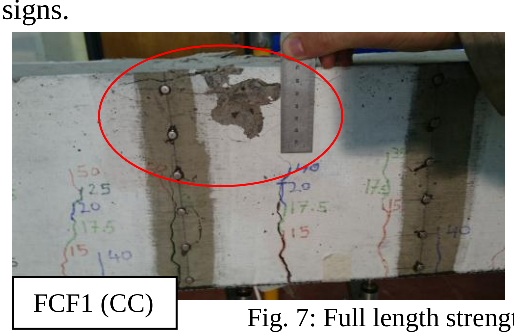


Fig. 6: Control beam (CON) mode of failure (SY- LCC).

4.3.2 Full Length Strengthened Beams (FCF): main failure mode was concrete crushing (CC) of 60mm deep; however, premature concrete tearing-off signs were clear before failure in (FCF2) and (FCF3) at 50kN and 60kN respectively, this mode of failure was referred as a percentage of sign load to the ultimate load reached such as (PCTO$^{83\%}$) and (PCTO$^{93\%}$) in Table 1. Energy dissipation poor as failure occurred with late/no pre-failure signs.



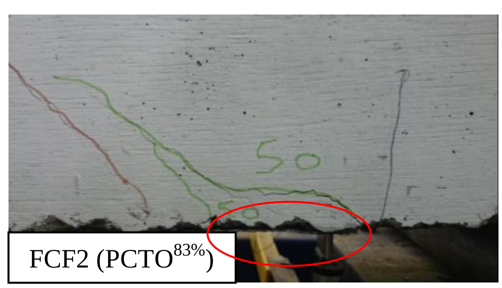


Fig. 7: Full length strengthened beams (FCF) modes of failure.

4.3.3 Intermediate Length Strengthened Beams (ICF): earlier signs of failure compared, main modes of failure varied, the first beam (ICF1) failed due to fibre rupture (FR) at the centre of the beam, yet horizontal cracks of premature concrete tearing-off were clearly seen at 50kN which referred as (PCTO$^{76\%}$). Second beam (ICF2) showed similar behaviour to (ICF1) but with plate-end debonding (PEDB), the horizontal cracks of premature concrete tearing-off were seen at 40kN which referred as (PCTO$^{63\%}$) comparing to the ultimate strength. Third beam (ICF3) failed with pure concrete tearing-off which started to show signs of failure after 50kN (CTO$^{83\%}$).

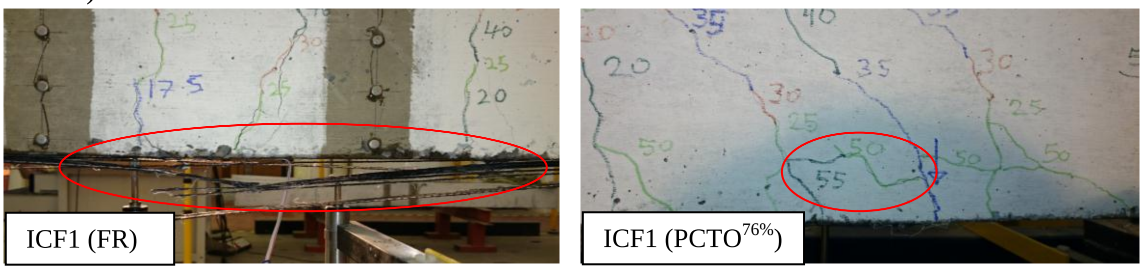


Fig. 8: Intermediate length strengthened beams (ICF) modes of failure.

4.3.4 Short Length Strengthened Beams (SCF): concrete tearing-off (CTO) mode of failure dominated in this category, but pre-failure signs were observed represented by horizontal cracks, which occurred in the fibre edge at 40kN (PCTO$^{75\%}$), 45kN (PCTO$^{85\%}$) for (SCF1) and (SCF2) respectively. Full concrete tearing-off occurred at 50kN (CTO$^{94\%}$) and 48.5kN (CTO$^{92\%}$) for (SCF1) and (SCF2) respectively, yet no signs were seen in (SCF3) as sudden (CTO) occurred. The energy dissipation for (SCF1) and (SCF2) was moderate as it failed due to steel yielding (SY) which followed the concrete tearing-off, the steel yielding was accompanied by local concrete crushing within the maximum moment zone (LCC) similar to (CON) beam. But this was not the case for (SCF3) where the sudden failure of the concrete cover caused immediate yield for the steel reinforcement (see Fig. 9).

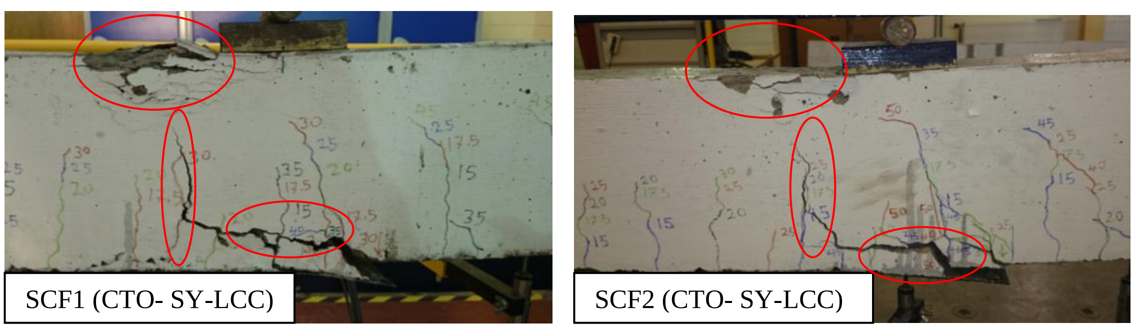


Fig. 9: Short length strengthened beams (SCF) modes of failure.

Table 1: Failure mode and strength gain for each element.

Ref.	Pre-Failure signs	Failure mode	Ultimate load (kN)	Strength gained
CON	None	SY-LCC	51.0	N/A
FCF1	None	CC	65.0	27.5%
FCF2	PCTO$^{83\%}$	CC	60.0	17.6%
FCF3	PCTO$^{93\%}$	CC	65.0	27.5%
ICF1	PCTO$^{76\%}$	FR-PCTO	65.5	31.0%
ICF2	PCTO$^{63\%}$	PEDB	63.2	24.0%
ICF3	PCTO$^{83\%}$	CTO	60	17.6%
SCF1	PCTO$^{75\%}$	CTO-SY-LCC	53	4.0%
SCF2	PCTO$^{85\%}$	CTO-SY-LCC	52.5	3.0%
SCF3	None	CTO	57.1	12.0%

4.4 Anchorage Length Needed

The equation used in calculating that length is according to the British standard [6] in terms of concrete cubes strength:

$$L_a = 2.11\sqrt{\frac{E_{frp}\, t_{frp}}{\sqrt{f_{cu}}}}$$

E_{frp}: Modulus of elasticity of the carbon fibre (MPa).
t_{frp}: Carbon fibre thickness (mm).
f_{cu}: Cubes compressive strength (MPa).

Both the modulus of elasticity and the fibre thickness are constant in all elements, therefore, only the minimum average cubes compressive strength was used to calculate the bond length which was in beam (FCF3), the anchorage length required for that compressive strength (42.7 MPa) was (L_a= 221.87 mm), this value meets the anchorage length done for both full length (FCF=475mm) and intermediate length (ICF=275mm), but it is more than double what is actually provided in the short length category (SCF=100mm).

5. Discussion

For all tested elements, concrete properties tests showed relatively consistent compressive strength results for cylinders and cubes as well as tensile splitting strength. While examining the load/deflection (Fig. 4) it can be seen that all strengthened beams showed very similar behaviour until steel yielding region, this behaviour for the short length category (SCF) indicates that even with insufficient strengthening length there was significant deflection reduction comparing to the control beam (CON). The failure in the short strengthened category (SCF) was a result of the steel reaching the yielding capacity outside the constant moment zone (CMZ), as the fibre did not long strengthening within that zone comparing to other longer anchorage categories, such as the intermediate category (ICF), as it managed to avoid leading the steel to yield even with staggering 31% strength gain, due to keeping the non-retrofitted steel section within the steel elastic limits.

On the other hand, pre-failure signs of both (SCF) and (ICF) were seen, as both categories started to show horizontal cracks between 40kN to 50kN, however the intermediate length category (ICF) started to show earlier pre-failure sign, this was due to the higher failure load, which allowed these cracks to propagate more and more visible before reaching failure load (see Table 1 and Fig. 8), but this was not the case with the full length category (FCF) due to the lower interfacial shear stresses concentrated at the fibre ends, which reduced the possibility of concrete cover failure at the carbon fibre ends, this stress reduction was clearly seen in Fig. 5 (a) where less strain was observed in the side fibre gauges comparing to intermediate category side strain gauge in Fig. 5 (b).

Cracks propagation inclination pattern at the plate ends were similar to a study by Teng, [7], the study examined the concrete cover separation behaviour with different fibre end distance from the support, the study showed that the closer the plate end is to the support, the more inclination will occur in the crack as it will behave similar to shear cracks, without propagating horizontally, which is less visible as can be seen in Fig. 10 for (FCF) and (ICF) elements.

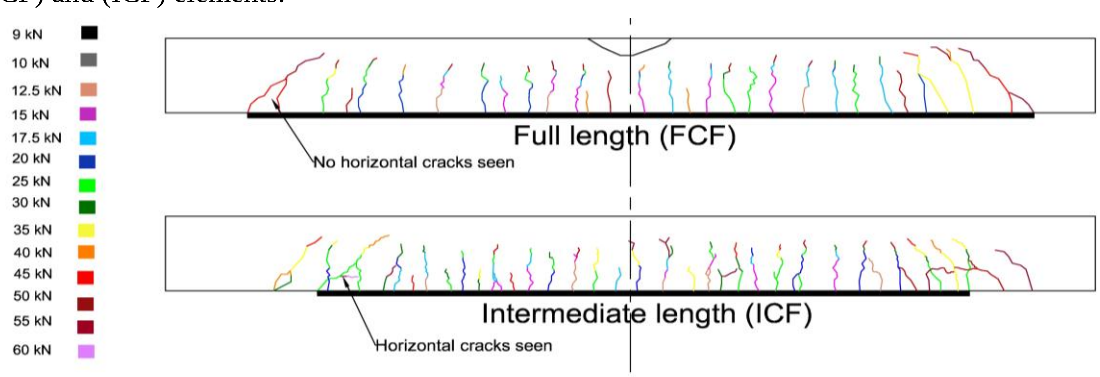


Fig. 10: Typical (FCF) and (ICF) cracks propagation showing different failure patterns at the plate end.

Presenting the strength gained for each element against the anchorage length along with a polynomial curve showed the general data trend in Fig. 11. It is clear that the increase of the anchorage length from zero (CON) up to 100mm (SCF) and 275mm (ICF) led to a significant semi constant strength gain, but it can be seen that after 300mm the curve tended to level showing no further strength gain in 475mm (FCF).

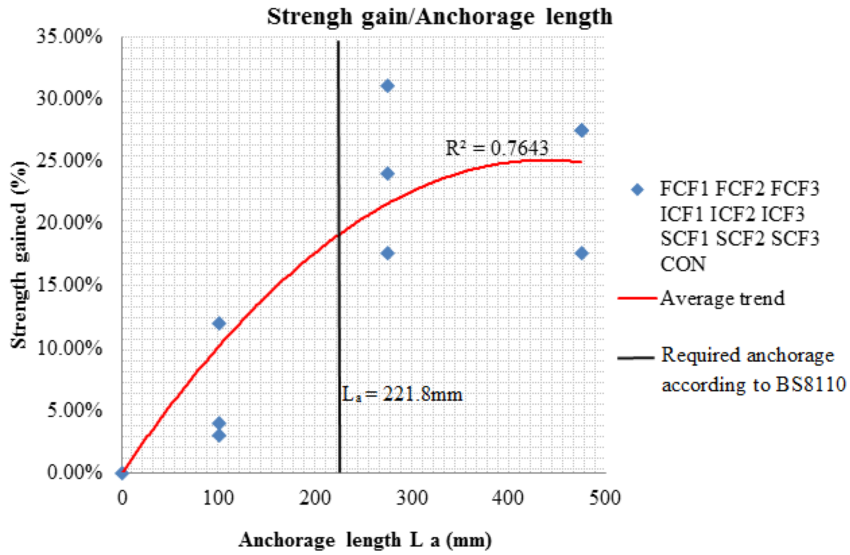


Fig. 11: The relation between the strength gained against anchorage length.

6. Conclusions

The following key points were concluded in this study:

- Anchorage length has a direct effect on the strength gain up to a point where further anchorage will not increase the ultimate strength.
- Decreasing the anchorage length will produce unpredictable failure as in the intermediate length (ICF), and insufficient anchorage as in the short length category (SCF).
- In short length category (SFC) failure tends to occur at the plate end section due to the high shear stress concentration comparing to longer anchorage categories.
- Intermediate length category (ICF) showed better overall performance in terms of strength, pre-failure signs and recommended ductility index.
- In further study, testing more elements will provide more accurate strength gained against anchorage length curve, which can be used to determine the recommended anchorage length that provide acceptable ductility index.

7. Acknowledgement

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