Article no. 49

THE CIVIL ENGINEERING JOURNAL 3-2021

EVALUATION OF EFFECTIVE POLYMER FIBRE LENGTH ON ENERGY ABSORPTION CAPACITY OF REINFORCED BEAMS BY EBR AND NSM METHODS

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ABSTRACT

This study presents a comparison of two methods used for retrofitting Reinforced Concrete (RC) beams, namely, the Externally Bonded Reinforcement (EBR) and the Near-Surface Mounting (NSM) methods. A parametric analysis was carried out using variables such as the retrofitted, the retrofitting method (EBR and NSM), and the thickness of the Carbon Fibre-Reinforced Polymer (CFRP) sheets. To achieve this goal, the finite element method and ABAQUS software were employed. An un-retrofitted beam was also simulated as the control specimen for comparison. Beam responses were compared through load–displacement and energy absorption capacity diagrams. Results show that the higher energy absorption capacity in all CFRP-retrofitted RC beams, which was 1.69–5.54 times higher than in un-retrofitted beams. Also, when half the length of the beam span is reinforced with a CFRP sheet, the entire beam assembly with CFRP participates in the bearing. In this situation, beam cracking occurs with a delay and leads to an increased energy absorption capacity of the beam. As a result, the energy absorption capacity of the beam, in this case, was less than that obtained in the previous one where half of the span of the beam was retrofitted.

KEYWORDS

Retrofitting, Externally Bonded Reinforcement (EBR) method, Near-urface Mounting (NSM) Method, Finite Element Method, RC beam

INTRODUCTION

Retrofitting reinforced concrete structure is essential due to the increased applied structural loads during operation, structural damage or destruction, and potential shortcomings in the design or construction of the structure [1,2]. Furthermore, because of the age of many historical buildings, monuments, and strategic buildings, and the fact that their potential collapse would inflict an enormous burden on the national economy, retrofitting has become a great interest to civil engineers today. On the other hand, the lower life expectancy of the newly-built structures in harsh climates has led engineers to substitute the incorporated materials with new ones [3].

DOI 10.14311/CEJ.2021.03.0049

Fig. 1 – FRP sheets bonded to the external surface of RC beams

Corrosion of the steel used inside reinforced concrete structures, the heavyweight of steel-reinforced structures, and the lower resistance of steel against acids and bases are among the disadvantages that can be enumerated for steel-reinforced concrete structures. For this reason, civil engineers in the 1980s turned to fibre-reinforced polymers (FRPs) for reinforcing concrete structures. Of the methods using FRPs, two are more prominent: (1) the EBR method which involves bonding FRP sheets to the external surface of a structure (Figure 1), and (2) the NSM method which is based on placing reinforcing materials along the grooves opened into the beam surface (Figure 2). In the NSM method, FRP straps are placed inside the grooves opened into the concrete surface, and subsequently, epoxy is used to provide a strong bonding between the FRP straps and the concrete [4]. The present study aimed to use the finite element method to study the effect of the effective FRP length on the energy absorption capacity of concrete beams reinforced through the EBR and the NSM methods. To this end, several RC beams were simulated using the finite element analysis by ABAQUS to examine the effect of FRP sheets and the role they can play in improving the flexural behaviour of these beams.

Fig. 2 – Use of FRP composites in surface grooves of a beam by the NSM method

Numerous studies have been conducted so far on retrofitting reinforced concrete buildings, a number of the most important are referred below. Abdoljalil (2014) studied the behaviour and performance of deep RC beams with openings retrofitted with CFRP linings. To this end, eight RC beams with external CFRP linings were tested. Several parameters were examined including the layout of the CFRP linings at different positioning angles inside the beam. The results of this experimental study showed that the use of externally attached CFRP straps is not only helpful in increasing the ultimate shear capacity but also in limiting the width of shear cracks, thus increasing the stiffness of deep RC beams with openings [6]. In another experimental study, Kharatmol et al. (2014) used CFRPs to retrofit RC beams. They also compared the retrofitted beams with un-retrofitted RC beams in their load-bearing capacity, as well as ductility, and evaluated the effects of such parameters as fibre thickness and fibre layout on the beam performance. According to their results, since CFRP linings can significantly increase the tensile strength of concrete, they can be effectively added to the tensile part of RC beams to improve their load-bearing capacity [7]. In their experimental study, Mofidi et al. (2015) used the NSM method for retrofitting RC beams with polymer composites and studied the behaviour of these beams in terms of their shear strength. To this end, six full-scale T-shaped RC beams (span= 4.52m) were built and subjected to incremental loading to examine the respective effects of such parameters as FRP rebars (by the NSM method), steel stirrups, and reinforcement ratio. According to their results, the steel stirrups used alongside the FRP rebars mounted near the concrete surface did not deteriorate the performance of any of the abovementioned elements [8]. In another experimental study by Tahsiri et al. (2015), the respective behaviours of RC beams retrofitted with FRP sheets and with steel jackets were compared and the respective characteristic of both these beam groups duly explained [9]. In the experimental study conducted by Khalifa (2016), six RC beams were retrofitted with CFRP rods buried in the concrete surface and their performance under flexural loading evaluated [10]. Ceroni (2010) experimentally examined FRP-retrofitted RC beams. To this end, FRP layers were used to retrofit the RC beams by the NSM method before the beams were subjected to uniform and cyclic loadings. A full comparison in terms of beam failure was made in this study between the obtained theoretical and experimental results [11]. Chen et al. (2018) studied experimentally the flexural behaviour of RC beams retrofitted with U-shaped basalt fibre linings. To this end, they conducted the three-point flexural loading test and then compared the failure modes and the structural responses obtained for the retrofitted beams with those obtained for the un-retrofitted beam. In addition, the formula used for predicting the flexural behaviour of FRP-retrofitted beams (in two cases: CFRP-retrofitted beams and GFRP[1]-retrofitted beams) using basalt fibres was evaluated [12]. Carlos et al. (2018) studied the flexural behaviour of beams retrofitted with CFRP linings against the conditions imposed by fire. The main objective of this study was to evaluate the behaviour of retrofitted beams in response to the heat generated by a fire. Fire-resistance tests were conducted by spraying vermiculite-perlite, Portland cement, and expansive clay over the specimens. The test beams were also placed on a concrete slab so that their circumferential interactions could be correctly simulated. The results of this study showed that the beams covered with the mentioned protective materials, while maintaining their robustness, could withstand fire for a longer time. It was also found that the concrete slab placed around the beams influenced the way heat was applied to the beams as well as the mechanical response of the beams [13]. Haville et al. (2018) used the nonlinear finite element method to study the shear strength of CFRP-retrofitted RC beams under unsymmetrical loading, comparing their simulation results with experimental results. According to their results, the type of applied load has a significant influence over the response of beams retrofitted with CFRP rods [14]. In an experimental study, Reddi (2018) compared the behaviour of the beams retrofitted with CFRP rods to the behaviour required or these beams in the relevant retrofitting codes. To this end, four RC beams were duly made and exposed to the four-point loading conditions. According to the results, retrofitting an RC beam with CFRP sheets could increase the load-bearing capacity of the beam by 23% at most. The experimental results obtained in this study were also in good agreement with the theoretical results obtained in the relevant construction codes [15]. In another study, experimental results and numerical analyses performed in the past showed that the failure load in RC beams reinforced with EBR could be influenced by the effect of the loading pattern [16].

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[1] Glass-reinforced plastic

THE FRAMEWORK OF THE PRESENT STUDY

As mentioned in the introduction, the use of FRP sheets using the EBR technique is applied to increase the flexural capacity of reinforced concrete beams. It assumed the EBR technique is not subject to physical damage, fire, temperature variation, and ultraviolet rays. Also, the NSM technique was introduced for increasing the flexural strength of reinforced concrete beams. Several studies have shown that the use of global externally connected CFRP sheets can increase the final shear capacity and limit the width of the shear cracks. The studied variables included: (1) method of attaching the CFRP strips to the beam (by the EBR and NSM methods); (2) thickness of CFRP sheets (t=0.165mm and 0.33mm): and (3) length of FRP strips (the full span of the beam or half of it). Nevertheless, among the variables mentioned and their limited range, the focus of the present study is on the length of the FRP strips. Thus, nine RC beams with identical dimensions, spans, and reinforcing bars were simulated under different conditions using ABAQUS [17]. The dimensions of the beams and their steel reinforcing bars were assumed to remain constant in all the simulations. In other words, a 6.00m x 0.50m x 0.0.30m beam with 4ϕ14 steel bars grade S400 was used in all the 9 simulation cases (Figure 3). The dimensions of the FRP strips were the same as those used in Khalifa (2016) [10]. Upon completion of the simulation, the energy absorption capacity values obtained for each beam in different cases were duly compared. The loading is applied incrementally in the center of the beam span and the corresponding displacement is considered in different states. The simulation outputs included the load-displacement diagram (which exhibits the ultimate capacity of the concrete beam) as well as the stresses developed in each beam. The specifications of the simulated samples are given in Table 1. Figure 4 shows different simulation samples applied to the retrofitted beams.

Tab. 1 - Different simulation cases used in the present study

Simulation Case	Characteristic Strength of Concrete (MPa) and steel bar	Retrofitting Method	FRP Sheet Thickness (t)	FRP Strip Thickness	Abbreviation
1	fc=21; 4ϕ14	---	---	---	Not Retrofitted
2		EBR	t=0.165mm	Half the beam span	EBR (t, L/2)
3			t=0.165mm	Entire beam span	EBR (t, L)
4			2t=0.33mm	Half the beam span	EBR (2t, L/2)
5			2t=0.33mm	Entire beam span	EBR (t, L/2)
6		NSM	t=0.165mm	Half the beam span	NSM (t, L/2)
7			t=0.165mm	Entire beam span	NSM (t, L)
8			2t=0.33mm	Half the beam span	NSM (2t, L/2)
9			2t=0.33mm	Entire beam span	NSM (2t, L)

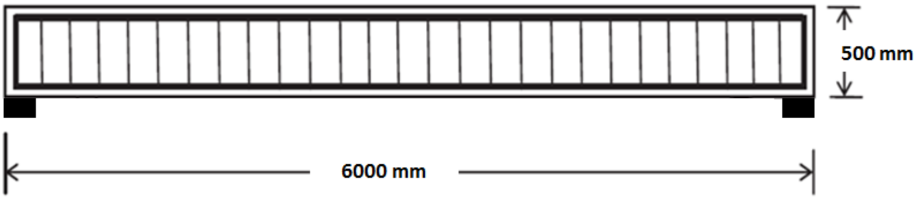


Fig. 3 – Dimensions of the retrofitted RC beam used in the study

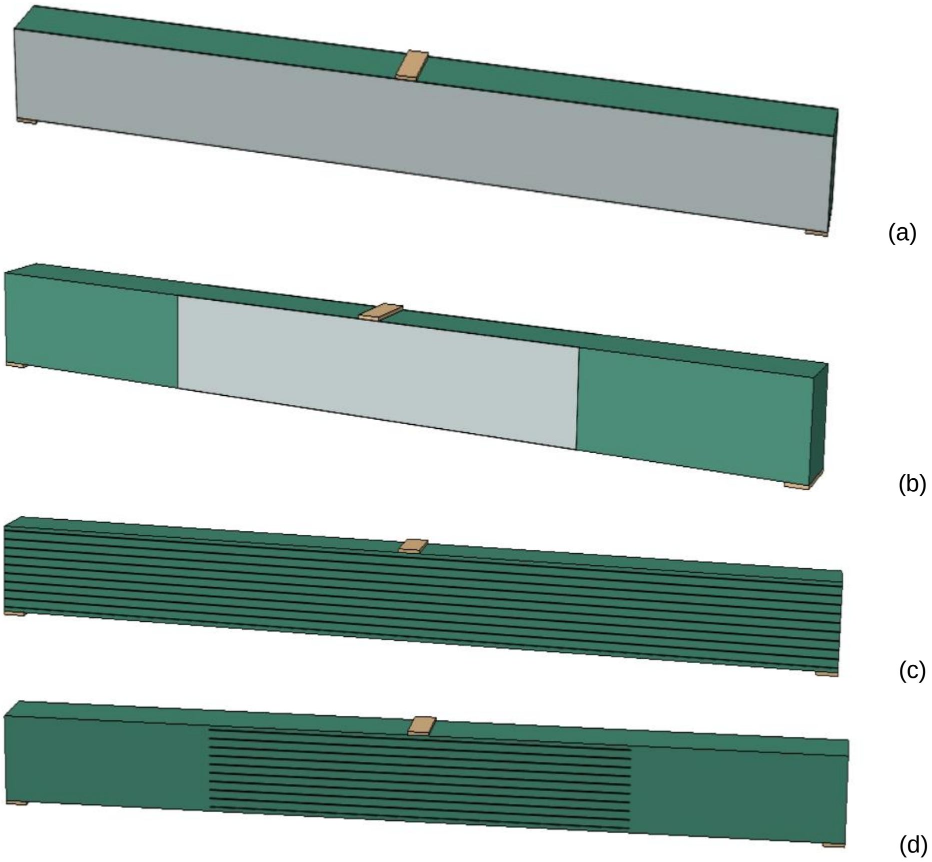
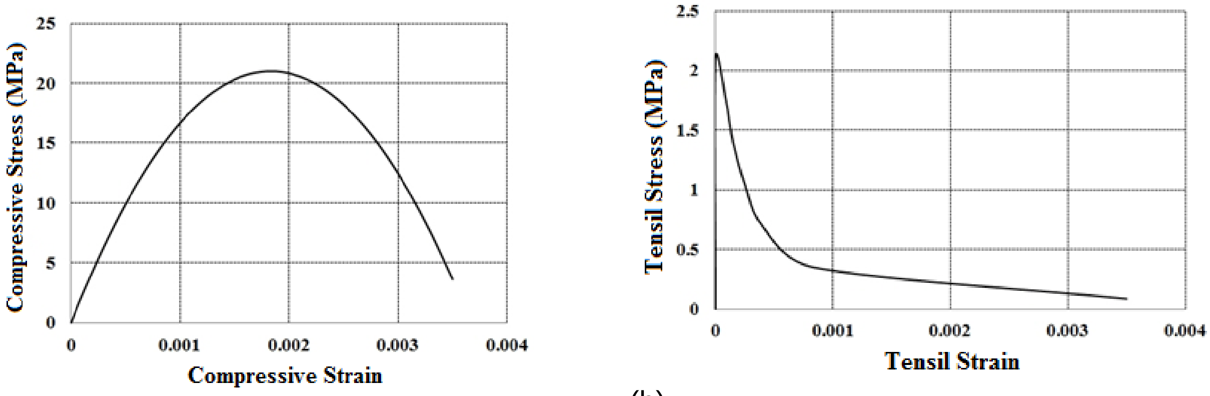


Fig. 4 – Different simulation cases applied to the retrofitted beams: (a) EBR method applied along the full span of the beam; (b) EBR method applied along half the beam span; (c) NSM method applied along the full span of the beam; and (d) NSM method applied along half the beam span

FINITE ELEMENT SIMULATION

In this section, the materials, the parameters, and the element types used in ABAQUS for simulating the RC beams are explained. The most important part of the numerical simulation of a reinforced concrete structure is to identify the nonlinear behaviour of the concrete. The nonlinear behaviour of brittle materials in ABAQUS is defined through three models: the smeared crack model, the brittle failure model, and the concrete damage plasticity model. Each model has certain advantages that can be used as required. The concrete damage plasticity model is the only model that can be used for both static and dynamic analysis of a structure. In this model, tensile cracking and compressive crushing are assumed to be the two main aspects of the concrete failure mechanism. The model was designed for simulating the failure of brittle materials and allows for stiffness recovery during loading cycles. Due to the model's lack of rupture criteria, elements cannot be removed by cracking during the analysis. However, this model can well predict the position and direction of crack formations. In the present study, the concrete damage plasticity model was used to simulate the nonlinear behaviour of concrete in tension and compression. The eight-node C3D8 and the Truss elements (with suitable sizes) were used for generating the meshes required for modelling concrete sections and reinforcing bars, respectively. Yield and ultimate strengths for longitudinal and transverse bars were assumed 400 MPa and 500MPa, and 280MPa and 380MPa, respectively. The density, Poisson's ratio, and modulus of elasticity for the CFRP sheets were assumed 1536 MPa, 0.25, and 2.4 x 10^5 MPa, respectively. Embedded region is used to define the behavior of rebar inside concrete; Therefore, one object can be assumed to be buried inside another object. The nonlinear analysis of reinforced concrete structures as well as their components can be conducted through the behaviour models used for either concrete and reinforcing bars or concrete–rebar bonding. However, as these behaviour models are costly due to their high computation times and multiple degrees of freedom, much attention has been focused in recent years on the use of smeared cracking and the concrete damage plasticity methods. The contact element is not explicitly modelled and adhesion is indirectly introduced in calculations through average behaviour models defined for concrete and reinforcing bars in two methods. In the concrete damage plasticity model, cracked concrete is assumed to be a continuous homogeneous material. In addition, the damage in the concrete specimen is demonstrated in this model by its reduced stiffness and not by modelling its developed cracks. The characteristic compressive strength of the concrete used in the beams was assumed to be 21 MPa. The stress-strain characteristic of this concrete is shown in Figure 5.



(a)

(b)

Fig. 5 – Stress–strain diagram obtained for the concrete with a compressive strength of 21MPa: (a) in compression, and (b) in tension.

Also, the accuracy of the simulation method used by modelling a CFRP-reinforced beam, which was made in the study of Kotynia and Cholostyako (2015) [18], and a good agreement was observed between the results of the finite element model and the experimental results. Figure 8 compares the load-displacement values of the finite element and experimental models of the B30-214-1T-15 beam [18]. As can be seen, the maximum load-displacement values corresponding to the experimental and numerical models have a relatively good correlation.

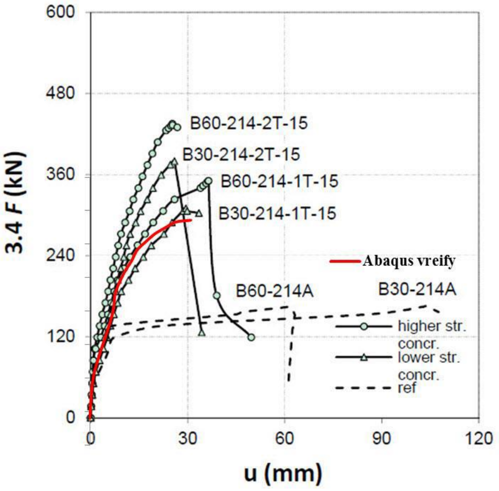
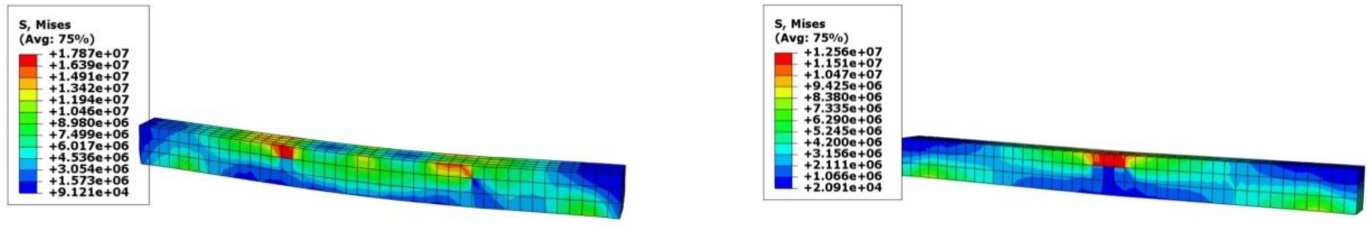


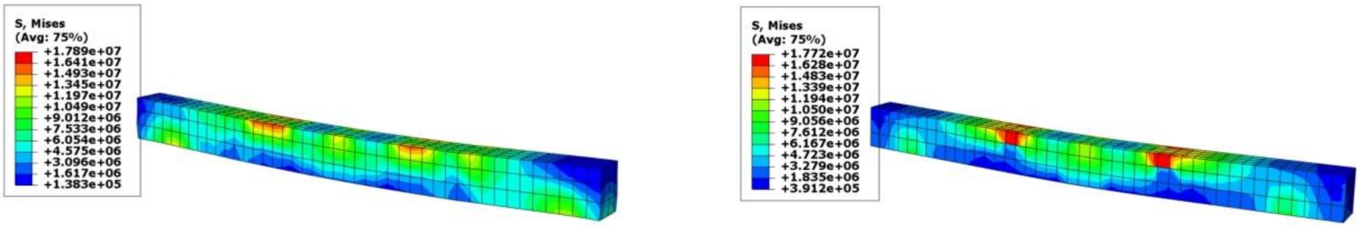
Fig. 6 – Finite element model validation and experimental results [18].

RESULTS AND DISCUSSION

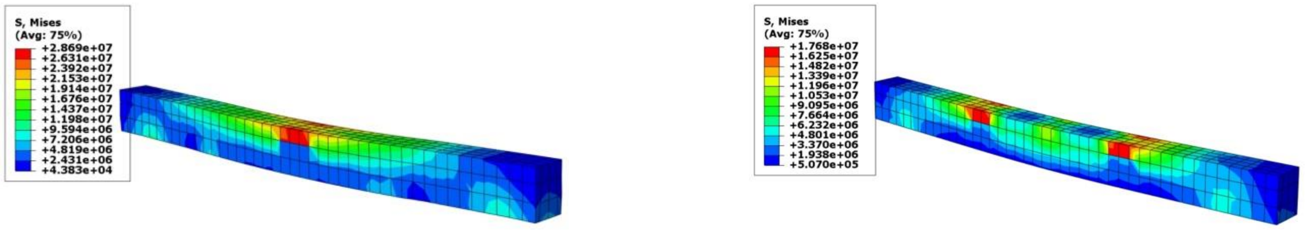
Figures .7 and 8 show the stress characteristics as well as the load-displacement diagrams obtained from the present simulation and finite element analysis of the models generated for the studied beams. The diagrams express stress, displacement, and force in kPa (kN/m2), m, and kN, respectively. When CFRP sheets coat on the surface of the beam, the beam's ability to prevent cracking and crack spreading and the flexural strength of the beam increased. In this situation, the combination of normal and shear stresses makes the von Mises stress criterion more prominent, while the NSM method is not considered crack propagation. The other concept considered in this study was the energy absorbed in different cases by the studied beams.



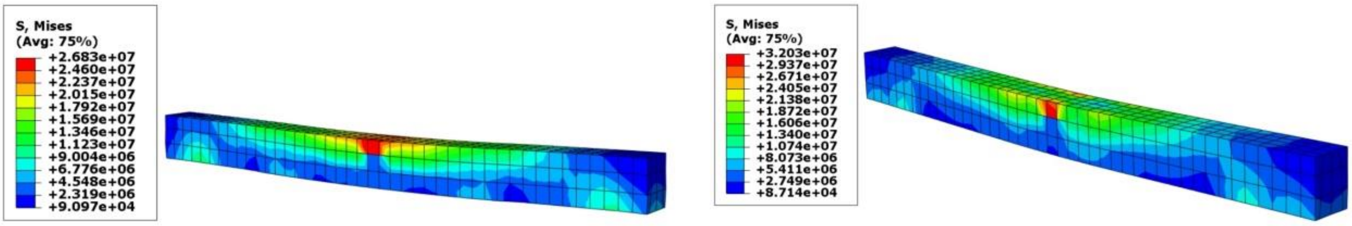
EBR (t, L/2, fc21) No Retrofitted (fc21)



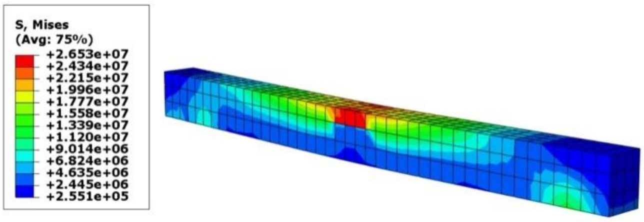
EBR (2t, L/2, fc21) EBR (t, L, fc21)



NSM (t, L/2, fc21) EBR (2t, L, fc21)

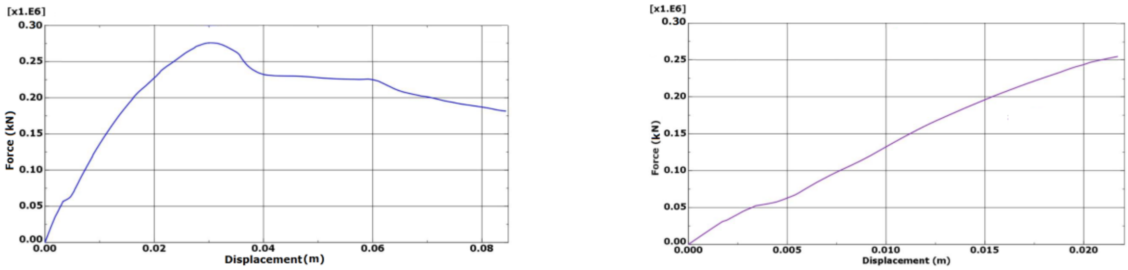


NSM (2t, L/2, fc21) NSM (t, L, fc21)



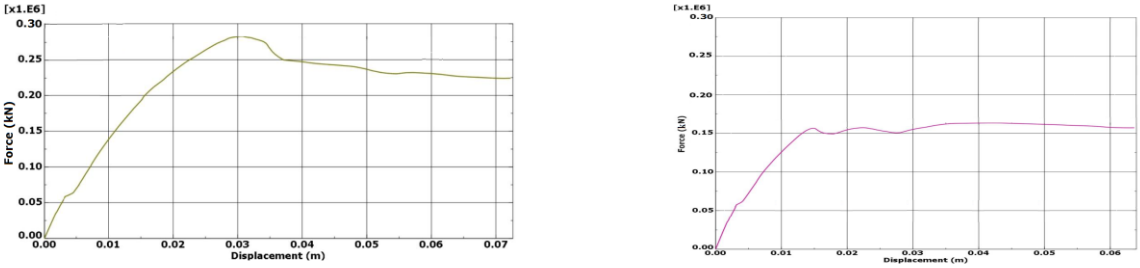
NSM (2t, L, fc21)

Fig. 7 – Stresses developed in the studied beams in different cases



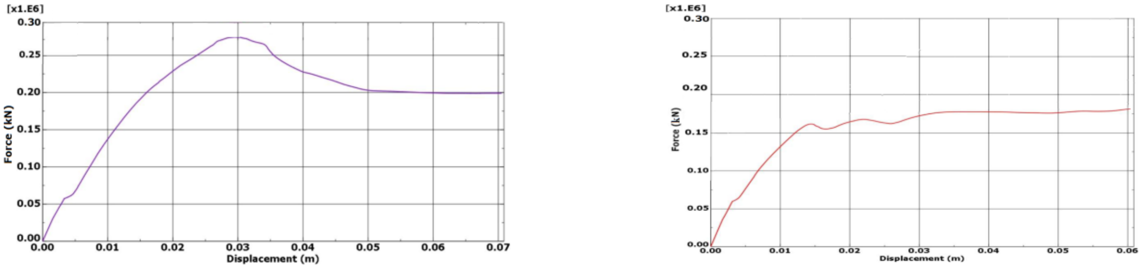
EBR (t, L/2, fc21)

No Retrofitted (fc21)



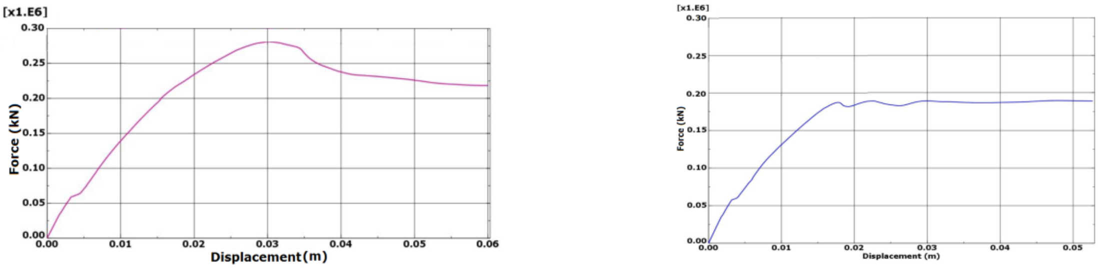
EBR (2t, L/2, fc21)

EBR (t, L, fc21)



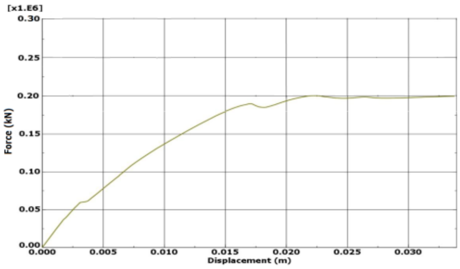
NSM (t, L/2, fc21)

EBR (2t, L, fc21)



NSM (2t, L/2, fc21)

NSM (t, L, fc21)



NSM 2t, L, fc21)

Fig. 8 – Load–displacement diagrams obtained for the studied beams in different cases

This energy is obtained by calculating the area under a load-displacement curve and is expressed in Figure 9. The energy absorbed and dissipated by a structure is among the most important factors in seismic retrofitting of that structure and must receive due attention. Accordingly, the area under the load-displacement diagram was calculated for each of the nine studied cases to represent the energy absorbed by the model in each case.

$$U = W = \int_0^{\delta} P_1 \, d\delta_1$$

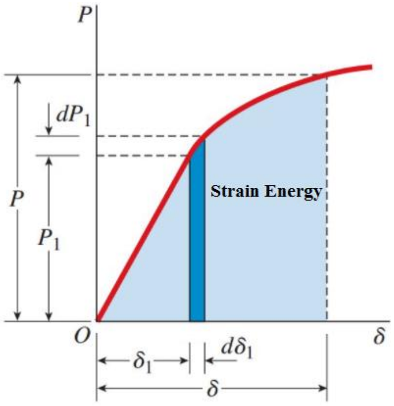


Fig. 9. - Load-Displacement curve

Figure 10 shows the energy absorption values obtained for the studied RC beams in different cases. The incorporation of CFRP sheets enhanced the energy absorption capacity of the beams in all studied cases, increasing the parameter up to 1.69-5.54 times that of the un-retrofitted beam. The energy absorption results are presented in Figure 11.

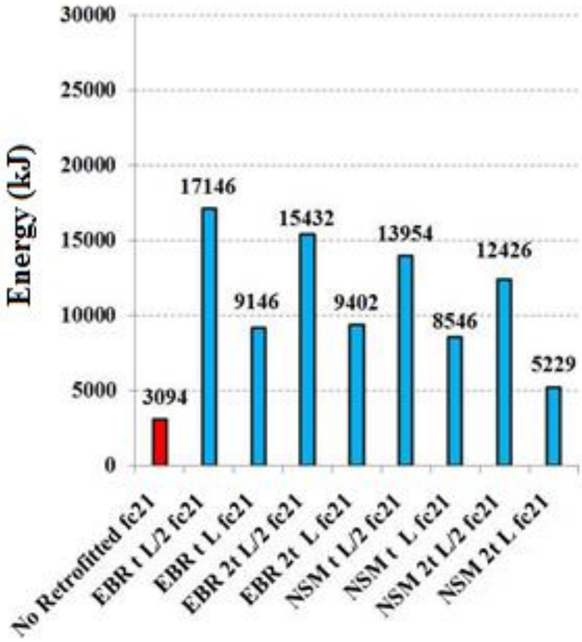


Fig. 10 – Energy absorption capacity of the simulated beams in different cases

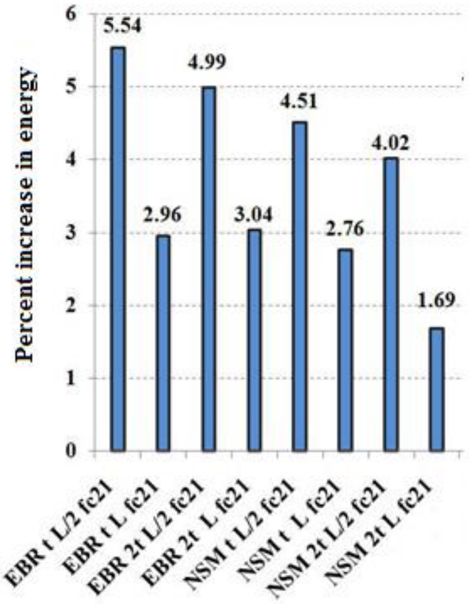


Fig. 11 – Percent increase in energy absorption ratios obtained in different cases

As already explained, the CFRP sheets used for retrofitting the studied beams were applied at two different lengths over the surface of each beam: (1) along the full span of the beam, and (2) along 50% (half) of the span of the beam, at equal distances from the middle of the beam.

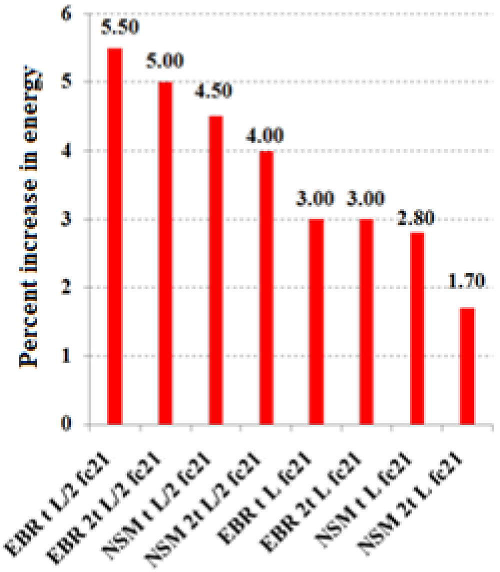


Fig. 12 – Comparison of energy absorption ratios for investigating the effect of retrofitted length in different cases

Figure 12 compares the energy absorption ratios of the beams in the eight different studied cases. The purpose of this comparison was to investigate the effect of retrofitted length on beam behaviour. As evident from the figure, in most studied cases, the percent energy absorption obtained for the 50% CFRP-retrofitted length was greater than that obtained for the 100% CFRP-retrofitted length. For example, in the case where the EBR method was applied to retrofit the RC beam (with compressive strength of 21MPa along 50% of its span with a CFRP sheet of 0.165mm thickness, the energy absorption capacity was increased 5.50 times; whereas, in the case where the same beam was similarly retrofitted along its full span, a lower energy absorption capacity increase of 4.23 times was obtained (compared with the un-retrofitted case). Incremental loading continues in the middle of the span until the beam reaches the destruction step. The reason is that in the former case (50% retrofitted length), the entire beam assembly (concrete plus reinforcing bars) contributed to load-bearing alongside the CFRP sheet, postponing occurrence of crack and increasing the energy absorption capacity of the beams. Conversely, in the case where retrofitting was applied along the full span of the beam, the CFRP sheet carried the greater share of the load without the full engagement of the beam assembly in load-bearing. As a result, the energy absorption capacity of the beam, in this case, was less than that in the case with the entire length of the beam retrofitted. It should be noted that this process is before the failure of CFRP, after which the steel reinforcement must be engaged and increase the absorption capacity.

Figure 13 compares the increase in the energy absorption capacity in different cases to determine the impact of the retrofitting method on the results. As evident from the figure, the energy absorption capacity increase in most studied beams retrofitted by the EBR method was greater than that obtained by the NSM method, amounting to more than 76% in the case abbreviated as EBR 2t L fc21MPa. This can be attributed to the fact that, when the entire length of the beam is retrofitted with CFRP sheets, crack formation and propagation in the beam will be better prevented, further increasing the load-bearing capacity.

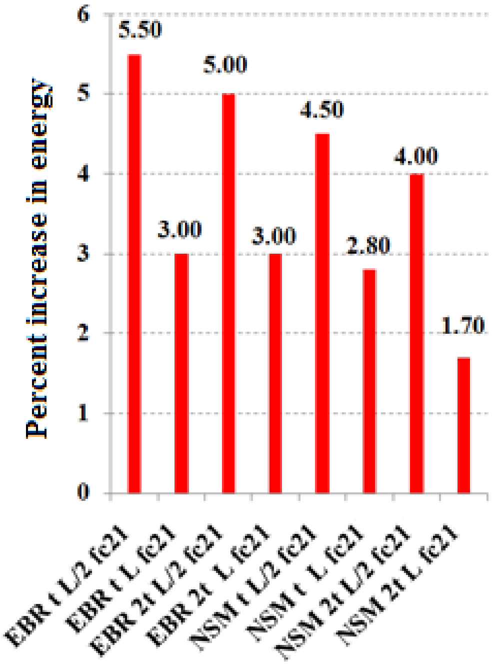


Fig. 13– Comparison of energy absorption ratios in different cases, demonstrating the respective effects of the employed retrofitting methods

CONCLUSION

A comparative study of the EBR and NSM methods used for retrofitting RC beams was created. For this purpose, the finite element method (using ABAQUS) was implemented. In the present study, variables such as the retrofitted length (equal to the entire beam span and half the beam span), the retrofitting method employed (EBR and NSM methods), and the CFRP sheet thickness (t and 2t) were investigated. An un-retrofitted beam was also simulated as the control specimen for comparison. The response of the beams was compared according to the load-displacement diagrams and energy absorption capacity. The most significant results obtained in the present study were:

1. Retrofitting RC beams with CFRP sheets increased the energy absorption capacity of the beams in all studied cases. The extent of this increase was between 1.69 and 5.59 times the corresponding value obtained for the un-retrofitted beam.
2. The energy absorption capacity of the retrofitted beam was greater when the CFRP sheet was applied to the entire length of the beam in most of the studied cases. For example, in the case of using the EBR method for retrofitting the RC beam (compressive strength=21 MPa) along 50% of its length with a 0.165 mm thick CFRP sheet, the energy absorption capacity was enhanced to 5.50 times that of the un-retrofitted control specimen. Meanwhile, in the case of the entirely-retrofitted beam (twice the retrofitted length as the previous case), the energy absorption capacity exhibited a lower increase as it rose to 4.23 times the capacity of the un-retrofitted control specimen.
3. In the case where half the span of the beam was retrofitted using CFRP sheets, the whole beam assembly (concrete plus rebars) and the CFRP sheets jointly participated in carrying the load, thus postponing cracking in the beam and increasing the beam energy absorption capacity. Conversely, when CFRP retrofitting was applied to the entire beam span, the CFRP sheets carried most of the load, thus preventing the beam assembly from realizing its load-bearing capacity in full. As a result, the energy absorption capacity of the beam, in this case, was less than that obtained in the case with to half (50%) of the length retrofitted.
4. In most of the cases studied, the EBR method proved more effective than NSM, by offering a greater beam energy absorption capacity. In some cases (the case of EBR 2t L fc21), the energy absorption capacity corresponding to the EBR method was 76% of that offered by NSM. The reason is, when the CFRP sheets cover the entire beam surface, crack formation and propagation are prevented more effectively, allowing for a further increase in the load-bearing capacity.

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