EXPERIMENTS ON INCREASED LOADBEARING CAPACITY OF CONFINED FRP REINFORCED BEAMS


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Dedicated to Prof. György L. Balázs
for his 65th birthday

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Fibre Reinforced Polymers (FRP) have been in use in aerospace engineering since the 1940s in military aircraft. Later as manufacturing technology developed it became available to other sectors. The use of FRPs in concrete construction can offers a variety of advantages over steel reinforcement. For the technology to be employable on a wider scale related research needs to address certain disadvantages and other properties of FRP rebars. One area that needs further discussion is the brittle failure of FRP reinforced concrete elements. There are several methods proposed aiming to modify the behaviour of elements in bending, among them is the utilization of concrete crushing failure and confinement to achieve a more ductile failure.

Keywords: FRP, Confinement, Strengthening, Structural elements

1. INTRODUCTION

The use of Fibre Reinforced Polymer (FRP) rebars, for reinforcing concrete is an alternative to steel. There are advantages to using them such as higher tensile strength, corrosion resistance, electromagnetic neutrality and ease of deconstruction (fib, 2007; Sólyom et al. 2018). This makes them preferable to steel in certain cases such as maritime structures and other aggressive environments, temporary structures, outdoor structures where self weight or thickness matter and special cases such as magnetic levitation trains or MRI rooms (ACI, 2015). However, certain properties of FRP reinforcements are different to that of steel. Due to this the design and construction of structures utilizing the technology need to take into account these differences (Mohammed et al. 2022; Sólyom et al. 2018). These include among others, the lack of plastic deformations before failure, the lower elastic moduli of most FRP rebars or the lack of bendability after production (JPCI, 2021; AFGC, 2023).

The subject of this paper is the elastic-brittle behaviour of FRP rebars. The plastic behaviour of steel reinforcement is utilized in the design of structures where plastic hinges can form and large deformations can occur without failure. But it also provides a visual indication of damage that anyone can understand without expertise in structural mechanics, importantly while the structure still maintains plastic capacity before collapse. In case of conventionally designed structures built with FRP rebars once they reach their ultimate stress capacity, the structure fails. There are multiple proposed ways to circumvent this problem, among them are the use of both FRP and steel reinforcements (Bencardino et al. 2016), the utilization of different fibre types, and the change from tension controlled to compression controlled failure. The implementation of steel-FRP and hybrid material systems results in higher costs, while the approach using concrete crushing as the primary mode of failure does not have a direct effect on cost. This has been proposed by multiple studies and recent model codes have taken care to includes sections on compression controlled failure (ACI, 2015; fib, 2007).

The design structural elements in bending with concrete crushing in mind is uncommon and there is room to refine and improve methods (Vu et al. 2009). One method proposed to enhance the load bearing capacity and ductility of concrete is the use of confinement, where reinforcement is used to restrict the deformations of a concrete section. The method is commonly used in elements subjected to large normal forces such as columns. This method can enhance loadbearing capacity, but further research needed before practical application can be achieved with confidence (Gouda, Asadian & Galal, 2022; Renic, 2022).

2. RESEARCH OVERVIEW

The aim of this research is to determine how certain parameters of confinement effect the load bearing capacity, ultimate deflection, crack pattern and mode of failure of reinforced concrete beams. To accomplish this, we conducted experiments on beams with varying reinforcements ratio and type, and supplemented the results with finite element analysis based on the experiments. The first set of experiments were carried out on rectangular beams of dimensions 2200 × 200 × 100 mm (length × height × depth), which were subjected to four point bending tests. The aim was to determine the influence the degree of confinement has. To achieve this, the central section of the beams, subjected to constant bending moment, was reinforced with varying number of stirrups. In order to assess the maximum achievable effect we also used external textile reinforcement to confine the entire middle section of a beam. Two specimens with steel longitudinal reinforcement were also produced with the same reinforcing ratio as the FRP reinforced ones as control.

There were seven beams produced in total with three 150 mm concrete cubes per beam to determine concrete strength.

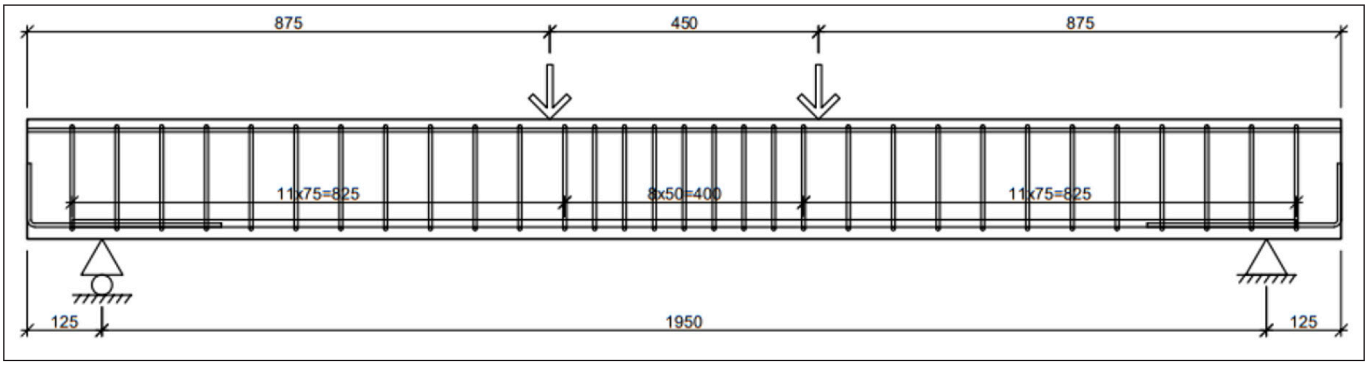
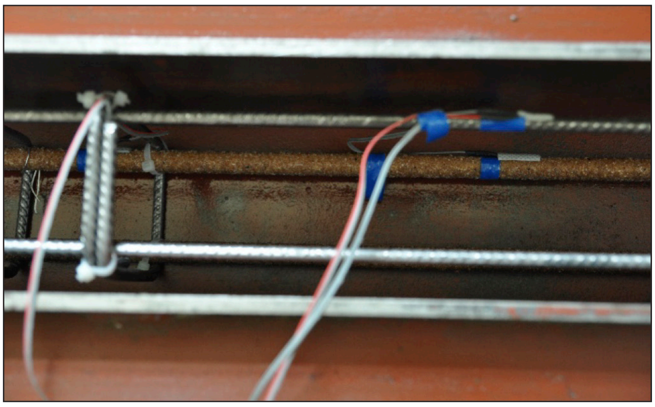


Fig. 1: Reinforcement plan of beam 5

All the beams were reinforced with two 12 mm diameter steel or Glass FRP (GFRP) on the tension side and two 8 mm steel rebars on the compression side. For the sake of clarity the beams reinforced longitudinally in tension with FRP rebars will be referred to as FRP reinforced and the ones with an entirely steel reinforcement will be referred to as steel reinforced. The tensile longitudinal reinforcement was chosen to be this size so that if made with steel the beam would fail in tension while if made with FRP the beam would fail in compression. Each specimen is divided into three zones by the four point bending test configuration (*Fig. 1*). The middle portion (under constant bending moment) is 450 mm and it is subject to the varying stirrup configuration and on one beam, textile wrapping. The outer sections of each beam measure 875 mm in length and are reinforced with twelve stirrups each with 75 mm spacing. Beams 1 and 2 are reinforced identically without stirrups in the constant moment zone. Beam 1 is the control specimen reinforced with steel longitudinally, while beam 2 is reinforced with GFRP rebars. Beams 3 through 5 are reinforced with progressively more stirrups 200, 100 and 50 mm spacing, respectively. Beams 6 and 7 are identical to beam 4 in their stirrup spacing, but 6 is reinforced with steel longitudinally while 7 is the only beam confined with the CFRP wrap. CFRP was chosen because it provides confinement while having minimal effect on the bending moment resistance directly like a steel wrapping would. The wrap was applied to the middle section of the beam, where the edges were grinded down in order to avoid damage to the wrap. A primer, a foundation layer and two adhesive layers (one before and one after application of the wrap) were used in the application following the instructions outlined in the manufacturers product catalogue (Mapei Kft. n.d.). The purpose of beam 6 was to demonstrate that increased confinement does not effect the loadbearing capacity or behaviour of steel reinforced elements failing in tension. The list of beams and their respective reinforcement can be seen in *Table 1*.

Fig. 2: Strain gauges on the reinforcement cage in the formwork



Symbol	Tensile reinforcement		Stirrup spacing in middle section [mm]				CFRP wrap	
	Steel	GFRP	-	200	100	50	Yes	No
Beam 1	X		X					X
Beam 2		X	X					X
Beam 3		X		X				X
Beam 4		X			X			X
Beam 5		X				X		X
Beam 6	X				X			X
Beam 7		X			X		X	

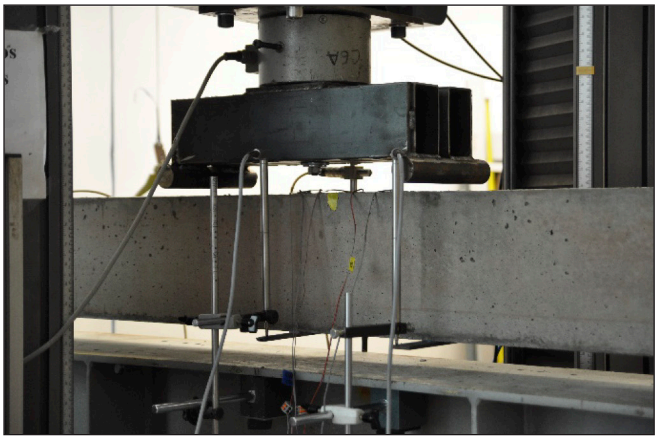
Table 1: List of beams and the type of reinforcements in them

The experimental setup included multiple LVDTs (linear variable differential transformers) to collect data regarding the deflections and crack openings in multiple positions. We also utilized multiple strain gauges applied to both the concrete and the reinforcement (*Fig. 2*). This formed the basis of numerical model calibration later. The load was applied by an Instron electromechanic testing machine with a capacity of 600 kN (*Fig. 3*). The load was applied in one phase at a rate of 1 mm/minute until first crack, when the LVDTs measuring crack openings were applied. From then onwards loading was applied in 15 kN increments until failure. At every step the crack pattern was marked and the first nine cracks were photographed with a handheld microscope.

The collected data was the following (*Fig. 4*):

1. Strain gauge at the top of the compression zone, in the centre, on concrete
2. LVDT measuring the first crack opening
3. LVDT measuring the second crack opening
4. Deflection below the force on one side
5. Deflection at the middle of the beam on one side
6. Deflection at the middle of the beam on the other side
7. Strain gauge on the compressed longitudinal reinforcement

Fig. 3: Test setup with LVDTs and load measuring cell



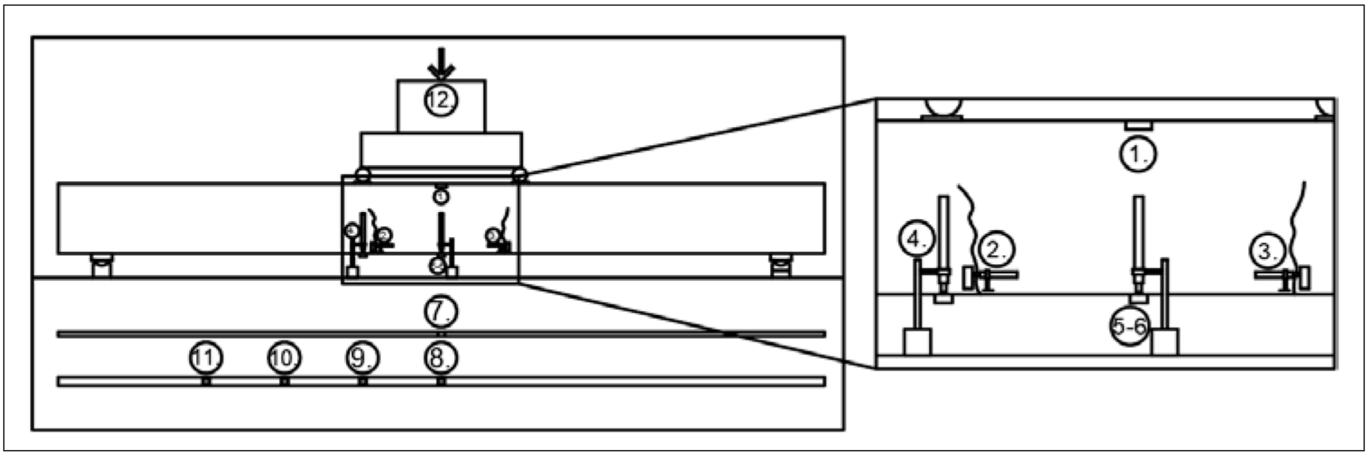


Fig. 4: Data collected during experiments

8. Strain gauge on the tensile longitudinal reinforcement at the centre
9. Strain gauge on the tensile longitudinal reinforcement at the force
10. Strain gauge on the tensile longitudinal reinforcement at 225 mm form force
11. Strain gauge on the tensile longitudinal reinforcement at 450 mm from force
12. Load .

The concrete mix used was designed to achieve at least 50 MPa compressive strength at testing. Every beam and the corresponding three test cubes were made with a new mixture due to the capacity limit of the mixing equipment. The reinforcement was pre-assembled and the strain gauges were installed in place. The beams were removed from the formwork one day after pouring the concrete and were subsequently wrapped in plastic to prevent dehydration and accelerate aging (*Fig. 5*). This was also necessary as the storage of the beams was only possible outdoors. The wrap was removed one day before testing and the specimen were brought indoors. The concrete cubes were subjected to the same treatment before testing. The tests were conducted seven days after pouring the concrete for both the beam and cube specimen.

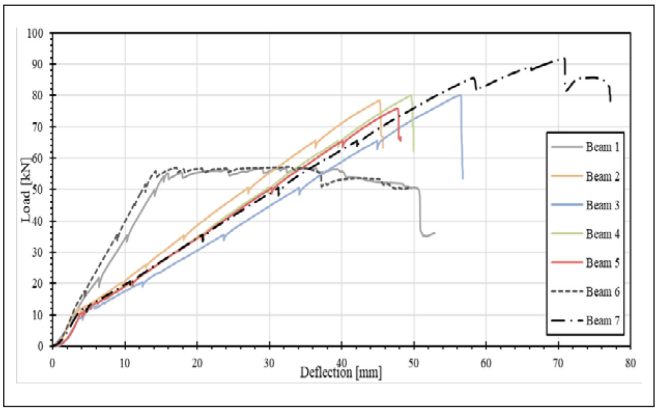
Fig. 5: Beams before testing with some still wrapped in plastic (left) CFRP wrapping on beam 7 (right)

3. EXPERIMENTAL RESULTS

The first results indicated the load-deflection diagrams (Fig. 6). They indicate the degree to witch the confinement resulted in an increase of loadbearing capacity. There are several important details to note. Most of the FRP reinforced beams have failed at similar load levels. This can be attributed to multiple causes, but the exploration of these is left to after all the results have been discussed. Another notable result is the load-deflection behaviour of Beam 7. The CFRP wrap reinforced beam displayed a significantly increased loadbearing capacity as well as a more ductile behaviour with larger deformations before failing. The capacity of the beam increased by approximately 10 kN and the maximum deflection by approximately 20 mm. The mode of failure in this case was concrete crushing next to the applied load, outside of the wrapped area. It is also notable that the two steel reinforced beams both failed at a similar, lower load level compared to the FRP reinforced ones. This demonstrates the increased load-bearing capacity of FRP reinforcements and confirms that confinement has no significant impact on load-deflection behaviour as anticipated.

Although the confinement did not noticeably effect the loadbearing capacity of the beams, it influenced the failure zone. On Beam 1 and 2, which were not constructed with confinement, the crushed concrete zone is triangular in shape. Beam 3 failed similarly but the depth of the failure zone is shallower than that of beams 1 and 2. Compared to these however, beams 4 and 5 failed with a layer of concrete on the top splitting from the rest. This indicates that the confinement did have an effect on the way the beams failed, but the effect can only be achieved under specific circumstances. The mode of failure of beams 4 and 5 seems to indicate that the

Fig. 6: Load-deflection diagram of all seven beams



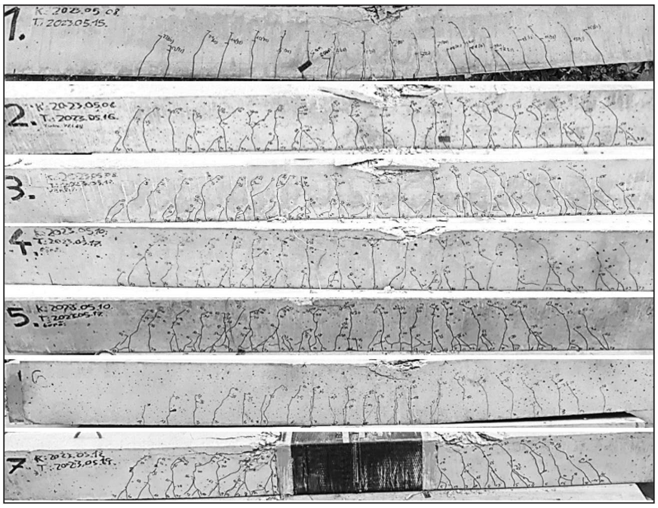


Fig. 7: The beams laid out after testing, their crack patterns and failure zones visible

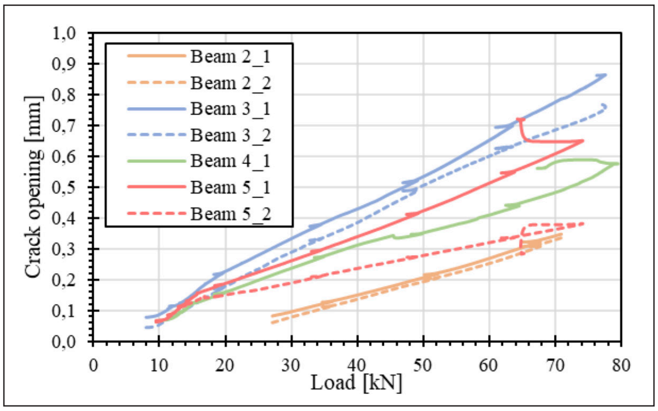


Fig. 8: Crack opening – load diagram of the first two cracks of beams 2-5 as measured by LVDTs put on after the first crack formation

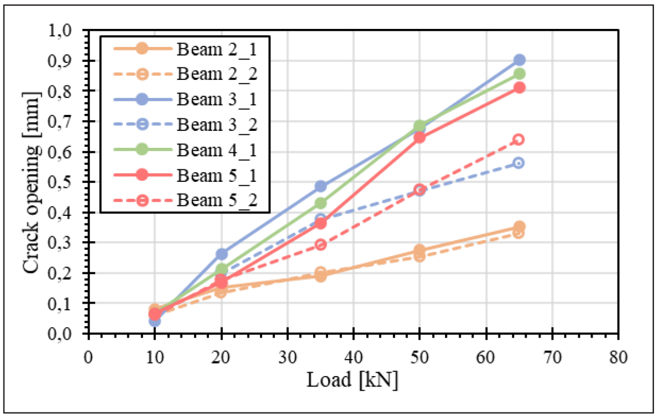


Fig. 9: Crack opening - load diagram of the first two cracks of beams 2-5 as measured on the pictures taken by hand held microscope

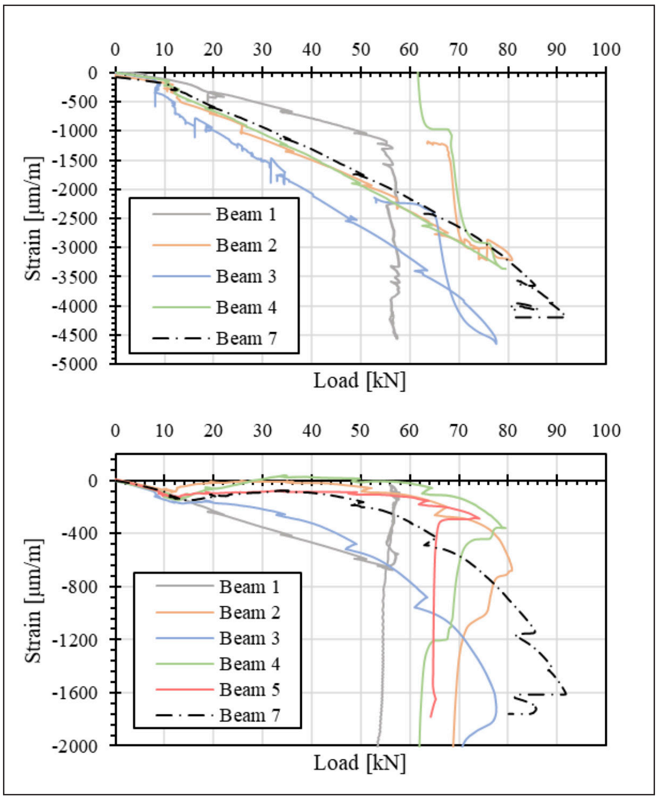
compressed concrete cover used was too large. However further experimentation is needed to properly understand the limitations of using stirrups to achieve confinement in structures subjected to bending. It should be noted that beam 7, which had GFRP and CFRP wrapping for reinforcement, showed a similar failure mode. The section where concrete crushing occurred was reinforced with stirrups with spacing of 75 mm.

Multiple methods were employed in order to observe the crack patterns and crack openings. However, neither the crack patterns nor the crack openings showed any remarkable change relating to the degree of confinement. The crack patterns in general are in line with expectations, the beams reinforced with GFRP rebars show development of cracks at earlier load levels, with overall smaller crack openings at failure. The crack patterns of beam 7 shows similarities with other GFRP reinforced beams, with the pattern even showing through the CFRP wrap. *Fig. 7* shows the crack patterns of all seven beams. The difference between steel and GFRP reinforced beams is observable, while any difference between the GFRP reinforced ones is hardly discernible. It is also visible that beams 1 and 6 have suffered permanent deformations while the rest have retained their shape. This demonstrates that the beams failed in compression and the FRP rebars did not fail.

Fig. 8 shows the first two opening cracks on every FRP reinforced beam, as measured by LVDTs. Although the results show a range of openings there in no trend that can be attributed to confinement. beams 2 and 3 showed the smallest and largest cracks respectively, while beams 4 and 5 fall between the two. These results indicate that crack opening does not seem to be influenced by the increase in confining reinforcement. The pictures taken with handheld microscope were used to measure the crack openings at set load levels (*Fig. 8 and 9)*. The cracks were on the opposite side to the LVDTs, thus they did not provide the same exact data. Similar results to the LVDT measurements can be observed. This trend reinforces the observations based on the other crack opening measurements.

The strains measured on the surface of the reinforcement were implemented to try to gauge the degree of confinement and to monitor the GFRP rebars. *Figs. 10 and 11* show the strain measurements on the concrete surface, on the compressed longitudinal reinforcements and the tensile reinforcements. As the beams failed at the same load level, the values measured at the concrete surface were expected to be similar to each other. This has largely proven to be true, with the exception of beam 3, which showed larger strain levels throughout loading, even compared to beam 7. Similar results were measured on the compressive reinforcements. Comparing the strain values of beam 7, that

Fig. 10: Concrete strain – Load diagram of beams 1-4 and 7 (beam 5's strain gauge failed)(top) Compressed reinforcement strain – Load diagram of beams 1-5 and 7 (bottom)



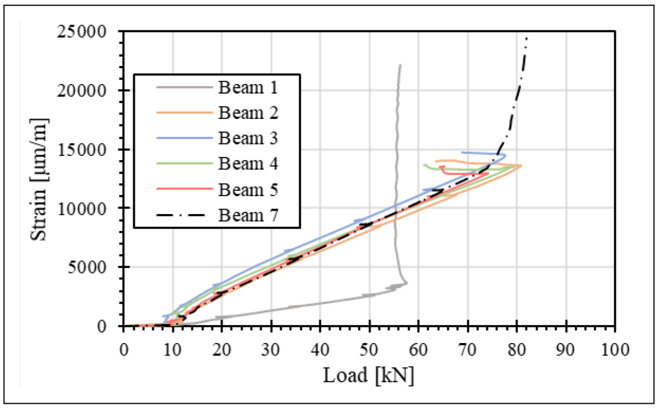


Fig. 11: Tensile reinforcement strain – Load diagram of beams 1-5 and 7 (bottom)

was in confinement, to the other FRP reinforced beams it is observable that the behaviour is similar to the other beams. This I also observable on the strain values measured at the tensile reinforcements. These results show that these methods were not adequate to measure confinement. They also show that the effect of confinement can mostly be observed near failure.

4. CONCLUSIONS

The goal of this research was to determine to what extent confinement can be utilized to strengthen FRP reinforced concrete beams. The experiments have proven that confinement can significantly increase the maximum deflection and loadbearing capacity of beams. The majority of the test specimens confined only with stirrups however did not indicate confinement effecting them. This is confirmed by the measurements of crack openings, strains of the reinforcement and the concrete. The exact reason behind this is not known, further testing has to be conducted in order to determine the cause. The failure zones of beams 4 and 5 indicate that the possible reason confinement could not take effect is that the concrete cover was too large, thus when it failed the loadbearing capacity of the remaining cross section was not enough to support the load. From the measurements taken, strains of the compressed and tensile longitudinal reinforcement are suitable to measure confinement.

In further testing strain of stirrups could be measured to obtain a better indicator. Furthermore, in addition to spacing of stirrups, variation on concrete cover, longitudinal reinforcement on the compressive side and size of beams has to be considered as variables. The results of our tests prove that confinement cannot be used in all circumstances to increase the loadbearing capacity of beams, further testing needs to be conducted in order to assess the parameters affecting it, and what values these parameters can take to reliably produce the desired results.

The aim of this research was to study the effect confinement can have on FRP reinforced beams in bending, designed for compressive failure. To achieve this we have conducted experiments on seven beams reinforced with varying tensile and confinement reinforcement. The results of these tests have proven that an approximately 13% increase of loadbearing capacity and an approximately 40% increase of deflection at failure can be achieved using confinement. This was achieved with wrapping a beam with CFRP textile. The beams produced with FRP reinforcement and a varying number of stirrups showed no sign of confinement. This is possibly to be caused by the compressed concrete cover of being too large. Further testing is needed to determine under what circumstances confinement can be used reliably to increase loadbearing capacity. The measurement of strains of reinforcement can be used to monitor confinement, but further testing is needed to assess other possible monitoring options. In light of these results the usage of confinement on beams designed to fail in compression, is only recommended if it can be reliably achieved, for example by wrapping. However, using stirrups as a confining method is not recommended without further research determining variables affecting confinement.

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