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Effect of Bonded Length on the Seismic Performance of RC Beams Strengthened with longitudinal and U-wrapped CFRP Sheets

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□ ABSTRACT □

The use of EB CFRP sheets to strengthen RC beams is generally accepted as effective due to its favourable mechanical properties in terms of strength and stiffness. However, improving the performance of beams requires ductility as well as strength and the brittle nature of the CFRP and the debonding and peeling off modes of failure always raise concerns about the ductility of the strengthened beams. Cyclic loading conditions increase debonding problems and lead to more material deterioration, stiffness and strength degradation in CFRP strengthened beams. Therefore, it is important to evaluate the cyclic performance of RC beams strengthened with CFRP sheets to assess their strength and ductility.

In this paper, the developed FE models for the strengthened beams, with unidirectional longitudinal CFRP sheets externally bonded to the top of the beam and CFRP sheets wrapped around the sides and the bottom of the beam, under monotonic and cyclic loading were validated. The predicted behaviour of the FE model for the RC beams have been shown to lie within the range of the values reported in the literature for similar geometry. Moreover, the proposed FE models for the strengthened beams under cyclic loading were validated. With the purpose of validating the cyclic performance of the FE model for the non-strengthened and the CFRP strengthened beams, further validation and comparisons with the experimental data obtained from previous experimental studies from Nottingham University were carried out. Thus this model can be used in the following parametric study to predict the effect of different parameters. Consequently, the parametric study was conducted for several bonded lengths to study their influence in terms of strength and ductility. The results showed that the length of the strengthened region significantly influence the cumulative deflection and the dissipated energy capacity up to specific value.

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تأثير أطوال التثبيت على الأداء الزلزالي للجوائز البيتونية المسلحة المقوّاة بشرائح الـ CFRP الطولية والملفوفة على شكل حرف U

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□ ملخّص□

تعتبر التقوية باستخدام شرائح الـ ***CFRP*** المثبتة خارجيا على الجوائز البيتونية المسلحة أنها فعالة نظرًا لخصائصها الميكانيكية المرغوبة من حيث القوة والصلابة. إلّا أنّ تحسين أداء الجوائز البيتونية المسلحة يتطلب المطاوعة بالإضافة إلى القوة، والطبيعة الهشة للبوليميرات المقوّاة بألياف الكربون وأنماط الإنهيار والتقشير دائمًا تثير مخاوف بشأن مطاوعة الجوائز المقوّاة. تزيد ظروف التحميل الدوري من مشاكل فقدان الترابط وتؤدي إلى مزيد من تدهور المواد والصلابة وتدهور القوة في الجوائز المقواة بألياف الكربون. لذلك ، من المهم تقييم الأداء الدوري للجوائز البيتونية المسلحة المقوّاة بشرائح الـ ***CFRP*** لتقييم قوتها ومطاوعتها.

تم التحقق في هذا البحث من موثوقية نماذج العناصر المنتهية المطورة للجوائز المقوّاة بشرائح الـ ***CFRP*** أحادية الاتجاه المثبتة خارجيًا طولياً بأعلى الجائز وشرائح ***CFRP*** ملفوفة حول الجوانب وأسفل الجائز، تحت تأثير التحميل الستاتيكي والتحميل الدوري. تم إظهار أن السلوك المتوقع لنموذج العناصر المنتهية المطور للجوائز البيتونية المسلحة يقع ضمن نطاق القيم الواردة في الدراسات المرجعية المماثلة تحت تأثير التحميل الستاتيكي. بالإضافة إلى ذلك فقد تم التحقق من موثوقية نماذج العناصر المنتهية المقترحة للجوائز المقوّاة تحت تأثير التحميل الدوري بهدف التحقق من موثوقية الأداء الزلزالي لهذه النماذج من خلال إجراء مزيد من التحقق والمقارنات مع البيانات التجريبية التي تم الحصول عليها من الدراسات التجريبية السابقة التي تمت في مخابر جامعة نوتينغهام في بريطانيا. وبالتالي يمكن استخدام هذا النموذج في الدراسة البارامترية للتنبؤ بتأثير العوامل المختلفة. وبناءً عليه أجريت الدراسة البارامترية لعدة أطوال تثبيت لدراسة تأثيرها من حيث القوة والمطاوعة. أظهرت النتائج أن طول المنطقة المقوّاة يؤثر بشكل كبير على السهم التراكمي وكمية الطاقة المبددة حتى قيم محددة لهذه الأطوال بحيث يتلاشى التأثير بعدها.

الكلمات المفتاحية : الاداء الزلزالي، مطوعة الجوائز البيتونية المسلحة، المطوقة على شكل حرف ***U***، التقوية الخارجية بألياف الكربون

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INTRODUCTION

In the last decades, the effect of ductile behaviour, bond length and wrapping Externally Bonded (EB) Carbon Fibre Reinforced Polymers (CFRP) composites on Reinforced Concrete (RC) members to improve their performance has been examined theoretically and experimentally under monotonic loading. Early experimental studies of the use of CFRP as external reinforcement for repairing and strengthening RC beams have been carried out by Meier (1995) and Meier (1999). The main objectives of their research were to investigate the strength and stiffness of RC beams strengthened with CFRP plates. Norris *et. al.* (1997) carried out an experimental and analytical study of the behaviour of damaged concrete beams retrofitted with CFRP sheets for various orientations of the fibres (0°, 90°, and ±45°) with respect to the axis of the beams. Their beams had a main reinforcement ratio, $\rho = 0.67\%$, close to the minimal amount allowed by ACI code, but were over-designed against shear. Their results showed that the CFRP sheets bonded to the tension face and web of RC beams enhanced the strength and stiffness, with respect to the unstrengthened beams, and various modes of failure were observed depending on the fibre orientation. The longitudinally strengthened beams (with 0°) showed the largest increase in strength and stiffness but had catastrophic brittle failures because of the peeling-off of the CFRP sheets with significant decrease in deflection. The beams with 90° fibres had an ultimate load carrying capacity which was 20% less than the longitudinally strengthened beams, but they had larger deflection at failure, with a more ductile mode of failure. They concluded that the strength and stiffness of RC beams strengthened with CFRP sheets could be increased without causing brittle failures by using fibres in different orientations. The results of the experimental work carried out by He (1998) demonstrated that the most significant effects of CFRP plate bonding on RC beams are in terms of crack control, increased stiffness and ultimate load capacity. In terms of plate peeling off failure, the results illustrated that this mode of failure is caused by stress concentrations due to the sudden change of the reinforcement stiffness at the plate ends. The strengthened RC beams failed prematurely without reaching their full load carrying capacity. This was followed by numerous experimental studies investigating the strength and ductility of RC beams strengthened with CFRP under monotonic loading, considering various parameters. The failure mode and the behaviour of strengthened beams were shown to be highly dependent on the existing steel reinforcement ratio and the thickness of external CFRP reinforcement (Esfahania et al. 2007; Rahimi and Hutchinson 2001). Studies on RC beams strengthened with different lengths of FRP composites concluded that the ultimate load capacity and ductility increases with increasing lengths of the FRP reinforcement and extending the FRP reinforcement to the supports as much as possible (Fanning and Kelly 2001; Nguyen et al. 2001). However, the use of the CFRP composites for strengthening RC beams in many situations might be uneconomic. This is because of the high material cost of CFRP and due to the fact that its strength might not always be fully exploited as debonding problems could lead to premature brittle failure, especially under cyclic loading (Buyukozturk 2004). RC beams strengthened with CFRP composites might be subjected to cyclic deformation in many situations, such as structures located in seismic regions, multi-storey car parks, structures subject to high wind loads and bridges. Compared to monotonic loading, CFRP strengthened RC beams experience a progressive reduction in performance under cyclic loading, including bond degradation and increased debonding problems (Buyukozturk et al. 2004). Suleiman et al. (2008) also studied the performance of RC beams strengthend with CFRP sheets both experimentally and numerically under cyclic loading. Their investigation introduced a finite element model in which the concrete cracking, bond between steel and concrete, and bond between CFRP sheets and concrete were incorporated. Ferrier et al. (2011) developed adhesive joint subjected to cyclic load to model CFRP strengthened RC beam under cyclic loading. Loo et al. (2012) conducted a numerical simulation of CFRP strengthened beam under cyclic loading with constitutive relation of material behaviour of concrete, steel reinforcement, FRP and bond stress-slip relation. They proposed FRP to concrete bond-slip model under cyclic load. The four-node isoparametric concrete element was used for concrete, bar element for steel reinforcement, elastic-plastic truss elements for FRP composites, and 1D bond interface element for bond slip between concrete and FRP interface. However, they neglected the degradation of FRP properties with number of cycles. Shaker and Kamonna (2016) carried out a nonlinear analysis of RC beams strengthened by prestressed CFRP sheets under static loads to investigate the efficiency of prestressing CFRP sheets as a reinforcing method for RC beams. They found that using CFRPs significantly enhanced the cracking load capacity.

The flexural strength of RC beams with and without end anchorages that were externally bonded CFRP laminates was studied by Jeevan and Reddy 2018. The results of their study showed that all of the applied strengthening techniques enhanced the ultimate load capacity. Hosen et al. 2019 investigated the structural performance of lightweight concrete beams reinforced with CFRP sheets using the side externally bonded reinforcing (S-EBR) method. According to the findings, the proposed strengthening approach considerably improved flexural capacity independent of the cracking state during the pre-repair stage. Al-Khafaji and Salim 2020 studied the use of CFRP sheets to reinforce continuous RC T-beams and discovered that the ultimate capacity of the strengthened beams increased by up to 90 %. Vuković, et al. (2020) carried out an experimental analysis of RC elements strengthened with CFRP strips to determine the efficiency of adding a composite material on improving the mechanical behaviour of old, full-size RC T-beams in service . The results illustrated that, for simply supported beams, lateral anchorages were shown to be unnecessary and there was no need to extend the CFRP strip beyond half the span length. Najaf et al. (2022) has shown that fibers, microsilica, and sustainable materials, such as nanosilica and waste glass powder, can improve the mechanical behaviour of concrete and the flexural strength of concrete could be greatly increased. Aref abadel et al. (2022) carried out an experimental study to examine the efficiency of CFRP in increasing the shear strength of deep beams. They found that the strengthening technique increased ductility significantly but did not increase stiffness for beams with a CFRP width-to-beam width ratio of less than 0.25. Many researchers found that, through the debonding process of the CFRP laminate, failure takes place in a brittle mode (Teng et al. 2002; Pham and Al-Mahaidi 2004). Therefore, this brittle behaviour must be carefully considered when using CFRP reinforcement in structural rehabilitation and strengthening design. While previous experimental studies focused on increasing stiffness and load capacity by applying CFRP to the tensile face of RC beams under monotonic loading, this study will consider the strength and ductility under cyclic loading. Moreover, most beams in existing RC structures work with slabs as T beams with high reinforcement ratio for bottom reinforcement compared to the top reinforcement. Thus, this should be considered in strengthening techniques and configurations. Minimum steel reinforcement was used in most previous experimental studies to provide the largest enhancement in load capacity and stiffness. However, this experimental research will use a larger reinforcement ratio for bottom reinforcement than the reinforcement ratio used in most of the previous research (ρ=2.5%) with relatively low reinforcement ratio for the top reinforcement (ρ=1.1%) to simulate existing structures designed for gravity loads. This paper presents in detail parametric study using the FE model suggested by Suleiman et al. (2008) and developed in this study and validated with the experimental work carried out at the University of Nottingham to examine a suggested strengthening technique for RC beams in terms of strength and ductility.

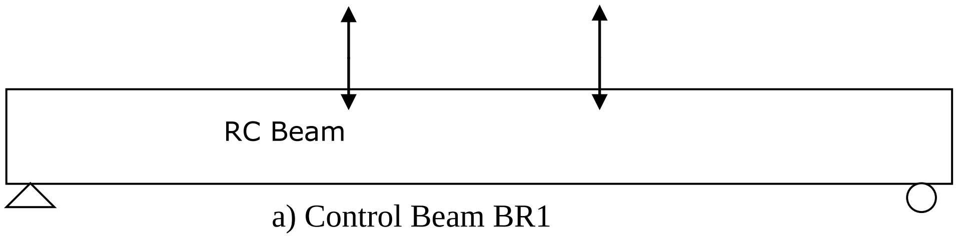
STRENGTHENING CONFIGURATIONS

Sets of RC beams, together with cubes, cylinders, prisms and concrete block specimens, were fabricated and tested. The RC beams were tested under large deformation cyclic loading. While one of these beam sets were strengthened with CFRP sheets, the other one was tested without strengthening and used as a control beam as shown in figure 1:

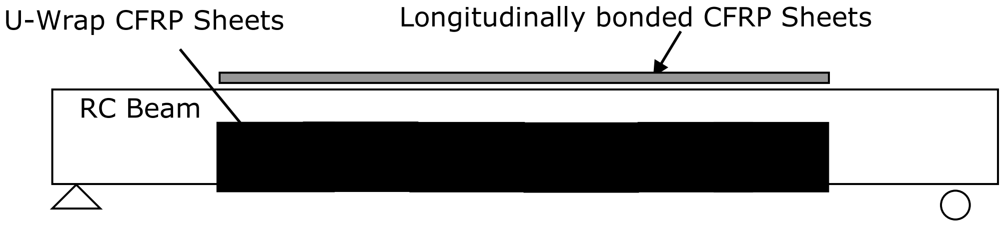
- Beam BR: control beam with no CFRP strengthening.
- Beam BUL: strengthened with CFRP sheets wrapped around the sides and the bottom of the beam. The orientation of the fibres was perpendicular to the length of the beam, referred to as U-wrap strengthening. A longitudinal layer of CFRP sheet was externally bonded to the top face of the beam.

GEOMETRY OF THE TEST BEAMS

The geometry of the test beams was designed to be as close as possible to the beams chosen from the literature for comparison purposes. The appropriate dimensions were selected and the maximum load was calculated. Accordingly, the test beams had a length of 2500mm and a cross-section of 150mm x 250mm. The simply supported span was 2300mm. When designing RC beams in structures designed to carry gravity loads, the bottom reinforcement ratio is calculated to ensure simultaneous yielding of the reinforcing steel in tension and crushing of the concrete at the extreme compression fibre. On the other hand, minimum reinforcement ratio is usually used for the top reinforcement. Thus, the bottom reinforcement ratio is usually significantly higher than the top reinforcement ratio. The control beam was designed to simulate the behaviour of RC beams in existing structures subjected to gravity loads. The test beams were, therefore, reinforced with three T20 mm diameter high yield steel bars in the bottom and two T16mm diameter bars in the top with 25mm concrete cover to the main bottom and top reinforcement. To ensure the control beam failed due to flexure and not shear, the specimens were adequately reinforced in the shear spans with 8mm mild steel links at 75mm centres against the shear forces produced when bending failure occurred.



a) Control Beam BR1



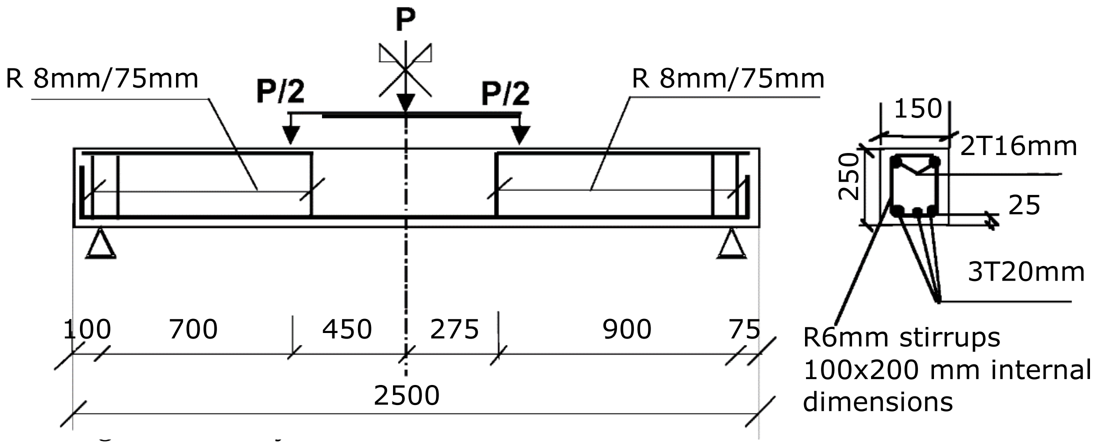
b) Beam BUL with Longitudinal and U-Wrap Strengthening

Fig. 1: The Main Test Beams with the Suggested Strengthening Techniques

Table 1 and fig. 2 summarise the dimensions and actual and predicted material properties of the control beam according to the BS8110 (1997). Minimum spacing and cover requirements were satisfied according to BS8110.

Table 1: General Geometric and Material Data

	Direction	Cover to main bars **c**	Diameter of main bars in tension	Effective depth **d**	Area main bars A_s	Concrete cube f_{cu}	Concrete tensile strength f_{ct}	Steel f_y	Concrete E_c	Steel E_s	Effective span **L**	Shear span **a**
		mm	mm	mm	mm^2	N/mm^2	N/mm^2	N/mm^2	kN/mm^2	kN/mm^2	m	m
Values according to BS8110	**-ve**	25	16	217	402	70.5	3.11	460	37.7	200	2.3	0.9
	+ve	25	20	215	942	70.5	3.11	460	37.7	200	2.3	0.9
Prediction using Actual values	**-ve**	25	16	217	402	70.5	4.37	522	38.0	193	2.3	0.9
	+ve	25	20	215	942	70.5	4.37	520	38.0	200	2.3	0.9



FE MODEL FOR THE TESTED BEAMS

SOLID65 element with eight nodes that capable of modelling concrete cracking in tension is used to model the concrete. For the tested beams, an effort was made to accurately obtain the actual elastic modulus, Poisson's ratio and stress-strain response under loading and unloading in uniaxial compression tests. Hence, the actual values and the experimental data for stress-strain response for each beam were used in the FE modelling. A simplified multilinear kinematic hardening relationship were used to model the concrete behaviour in compression. In monotonic tension, concrete is assumed to be an isotropic elastic material and the stress-strain curve for concrete is characterized by a linear stress–strain relationship up to the maximum tensile strength. After cracking, the concrete is assumed to be orthotropic with a bilinear softening stress-strain response and the strength of concrete decreases gradually. While concrete behaves as a brittle material in tension and low confined or nonconfined compression, its behaviour is rather ductile in compression with moderate or high confinement (Eshghi and Farrokhi, 2003). Hence, the behaviour of the concrete under U-confinement greatly depends on the multi-axial stress state. In the concrete model available in ANSYS software, the Drucker-Prager function is implemented to measure plasticity and multi axial effects of the stress. The multilinear kinematic hardening with the Bauschinger effect is adopted to model the behaviour of concrete under cyclic loading in this study as it represents the real behaviour of concrete and gives a very good agreement between the FE model and the experimental results, as shown in Fig 3. As the (Willam and Warnke (1975)) failure criterion has been adopted in this study, the smeared representation of cracking is used with element SOLID65 in ANSYS11.0.

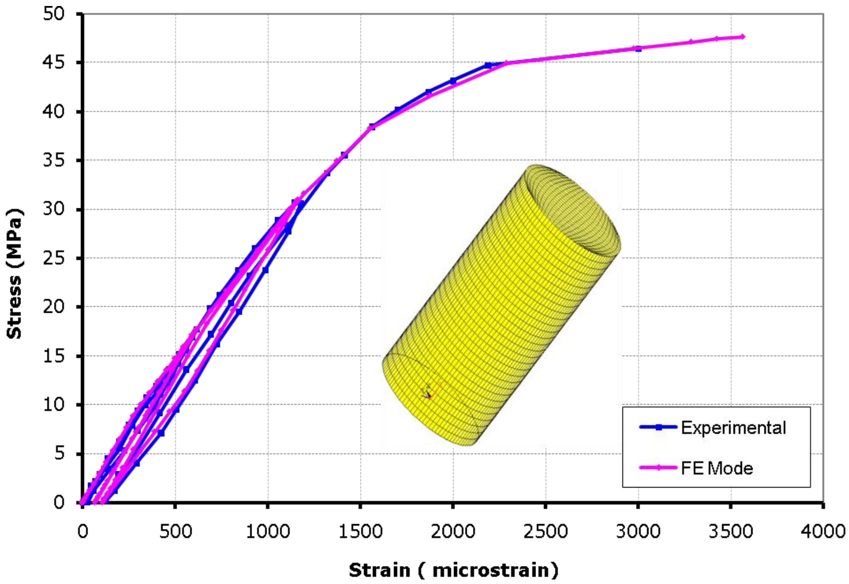


Fig. 3: Stress-Strain Behaviour for the Experimental Data and the FE Model of the Tested Concrete Cylinder

LINK180 element is used to model the reinforcing steel rebars and stirrups. The steel reinforcement rebar is assumed to be a multilinear kinematic hardening with identical tension and compression. The Bauschinger effect is included in the kinematic hardening option. The model parameters were obtained from experimental stress-strain curves for steel bars loaded monotonically in tension as shown in table 2. For this study, steel is modelled as a one-dimensional element and the dowel action is neglected.

The layered element 'SOLID46' defined by eight nodes was used to model the CFRP sheet and adhesive layers. This element is a layered version of the solid element, SOLID45, that allows up to 250 different material layers per element with different orientations and orthotropic material properties in each layer. The CFR is typically stiffer and stronger than the matrix. This makes the CFRP sheets orthotropic material. The local coordinate system for the SOLID46 layered elements is defined where the x direction is the same as the fibre direction. Hence, the properties of the CFRP sheets were assumed to be nearly the same in any direction perpendicular to the fibres direction. The material properties, layer orientation angle and layer thickness were specified in the element real constant table.

Table 2: Material Properties for the Reinforcing Steel

Reinforcement Ref			T20mm	T16mm	R8mm
Linear Isotropic	Elastic modulus *(GPa)*		200	193	200
	Poisson's ratio		0.27	0.27	0.27
Multilinear Kinematic Hardening	Point1	Stress (MPa)	520	522	250
		Strain	0.00260	0.00270	0.00125
	Point2	Stress (MPa)	520	522	260
		Strain	0.004	0.01	3.25E-03
	Point3	Stress (MPa)	630	617	-
		Strain	0.20	0.15	-
	Point4	Stress (MPa)	-	600	-
		Strain	-	0.2	-

Uniaxial tensile tests were carried out on 0.117 mm thick CFRP samples to determine their failure stress, strain, and modulus of elasticity. The samples behaved linearly until rupture occurred. The average data of the tensile strength and Young's modulus were 913.0MPa and 58.0GPa, respectively. The analytical model, which is applied according to several assumptions gives the following values 845.0MPa and 54.5GPa for the tensile strength and Young's modulus, respectively. Tsai–Wu failure criterion has been extensively used in the CFRP literature and is adopted in this research for the CFRP sheets. As orthotropic material, the strength values must be defined for all directions. However, since the CFRP sheets are subjected to uniaxial stresses in the longitudinal direction only, the transverse parameters should not have a significant effect on the behaviour of the strengthened beams.

The two-node nonlinear spring element, COMBIN39, have been used to model the bond-slip between the steel reinforcement and concrete. This element is a one-dimensional element with nonlinear force-deflection capability. It has very small dimension that can be used to connect the nodes of 'LINK180' elements and 'SOLID65' elements in this study.

Also, COMBIN39 was used for the bond slip between FRP, adhesive and concrete interfaces. FRPs are assumed to be linear and elastic until the tension stress reaches its ultimate strength which causes brittle rupture and then reduces to zero. For concrete in compression, Thorenfeldt's model is employed, and for concrete in tension, the stress-strain curve is assumed to be isotropic and linearly elastic

In this paper, the predicted behaviour of the FE model for the RC beam was validated under monotonic loading and has been shown to lie within the range of the values reported in the literature for similar geometry (He *et al.* 1997 and Yang *et al.* 2003). Moreover, the proposed FE models for the strengthened beams under cyclic loading were validated. With the purpose of validating the cyclic performance of the FE model for the non-strengthened and the CFRP strengthened beams, further validation and comparisons with the experimental data obtained from previous experimental studies were carried out. It was found that the smeared crack approach, which is not capable for predicting local fracture, cannot predict local debonding and peeling off failure or any kind of failure associated with local fracture. However, the proposed FE model can still capture the main behavioural characteristics, in general, of the RC beams strengthened with different techniques. Thus this model can be used in the following parametric study to predict the effect of different parameters. The parametric study was conducted for several bonded lengths to study their influence in the strength and ductility. Also, according to many previous studies, the number of layers affects the strength and stiffness of the strengthened beams under monotonic loading conditions (He *et al.* 1997). This can affect the ductility and the dissipated energy under cyclic loading conditions. Therefore the number of layers is considered as a second parameter.

Owing to the gap found in the literature and the lack of studies available to describe both strength and ductility of CFRP strengthened beams under cyclic loading, the main purpose of this research is to focus on the performance of these beams under cyclic loading conditions and to develop a FE model for evaluating this performance. To achieve its objectives, this study adapts a comprehensive analysis within ANSYS to develop a reliable and efficient FE model. The cyclic response of the studied beams is described using recorded mid-span deflection, load-strain plots, crack patterns and distribution and modes of failure. The ductility of each beam was considered by calculating the displacement ductility factor and the dissipated energy under cyclic loading conditions.

RESULTS AND DISSCUSSION

In order to provide a baseline to make a comparison and to show how the bonded length of the CFRP sheet affects the cyclic response of the CFRP strengthened beams, different bonded lengths were considered. As the parametric study was performed only to show the difference in the global load-deflection history of a RC beams strengthened with CFRP sheets, this study was conducted for the U-wrap technique in the bottom only with longitudinal strengthening in the top (BU700, BU1300 and BU1900). To distinguish between different beams, the second character U for these beams stands for longitudinally strengthened on the top and U-wrap on the bottom. The subsequent number represents the total bonded length of the CFRP sheet in mm.

1. Global Load-Deflection Envelops

From figure 4, it can be observed that the stiffness of the beams BU1300 and BU1900 are almost the same in both directions. By comparing the behaviour of the beam BU700 with the behaviour of beams BU1300 and BU1900 it can be observed that the stiffness of beam BU700 in the negative direction is lower than the stiffness of the other two beams.

On the other hand, the small drop in the load before failure of beam BU1900 may indicate a high deformation in one of the interface elements. The stiffness after this drop is similar to the stiffness of beam BU1300. While the ultimate deflection for beam BU1900 is less than the ultimate deflection of beam BU1300 in the positive direction by about 5.2%, the ultimate deflection for BU1900 is 20% higher than that for beam BU1300 in the negative direction. This is reasonable as the longitudinal top CFRP sheet carry tensile stress when loading in the negative direction, while the U-wrapped sheets at the bottom provide a confinement for concrete under compression and increase the strength and ductility of the confined concrete.

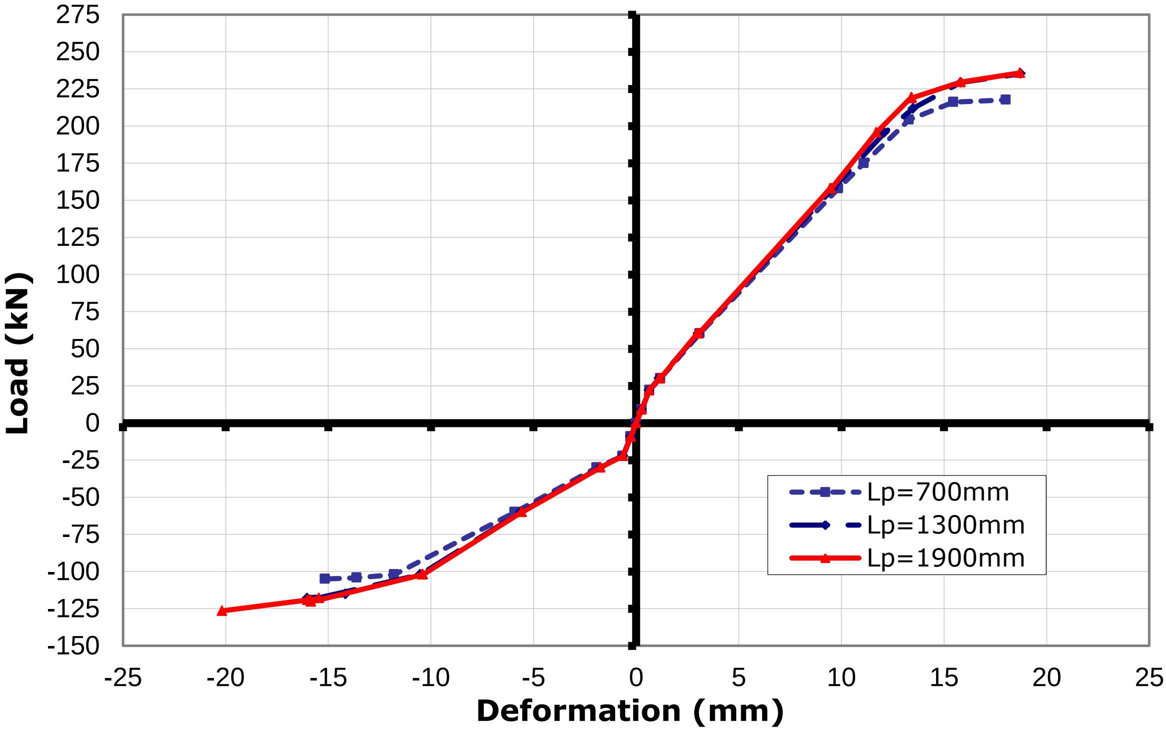


Fig. 4: Load - Deflection Envelops for the U-Wrapped Beams

2. Global Load-Deflection History

The hysteretic curves for beams BU with shorter strengthened regions are within a narrower band than those with a longer strengthened region. A longer strengthened length of RC beams with U-wrap in the bottom considerably increases the number of cycles and the ultimate deformation and leads to more stable hysteresis loops than for the shorter strengthened length; as can be seen in Figures 5, 6 and 7.

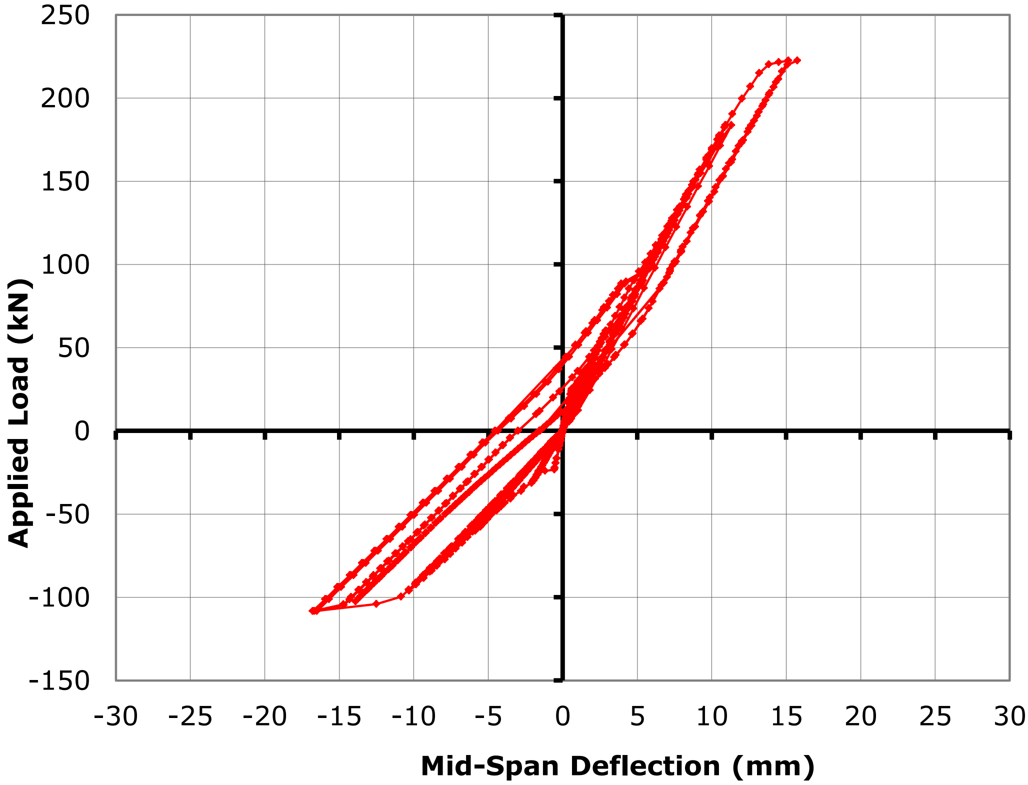


Figure 5: Predicted Load Deflection Hysteresis for Beam BU700

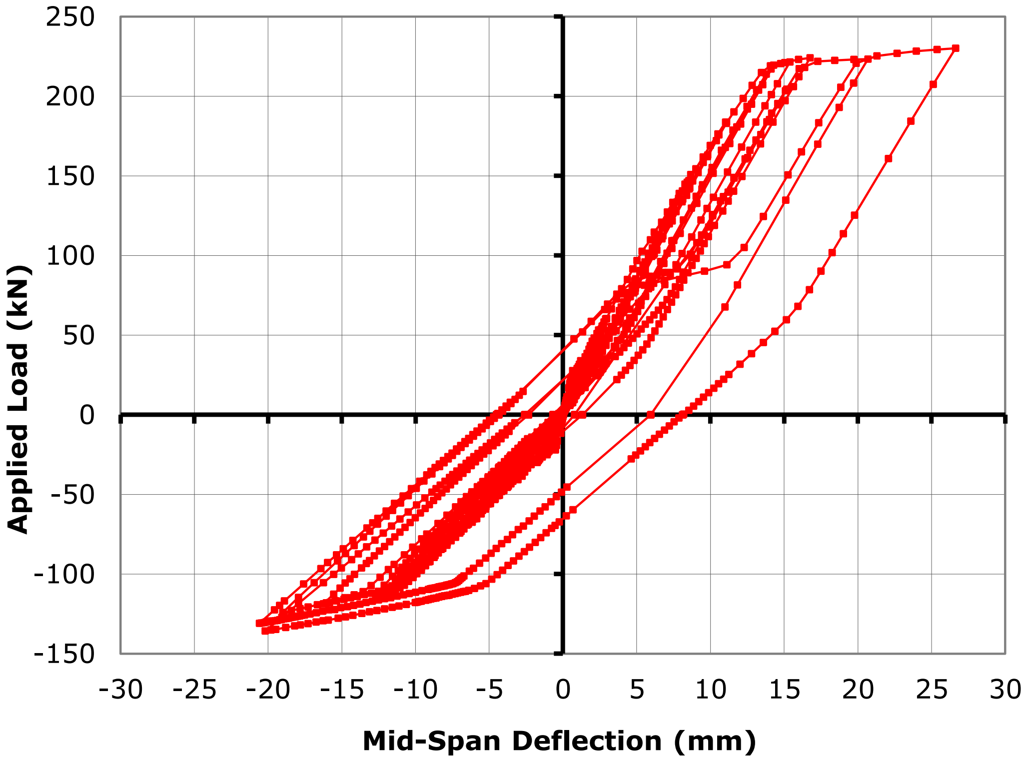


Figure 6: Predicted Load-Deflection Hysteresis for Beam BU1300

Figure 7: Predicted Load-Deflection Hysteresis for Beam BU1900

3. Ultimate Loads

Figure 8 illustrates the relationship between the length of the strengthened zone and the increase in ultimate load relative to the nonstrengthened beam for the beams strengthened with U-wrap in the bottom and longitudinally at the top. This relationship indicates that the K_u* ratio increases with the increase in bonded length in both directions until a certain effective length is reached, beyond which no increase in the ultimate load capacity could be obtained.

While a difference of 4% and 25% are noted when changing the bonded length from 700 to 1300 mm in the positive and negative directions, respectively, a very slight increase in the K_u ratio occurs beyond 1300mm. it can be noticed that the increase achieved in the negative direction is much higher than the increase in the positive direction. This is due to the fact that the CFRP sheets are bonded longitudinally to the top side of the beam while U-wrap in the bottom of the beam makes the direction of the fibres perpendicular to the length of the beam and the direct contribution of the fibre to the stiffness and the load carrying capacity is negligible.

To check the change between 700 and 1300mm, an intermediate bonded length of 1000mm was used. It was found that the increase in K_u when increasing the length from 700 to 1300mm was linear.

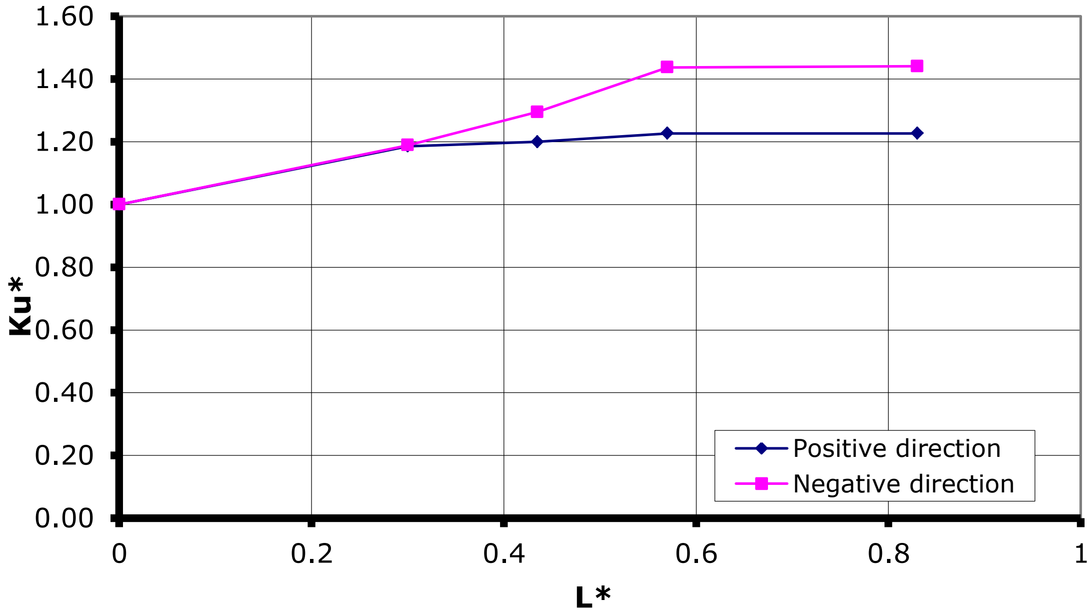


Figure 8:Ultimate Load Increase for Beams BU with Different Strengthened Lengths

4. Dissipated Energy and Ductility

Figure 9 gives a general idea about the development of the dissipated energy at different stages versus cumulative deflection. The increase in the final dissipated energy in respect to the nonstrengthened beam is shown in figure 10.

It is important to mention here that as the longitudinally bonded CFRP sheets could resist crack formation, the use of the u-wrap strengthening technique could control and restrict crack propagation during loading process. Therefore, increasing the length of strengthened regions might reduce the dissipated energy at some stages of loading when they stop cracking in ductile areas.

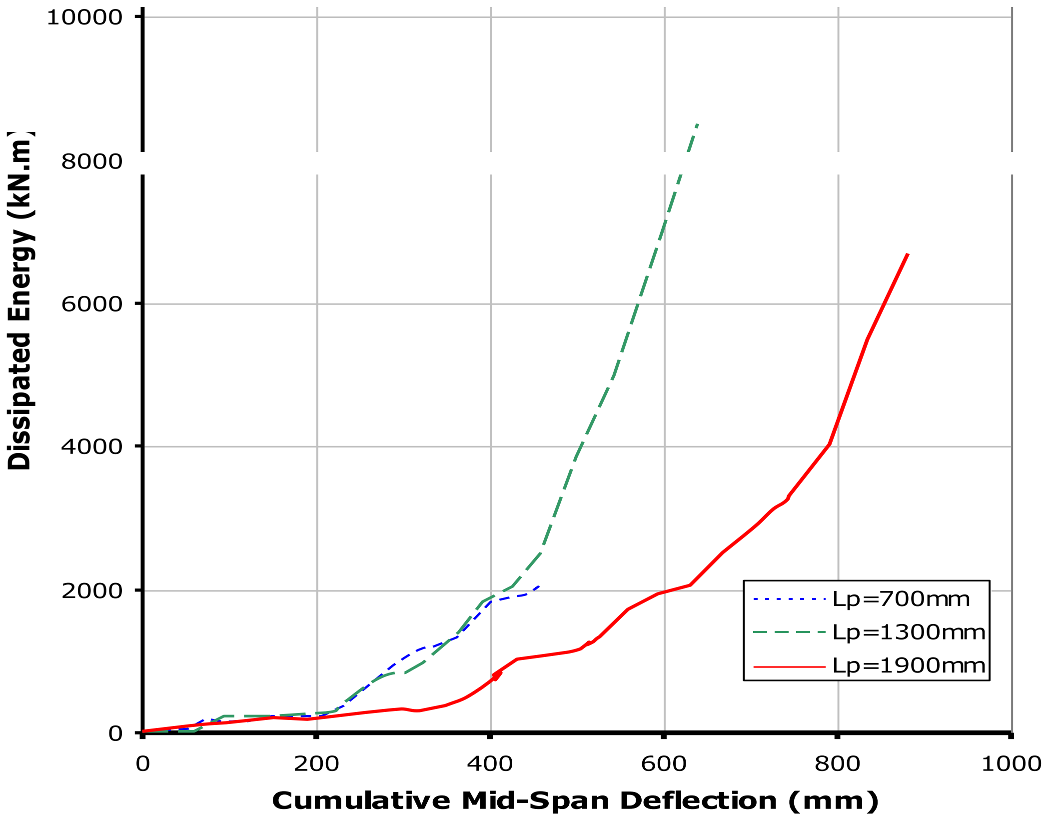


Figure 9: Cumulative Deflection versus Dissipated Energy Plots

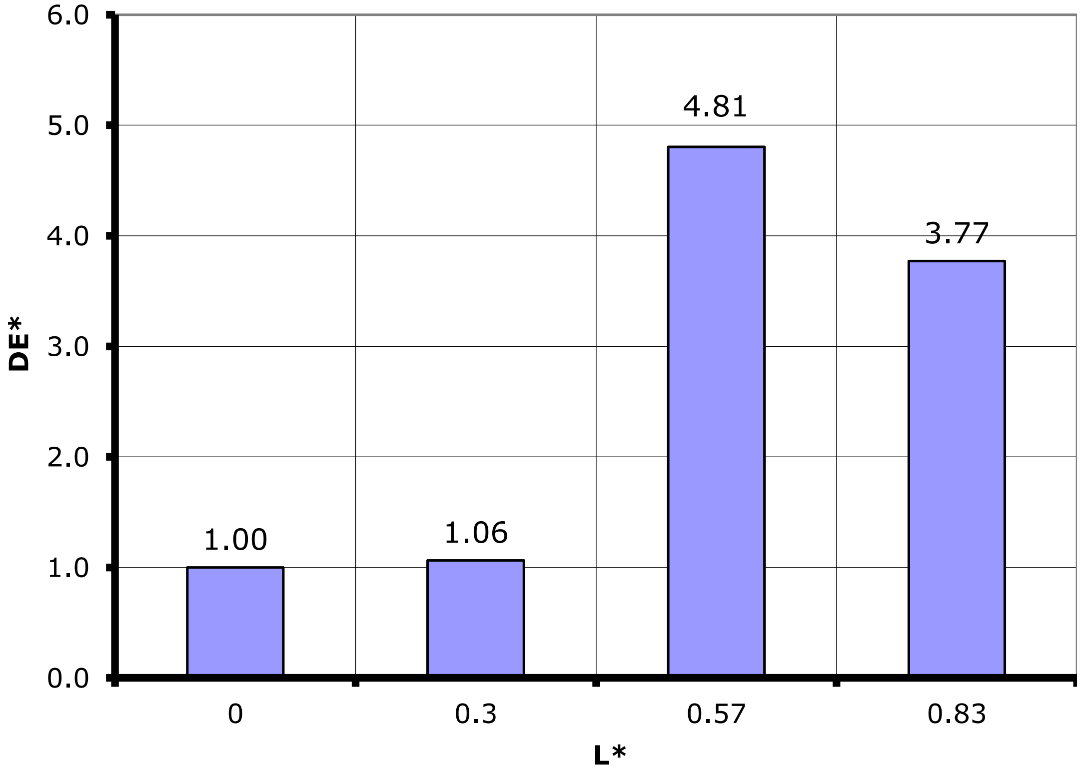


Figure 10: Final Dissipated Energy at the Ultimate Load for the BU Strengthened Beams

It can be noted that the length of the strengthened region significantly influence the dissipated energy capacity of BU beams. The final dissipated energy of beam BU1300 is higher than that of beam BU700 by 255% . However, although the final cumulative deflection for beam BU1900 is considerably higher than that for beam BU1300, the final dissipated energy of beam BU1300 is higher than that of beam BU1900 by 27%. This is due to the fact that increasing the length of the U-wrapped region of the beam resists crack propagations for some cracks in the shear span, which is ductile by design for this beam. Since the stiffness of the uncracked elements, in smeared crack approach, is significantly higher than that for the cracked elements, this can affect the final stiffness of beam BL1900 and reduce the dissipated energy compared to beam BU1300.

Figure 11 shows that the increase of the displacement ductility factor in the negative direction is almost linear. However, the increase in ductility here is considerably larger than that when longitudinal sheets bonded to the top and bottom sides of the strengthened beams given in previous studies (Suleiman et al 2008). This is because of the confinement provided by the U-wrapped sheets to concrete in compression. On the other hand, while a significant increase in the DDF can be observed in the positive direction when the length of the strengthened region was increased from 700mm to 1300mm, a slight improvement in DDF was achieved by increasing the length of the strengthened region from 1300mm to 1900mm. This can be argued in the same way that the results of the dissipated energy, which are shown in Figure 10, are discussed.

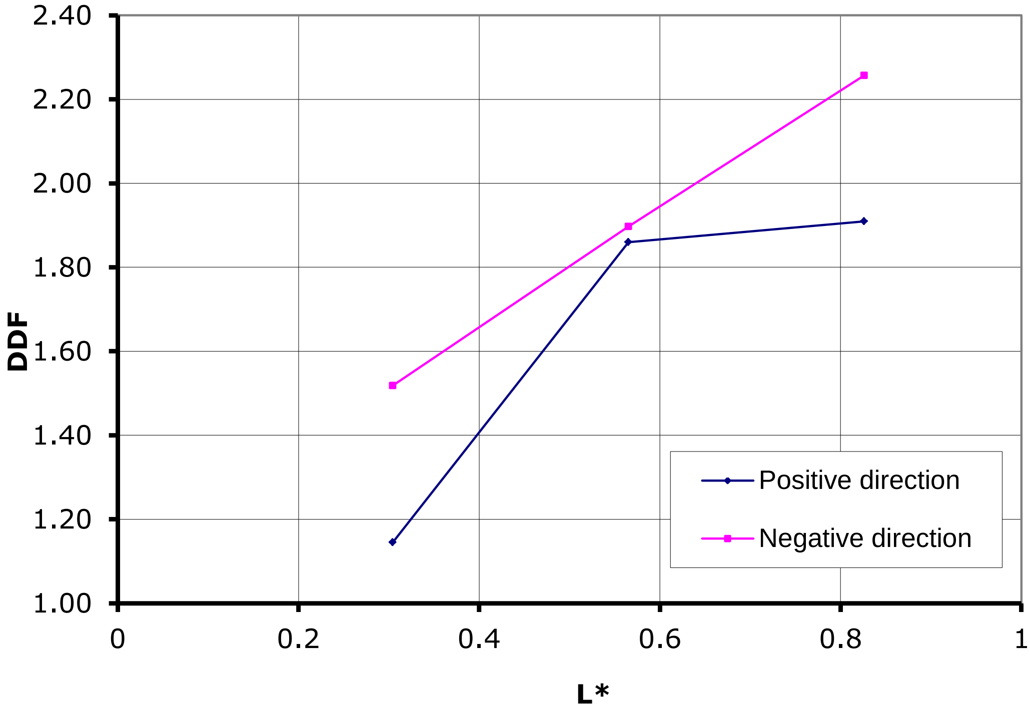


Figure 11: Displacement Ductility Factors for the BU Beams with Different Length of the Strengthened Regions

CONCLUSIONS

It can be concluded that the ultimate load capacity of the CFRP strengthened beams increases with the bonded length until an effective length, Le, beyond which no increase in the ultimate load is obtained with the increase in CFRP sheet length. This agrees well with the findings of Thomsen et al. (2004), who found that the effective bonded length, Le, equals to 0.93L and 0.89L, respectively. In this study, however, the value of the effective length is found to be dependent on some factors such as the reinforcement ratio and the strengthening configurations and could be less than the previous two values and equals to 0.6L for the studied cases. Furthermore, it can be noticed that the increase achieved in the negative direction, where the area of reinforcement in tension is low, is much higher than the increase in the positive direction, where heavy tensile reinforcement were used. This confirms that the lower the ratio of reinforcement in tension, the more effective the CFRP is. A longer strengthened length of RC beams with the suggested technique increases the number of cycles and the ultimate deformation and leads to more stable hysteresis loops than for the shorter strengthened length.

Since the use of the U-wrap strengthening technique could control crack propagation during loading process, increasing the length of strengthened regions beyond certain values might reduce the dissipated energy at some stages of loading. Moreover, the length of the strengthened region significantly influence the dissipated energy capacity up to specific length. This is because increasing the length of the U-wrapped region of the beam resists crack propagations in the shear span, which is ductile by design.

The increase of the displacement ductility factor in the negative direction is almost linear. However, the increase in ductility here is considerably larger than that when longitudinal sheets bonded to the top and bottom sides of the strengthened beams given in previous studies (Suleiman et al. 2008). This is because of the confinement provided by the U-wrapped sheets to concrete in compression. While a significant increase in the DDF can be observed in the positive direction when the length of the strengthened region was increased from 700mm to 1300mm, a slight improvement in DDF was achieved by increasing the length of the strengthened region from 1300mm to 1900mm.

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