Influence of bonded length of the Carbon Fiber Reinforced Polymer Plates on the behavior of a concrete beam

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Abstract
*Sometimes Aged or Damaged Structures need to be reinforced and retrofitted to enhance their performances and structural life, for this reason, the rehabilitation has been the subject of extensive research. The strengthening Reinforced Concrete (RC) structures is one of the most difficult and important tasks of civil engineering. Among the ways used to strength the concrete; the reinforcement using Carbon fiber reinforced polymer. This material has proved to be more efficient than other composites because of its high elastics modulus, its durability and this kind of materials are less affected by corrosive environmental conditions. The technique used in this study will be the external bonding of Carbon fiber reinforced polymer (CFRP) to a concrete beam. In this paper, the focus will be on the influence of bonded length of the CFRP Plates on the global behavior of the beam. The study is developed by the finite element program ABAQUS and will contain 11 specimens with a dimension of 100*200*1000mm and the length of the CFRP will be 100 mm, 200 mm, 300 mm, 400 mm, 500 mm, 600 mm, 700 mm, 800 mm, 900 mm, and a fully reinforced beam. Numerical results are presented and discussed herein.*

Keywords: External reinforcement, Concrete behavior, bonded length of CFRP, Abaqus, Stiffness.

1 Introduction
Upgrading of reinforced concrete structures may be required for many different reasons. The concrete may have become structurally inadequate for example, due to the lack of strength, poor initial design and/or construction, lack of stiffness or durability, increasing of design loads or accident events such as earthquakes. In the past, the technique used for strengthening the concrete was the application of steel plates to the surface of concrete. However, due to the vulnerability of steel to aggressive environment and its weight, this method was abandoned in favor of composite materials for rehabilitation. The use of FRP to repair and rehabilitate concrete structures has become increasingly attractive due to the well-known good mechanical properties of this material, with particular reference to its very high strength to density ratio. Although FRP sheets are much more expensive than steel plates but they are much lighter, which makes the installation much easier and less labor intensive.

FRP sheets are also considerably more resistant to any aggressive environments. These advantages make FRP, a promising material for retrofitting existing structures.
Fiber-reinforced polymers (FRP) is a composite material made of resin matrix reinforced with fibers. Load is carried mostly by the fibers and the matrix works as a protector of fibers and the load transfer from fiber to fiber, therefore the matrix must have good bond with fibers to transfer the load effectively to them. The nature of the matrix can be materials such as polyester or vinyl ester. The load is transferred through the interface of the FRP sheet and the concrete. The strength and stiffness of interface substrate is of critical importance for the effectiveness of the technique.
Although the reinforcement of concrete by CFRP plates increase in a remarkable way the failure load, there is an effective bond length for a joint beyond which no further increase in failure load can be achieved[1,2,3]. For this purpose, a numerical study was conducted using a finite element program ABAQUS on 11 beams to investigate the effect of the bonded length of the CFRP plates. All beams had the same rectangular cross-section geometry and were loaded with same value, but differed in the length of the carbon fiber reinforced plastic (CFRP) plate. The soffit of the beam was retrofitted with CFRP laminates 100 mm wide and of eleven different lengths, from 100 mm, to 1000 mm. The laminate was positioned at the center of the beam.

2 Finite Element Analysis

Finite element failure analysis was performed to model the behavior of the beams. The FEM package Abaqus/standard [4] was used for the analysis.

2.1 Material properties and constitutive models

2.1.1 Concrete

A plastic damage model was used to model the concrete behavior is called the Concrete Damage Plasticity defined in the Abaqus library. This model assumes that the main two failure modes are tensile cracking and compressive crushing [4]. The model considers the total strain as the addition of elastic ε^{el} and plastic ε^{pl} strain;

$$\varepsilon = \varepsilon^{el} + \varepsilon^{pl} \qquad (1)$$

The stress-strain relation associated with damage corresponds to:

$$\sigma = (1-d)D_0^{el}:\left(\varepsilon - \varepsilon^{pl}\right) = D^{el}:(\varepsilon - \varepsilon^{pl}) \qquad (2)$$

Where σ is Cauchy stress tensor, by d is the scalar stiffness degradation variable, respectively, ε is the strain tensor, D_0^{el} the initial (undamaged) elastic stiffness of the material, while D^{el} is the degraded elastic stiffness tensor.
Under uni-axial tension, the stress–strain response follows a linear elastic relationship until the value of the failure stress is reached. The failure stress corresponds to the onset of micro-cracking in the concrete material. Beyond the failure stress, the formation of micro-cracks is represented with a softening stress–strain response.
The table 1 summarize the properties of the concrete used in our study, and the main parameter for modeling the behavior of the concrete using CDP is summarized on table 2. For the identification of the constitutive parameters of CDP model, the following laboratory tests are necessary:

- The uniaxial compression.
- The uniaxial tension.
- The biaxial failure in plane state of stress (the Kupfer’s curve for concrete class B50).
- The triaxial test of concrete (superposition of the hydrostatic state of stress and the uniaxial compression stress).

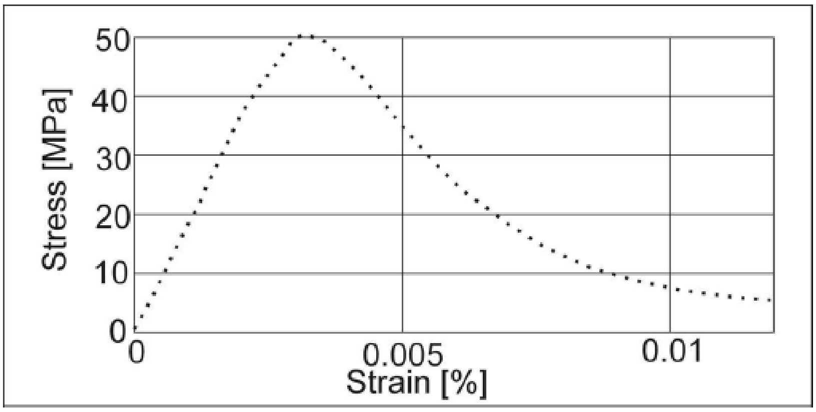

Fig. 1 Uniaxial compression test of concrete, class B50 – experimental curve [5]

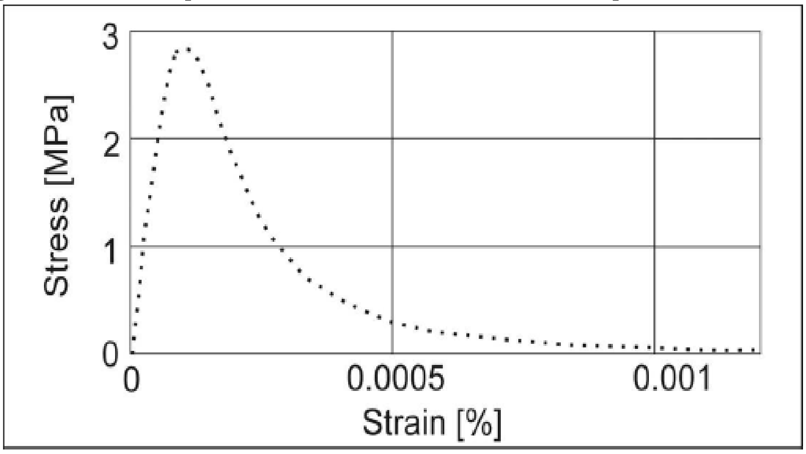

Fig. 2. Uniaxial tension test of concrete, class B50 – experimental curve [5]

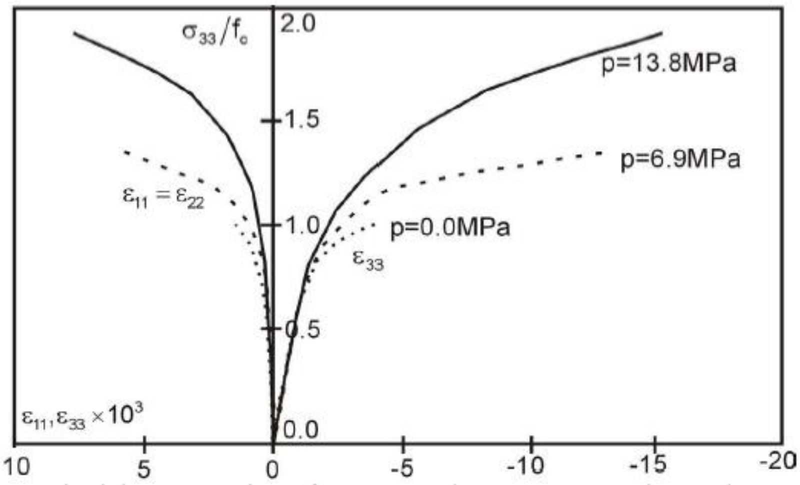

Fig. 3. Triaxial compression of concrete, class B50 – experimental curve [6]

Table 1. Properties of Concrete B50 [5]

Material	Concrete B50
Young's Modulus E [MPa]	19700
Shear Modulus [MPa]	8270
Poisson ratio	0.19

Table 2. Parameter of CDP model [5]

Β	38°
Μ	1
$f = \frac{f_{b0}}{f_c}$	1.12
Γ	0.666

The hardening and softening rule and the evolution of the scalar damage variable for compression and tension are presented in the table 3 & 4 both depend on the crushing or cracking strains.

Table 3. Concrete Compression hardening and damage [5]

Stress [MPa]	Crushing Strain	Damage
15	0	0
20.197804	0.0000747307	0
30.000609	0.0000988479	0
40.303781	0.000154123	0
50.007692	0.000761538	0
40.236090	0.002557559	0.195402
20.236090	0.005675431	0.596382
5.257557	0.011733119	0.894865

Table 4. Concrete tension hardening and damage [5]

Stress [MPa]	Cracking Strain	Damage
1.99893	0	0
2.842	0.00003333	0
1.86981	0.000160427	0.406411
0.862723	0.000279763	0.69638
0.226254	0.000684593	0.920389
0.056576	0.00108673	0.980093

2.1.2 CFRP plates and Epoxy

The model used in this study consider the CFRP material as a linear elastic orthotropic material. The table below show the characteristics of the CFRP used in this paper. The young and shear modulus of the epoxy is respectively 2.5 GPa and 0.665 GPa.

Table 5. Carbon fiber Properties [7]

Young's modulus	E_{11} 235 GPa
Young's modulus	E_{22} 17 GPa
Young's modulus	E_{33} 17 GPa
Poisson's ratio	n_{12} 0.32
Poisson's ratio	n_{13} 0.32
Poisson's ratio	n_{23} 0.45
Young's modulus	G_{12} 4.5 GPa
Young's modulus	G_{13} 4.5 GPa
Young's modulus	G_{23} 2.5 GPa
Tensile failure stress	X_{1t} 3900 MPa
Compressive failure stress	X_{1c} 2400 MPa
Tensile failure stress	X_{2t} 111 MPa
Compressive failure stress	X_{2c} 290 MPa
Tensile failure stress	X_{3t} 50 MPa
Compressive failure stress	X_{3c} 290 MPa
Failure shear stress	S_{12} 120 MPa
Failure shear stress	S_{13} 137 MPa
Failure shear stress	S_{23} 90 MPa

2.1.3 CFRP-Concrete interface

The model used to represent the interface between concrete and CFRP was a cohesive zone model. Fig.4 shows a graphic interpretation of a simple bilinear traction-separation law written in terms of the effective traction τ and effective opening displacement δ. The interface is modelled as a rich zone of small thickness and the initial stiffness K_{nn} and K_{ss} is defined as [8]:

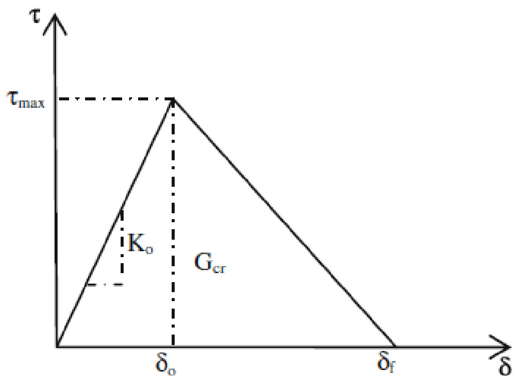

Fig 4. Bilinear traction–separation constitutive law

$$K_{nn} = \frac{1}{\frac{t_c}{E_c}+\frac{t_i}{E_i}};\ K_{ss} = K_{tt} = \frac{1}{\frac{t_c}{G_c}+\frac{t_i}{G_i}} \quad (3)$$

Where t_c and t_i is respectively the concrete thickness and resin thickness, G_c and G_i is the shear modulus of the concrete and the resin, E_c and E_i is Young modulus of the concrete and the resin respectively. The value used in this study were t_i = 1mm and t_c = 5mm.

From Fig. 4, it is obvious that the relationship between the traction stress and effective opening displacement is defined by the local strength of the material, $\tau_{max,}$ the stiffness, K_{ss}, a characteristic opening displacement at fracture, δ_f, and the energy needed for opening the crack, G_{cr}, which is equal to the area under the traction–displacement curve. The maximum shear stress can be calculated by the following equation.

$$\tau_{max} = 1.5 \times f_t \times \sqrt{\frac{2.25-\frac{b_f}{b_c}}{1.25+\frac{b_f}{b_c}}} \quad (4)$$

Where: b_c is concrete width, b_f is CFRP plate, and f_{ct} is concrete tensile strength can be calculated by:

$$f_{ct} = 0.33\sqrt{f'_c} \quad (5)$$

Where f'_c is the compressive strength.

For fracture energy, G_{cr}, previous researches have indicated values from 300 J/m2 up to 1500 J/m2 [9, 10]. For this study the value 900 J/m2, in the middle of the interval proposed by previous studies, was used.

The interface damage evolution was expressed in terms of energy release. The description of this model is available in the Abaqus material library [4]. The dependence of the fracture energy on the mode mix was defined based on the Benzaggah–Kenane fracture criterion [4]. Benzaggah–Kenane fracture criterion is particularly useful when the critical fracture energies during deformation purely along the first and the second shear directions are the same.

2.2 Geometry of the studied beams

The beam used in this study is a concrete beam with a span of l=1000 mm, the beam’s width is b=100 mm and the height is h=200mm. the length of the CFRP Plate vary from 100 mm to 1000 mm. Fig 5 shows the different dispositive of the plates for the beams.

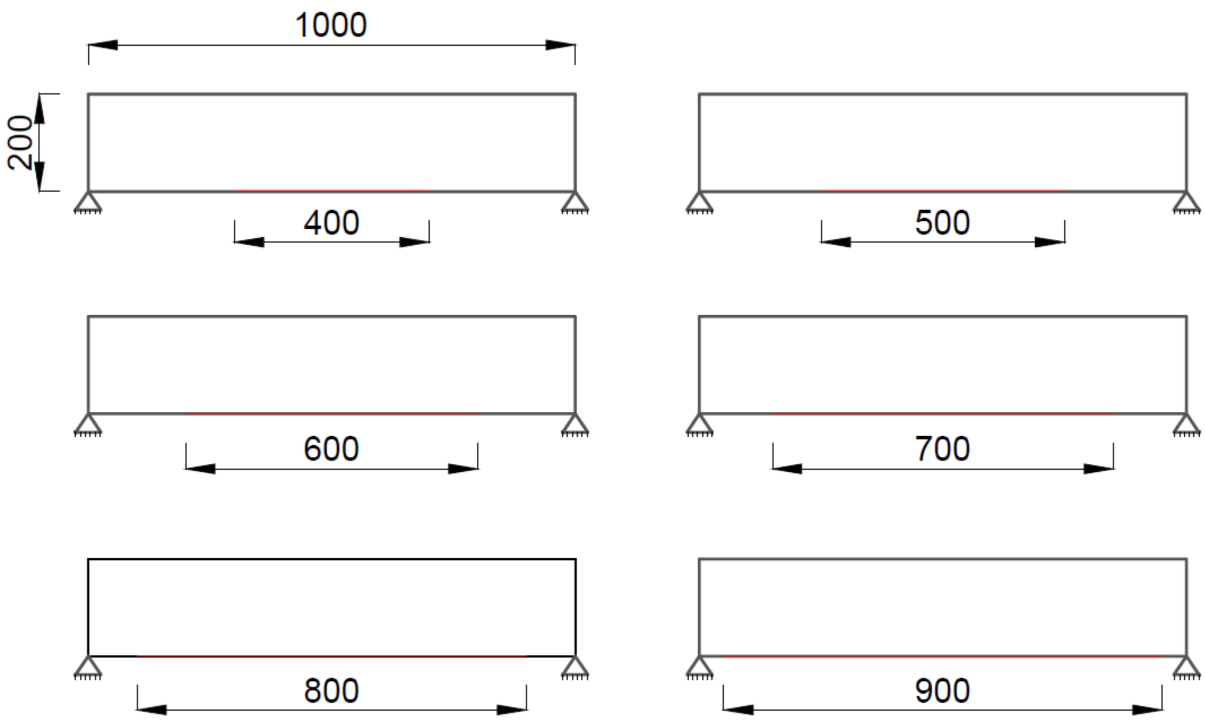

Fig 5. Length of CFRP Plates in the six beams

2.3 Load and boundary condition

In order to validate the relevance of the proposed technique, each beam was loaded with the same type of load; it was a uniform distributed load with a value of 0.35 N/mm². The boundary conditions considered in this study was a clamped-clamped beam. The figure below show in a clearly way the boundary condition and the mode of load applied in each beam.

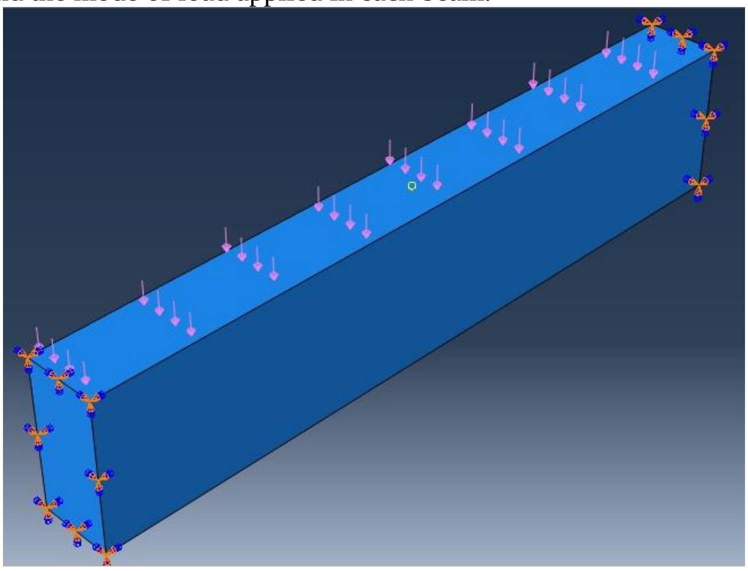
Fig 6. Beam under uniform loading

3 Result and Discussion

Fig. 7 shows the evolution of stress in the unreinforced beam. As can be seen on the same fig. the concentration of the stress is maximal at the support, and this is due to the boundary condition. On the fig. 8 we can see that the shape of the beams and the concentration of stress is exactly the same for the other beams, which means that the length of CFRP plate do not interfere or influence on the shape of the beam.

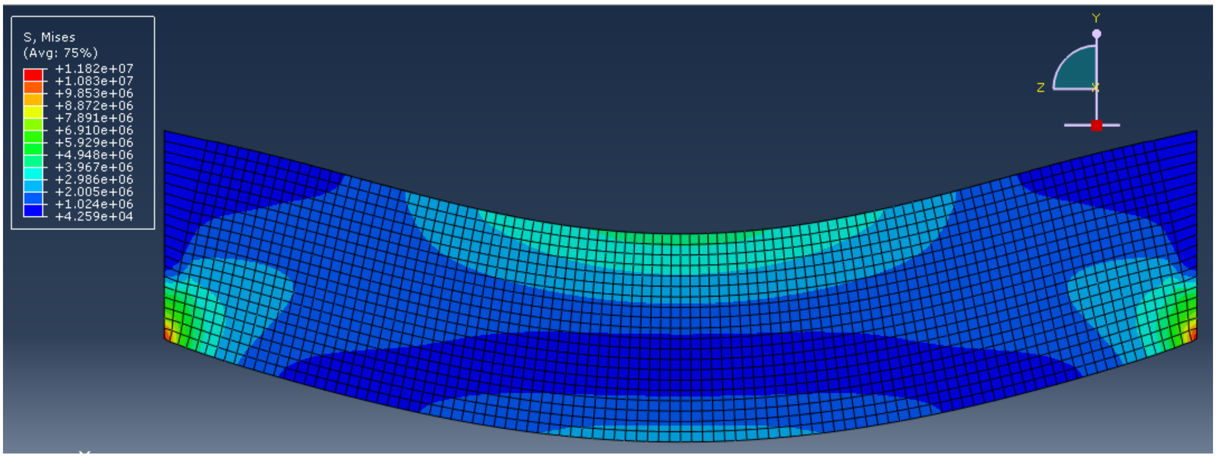

Fig 7. Evolution of the stress for the unreinforced beam (Pa)

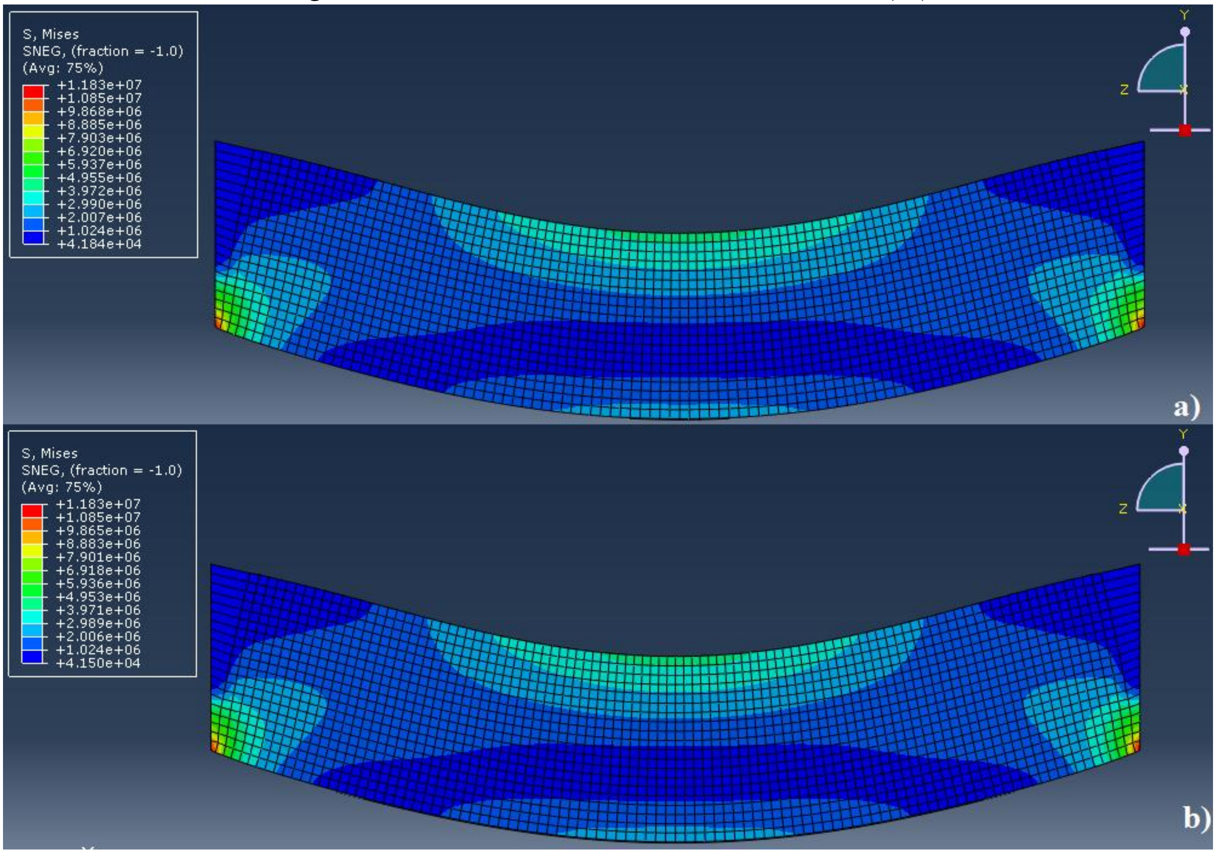

Fig8. Evolution of the stress of the reinforced beam by a CFRP plate (Pa). a) Length of 100-mm. b) Length of 700 mm

The effect of the variation of the length of CFRP Plate is clearly shown on the fig 9, we can notice from the curves a good change in the behavior of our beam, we can see an increase in the strength and the ductility of the beam.

If we compare the elastic zone for the different beams, we cannot neglect the effect of increase the CFRP plate length; we can notice that if we increase the length of CFRP plate we can improve the behavior of the beam. Because for the unreinforced beam, the elastic behavior was stopped for a value of 0.16 MPa and for a beam who was reinforced by 300 mm of CFRP plate the value is increased to 0.18 MPa and a value of 0.19 for a 500 mm of CFRP plates. The largest value was 0.23 MPa for the fully reinforced beam. Which means that our beam can support an increase of 43% in the stress (from 0.16 MPa to 0.23 MPa) while staying within the elastic zone.

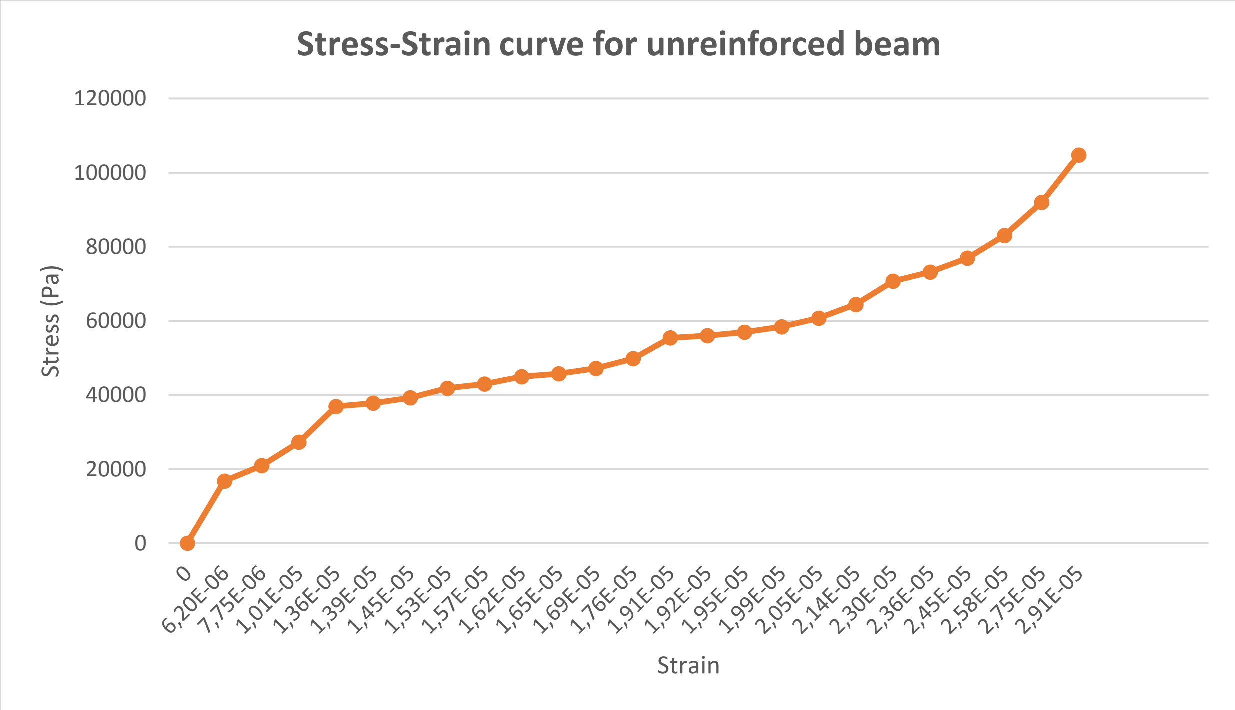

Fig9. Stress-Strain curve for the unreinforced beam

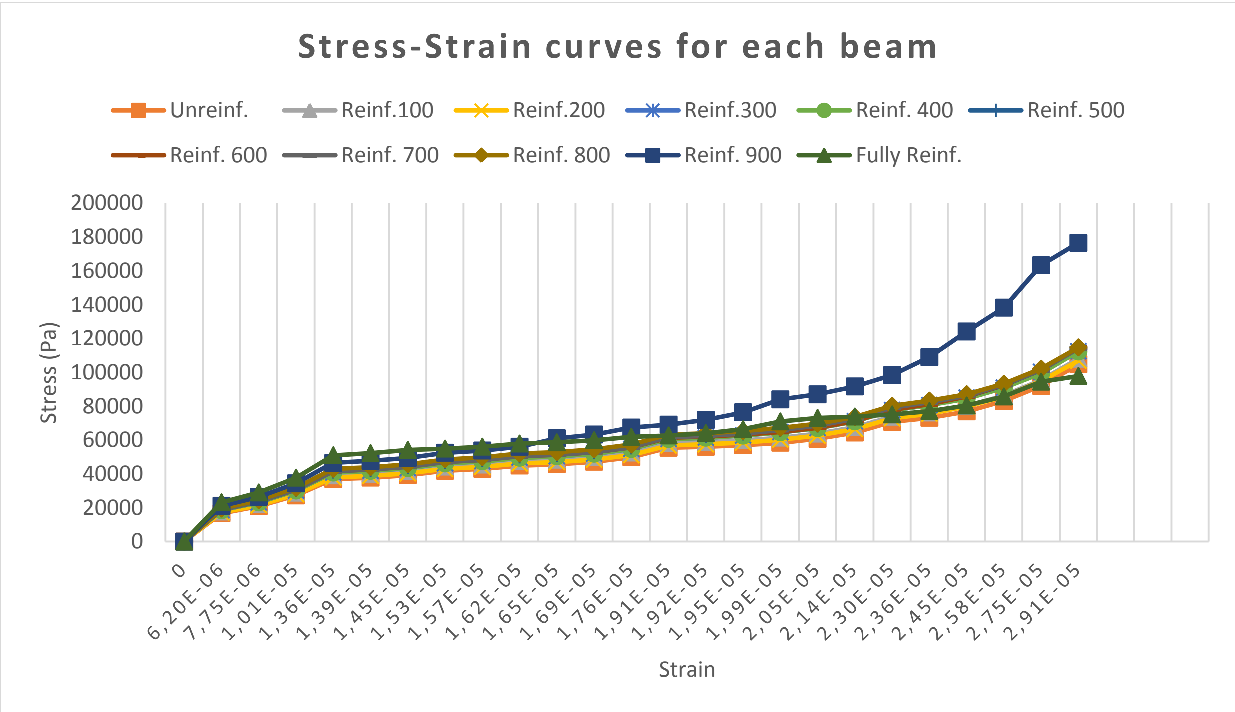

Fig10. Stress-Strain curves for each beam

From the curves and the observation mentioned above we can say that strengthening by CFRP plate is an encouraging solution and is the most suitable solution to strength the aged structures or the one who has changing their functionality. The first reason is by using a simple light CFRP plate and the same section of concrete we had noticed an increase of 43% of the strength of the concrete beam, and the second one is the several advantage of the CFRP materials as the good ration weight / resistance, its resistance to fatigue, corrosion or even his fire resistance.

4 Conclusion

In this study, a finite element model was developed to analyze the influence of CFRP plate length on the behavior of the concrete beams. The concrete damage plasticity was the model used to describe the concrete behavior. Elastic orthotropic behavior was used to represent the CFRP behavior; also, a cohesive model was used to address the interfacial behavior between CFRP and concrete. The following conclusions can be drawn from this study:

- The behavior of the beam has really improved when we had applied the CFRP plate.
- The length of CFRP significantly influences the behavior of the retrofitted beams. the ultimate load increases with the length of the CFRP.
- The variation of the CFRP plate length do not influence the shape of the beam and the concentration of the stress.
- The cohesive model proved able to represent the bond behavior between CFRP and concrete.

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