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Energy absorption of reinforced concrete deep beams strengthened with CFRP sheet

Mohammad Panjehpour *, Abang Abdullah Abang Ali [a] and Farah Nora Aznieta [b]

Housing Research Centre, Faculty of Engineering, Universiti Putra Malaysia,
43400, Serdang, Selangor, Malaysia

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Abstract. The function of carbon fibre reinforced polymer (CFRP) reinforcement in increasing the ductility of reinforced concrete (RC) deep beam is important in such shear-sensitive RC member. This paper aims to investigate the effect of CFRP-strengthening on the energy absorption of RC deep beams. Six ordinary RC deep beams and six CFRP-strengthened RC deep beams with shear span to the effective depth ratio of 0.75, 1.00, 1.25, 1.50, 1.75, and 2.00 were tested till failure in this research. An empirical relationship was established to obtain the energy absorption of CFRP-strengthened RC deep beams. The shear span to the effective depth ratio and growth of energy absorption of CFRP-strengthened deep beam were the significant factors to establish this relationship.

Keywords: energy absorption; deep beam; CFRP; strengthening

1. Introduction

According to ACI 318-11, deep beam has a clear span equal to or less than four times the overall depth. The regions with concentrated loads within twice the member depth from the face of support are also taken as a deep beam into account (ACI 2011). Deep beam is commonly used in tall buildings, offshore structures and foundations (Vecchio and Collins 1986, Kong 1990). It largely occurs as transfer girder with single span or continuous (Zhang and Tan 2007, Wight and Macgregor 2009).

Among experimental works conducted on fibre reinforced polymer (Altin *et al*. 2011, Egilmez and Yormaz 2011, Panda *et al*. 2012) strengthening of concrete structures with carbon fibre reinforced polymer (CFRP) has become a topic of interest among researchers, for CFRP advantages of being lightweight and corrosion resistant (Lu *et al*. 2005, Sayed-Ahmed *et al*. 2009, Issa *et al*. 2011, Barros *et al*. 2012, Cree *et al*. 2012, Godat *et al*. 2012, Jain and Lee 2012). In addition to the advantages, its ease of installation and high tensile strength make CFRP a useful tool for strengthening of concrete structures particularly beams (Belakhdar *et al*. 2011, Krour *et al*. 2013, Guenaneche *et al*. 2014). Furthermore, CFRP has a wide application in repair of concrete

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*Corresponding author, Ph.D., E-mail: mdpanjehpour2006@yahoo.com
[a] Professor, aaaa@eng.upm.edu.my
[b] Ph.D., E-mail: farah@eng.upm.edu.my

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structures (Al-Saidy and Al-Jabri 2011, Panjehpour *et al*. 2011, He *et al*. 2013).

The ductility of concrete elements can be defined as its capability to sustain inelastic deformation without loss in load carrying before failure (Barrera *et al*. 2012). Moreover, the deflection is known as the primary measurement of ductility. In essence, the ductility and energy absorption of concrete member are referred to the conversion of mechanical energy into the internal potential energy in concrete member (Issa *et al*. 2011, Anastasiadis *et al*. 2012, Barrera *et al*. 2012). The energy absorption of concrete member comprises various complex processes including fracture mechanics of crack initiation and propagation, elastic and plastic deformation as well as notch sensitivity (Wang and Belarbi 2011, You *et al*. 2011, Oudah and El-Hacha 2012). The energy absorption capacity is defined as the integral of the load-deflection curve. Numerous studies have shown a consistent positive correlation between energy absorption and ductility (Issa *et al*. 2011, Barrera *et al*. 2012).

Apart from research conducted on the ductility of beams using CFRP, there has been no research done on the ductility of CFRP-strengthened RC deep beams with different shear span to effective depth ratio (Maghsoudi and Bengar 2011, Wang and Belarbi 2011, Oudah and El-Hacha 2012). Thus, the goal of this research is to investigate the effect of CFRP-strengthening on the energy absorption of RC deep beams with different shear span to effective depth ratios. This research is confined to the ordinary concrete RC deep beams strengthened using one layer of CFRP sheet with two-side wet lay-up system.

2. Methodology

Two sets of RC deep beams were cast and tested in this research project. Each set consisted of six simply-supported specimens loaded in 4-point bending. The first set had no CFRP-strengthening, while the second was strengthened by means of CFRP sheets. Each set consists of six RC deep beams with shear span to the effective depth ratio of 0.75, 1.00, 1.25, 1.50, 1.75, and 2.00. For small shear span-depth values the web behaviour is controlled by concrete tensile strength, and for large values the yielding of the reinforcement comes into play since the tests are conducted on different shear span-effective depth ratio ranging in 0.75-2.00.

The area under load-deflection curve is calculated using Simpson’s rule for all deep beams. The initial little part of load-deflection curve likely represents the initial settlements of the beams within the testing rig. However, the effect of this part of curve on the accuracy of calculation for the value of the area under load-deflection curves is not the major concern in this research.

2.1 Details of deep beams

All deep beams were identical in every aspect excluding the position of steel cages. Each beam was 1840 mm long with a rectangular cross-section as indicated in Fig. 1. The flexural reinforcement consisted of 9T16 deformed steel bars in three layers with yield strength of 440 MPa. These steel bars were welded to 10 mm thick steel plates at both ends of the beams to provide the adequate anchorage capacity. The anchorage steel plates with the height of 120 mm fully covered the width of the beams. The orthogonal transverse reinforcement comprised T6 steel bars with 100 mm spacing. It provides the minimum amount of web reinforcement requirements recommended by ACI 318-11 and AASHTO LRFD. Additional steel bars were provided under the load plates and atop the support plates to prevent bearing stress as illustrated in Fig. 2. However,

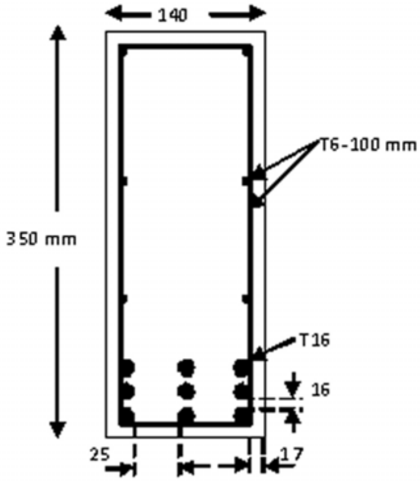

Fig. 1 Beam cross-section details

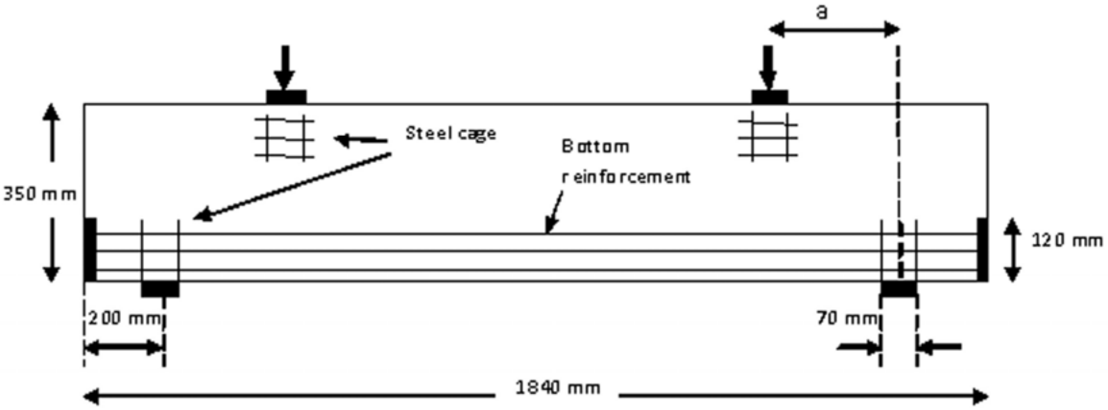

Fig. 2 Typical reinforcement details

the transverse reinforcements are not shown in Fig. 2 to avoid disordering of the figure. The beams were cast using single supply of ready-mix concrete. The cylindrical compressive strength and cylinder splitting tensile strength of concrete were 37.02 MPa and 3.31 MPa respectively.

2.2 Material and method

One layer of unidirectional woven carbon fibre fabric having thickness of 0.111 mm/ply with two-part epoxy impregnation resin were utilised to strengthen the RC deep beams with wet lay-up system. The typical properties of the CFRP sheet and epoxy resin provided by the manufacturer are given in Table 1. Both CFRP sheet and epoxy resin were provided from Sika Company with product data sheet of Sikadur-330 and SikaWrap-230. The strengthening with CFRP sheet was carried out on the surface of beams between load plate and support plate to merely cover the shear span of deep beams. The curing time for CFRP-strengthening was at least two days following the manufacturer recommendation regarding ambient temperature. The strengthening process using CFRP sheet was conducted on the third week after the beams casting. The support and load plates fully covered the beneath and above the beam with 70 mm in width and 10 mm in thickness. The deep beams were tested 28 days after casting.

2.3 Test procedure and instrument

The beams were tested with simple supports till failure under four-point bending configuration. The rate of loading was constant up to failure using hydraulic actuator with a maximum capacity of 5000 kN. The mid-span deflection of beams was measured using two digital LVDTs at both sides of beams to obtain the average accurate results. Figs. 3 and 4 indicate the test set up for the two status of ordinary concrete RC deep beam and CFRP-strengthened RC deep beam.

Fig. 3 Test set up for ordinary RC deep beam

Fig. 4 Test set up for CFRP-strengthened RC deep beam

Table 1 Typical properties of CFRP sheet and epoxy

Materials	Tensile strength (MPa)	Tensile modulus of elasticity (GPa)	Elongation at break	Bond strength (MPa)	Thickness (mm/ply)
CFRP sheet	3900	230	1.5% (7days at +23°C)	–	0.111
Epoxy resin	30	4.5	0.9% (7days at +23°C)	> 4	–

Table 2 Ultimate shear strength of RC deep beams from the test

a/d	$P_{u\text{-control}}$ (kN)	$P_{u\text{-FRP}}$ (kN)	Δ_{ordinary} (mm)	$\Delta_{\text{CFRP-strengthening}}$ (mm)
0.75	756.95	905.31	3.29	3.99
1.00	709.01	857.89	3.40	4.13
1.25	604.08	740.02	3.54	4.53
1.50	555.91	691.04	3.59	4.66
1.75	403.02	510.01	3.64	5.00
2.00	360.02	468.05	3.74	5.17

3. The Load-deflection curve of deep beams

According to the experimental observation, the tendency of having brittle failure increases among the ordinary RC deep beams as the shear span to the effective depth ratio decreases. Nonetheless, the foregoing tendency was perceptibly observed for CFRP-strengthened RC deep beam lower than those of ordinary RC deep beams. The ultimate shear strength of ordinary RC deep beams and CFRP-strengthened RC deep beams with the corresponding mid-span deflection are shown in Table 2.

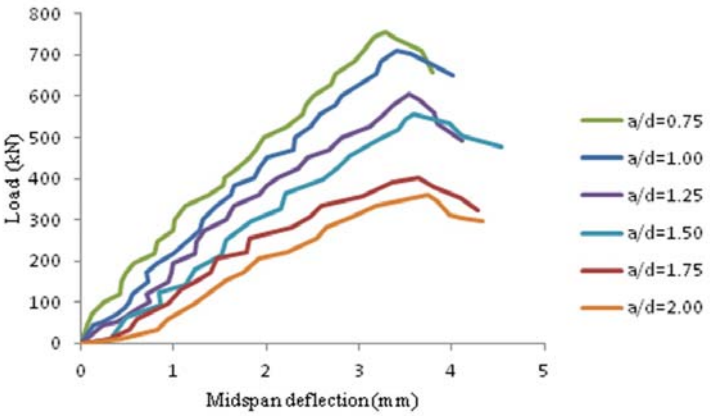

Fig. 5 Load-deflection curves of ordinary RC deep beams

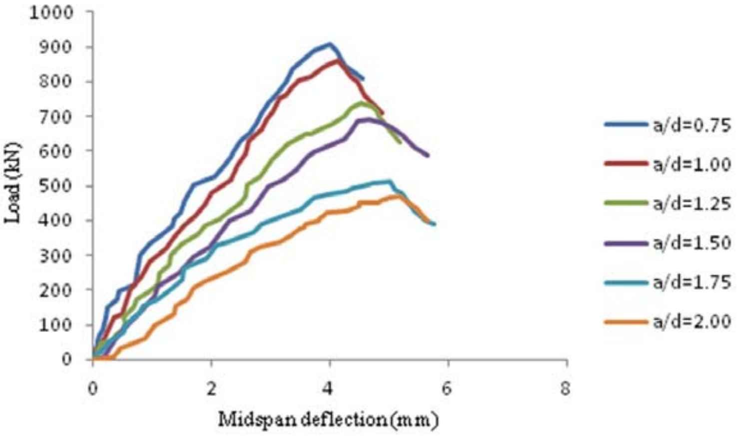

Fig. 6 Load-deflection curves of CFRP-strengthened RC deep beams

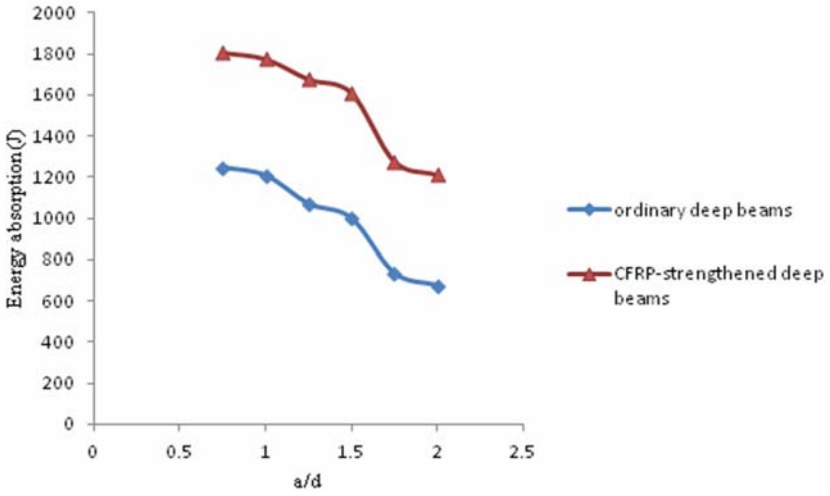

Fig. 7 Energy absorption capacity of ordinary and CFRP-strengthened RC deep beams

The load-deflection curves of ordinary and CFRP-strengthened RC deep beams are illustrated in Figs. 5 and 6 respectively. According to these figures, the mid-span deflection of ordinary and CFRP-strengthened RC deep beams corresponding to the ultimate load slightly increases with the increase of the shear span to effective depth ratio.

4. The effect of CFRP-strengthening on the ductility of RC deep beams

According to Fig. 7, the energy absorption of both ordinary and CFRP-strengthened RC deep beams decreases as the shear span to effective depth ratio increases. However, the growth of energy absorption of RC deep beams from CFRP-strengthening with high shear span to effective

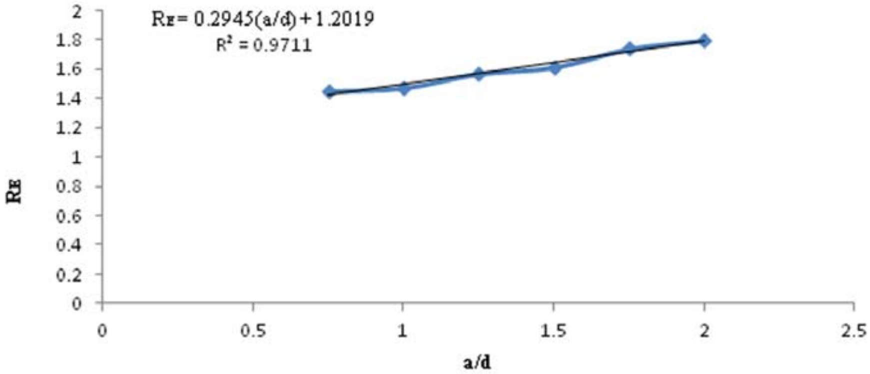

Fig. 8 Empirical relationship to predict the energy absorption of CFRP-strengthened RC deep beams

depth ratio is greater than those of low shear span to effective depth ratio. This trend can be discernibly observed in Fig. 8. Hence, an empirical relationship is established between the growth of energy absorption capacity and the shear span to effective depth ratio to evaluate the effect of CFRP-strengthening on the energy absorption of RC deep beams as shown in Fig. 8. Based on Fig. 8, the growth of energy absorption of RC deep beams from CFRP-strengthening varies from approximately 45% to 80% for shear span to effective depth ratio from 0.75 to 2.00 respectively.

5. Conclusions

This paper addresses the issue of energy absorption of ordinary and CFRP-strengthened RC deep beams. It investigates the effect of CFRP-strengthening on the energy absorption of deep beam with shear span to effective depth ratios ranging in 0.75-2.00. According to this research, the following conclusions can be drawn:

- The energy absorption of both ordinary and CFRP-strengthened RC deep beams decreases as the shear span to effective depth ratio increases.
- The CFRP-strengthened deep beams exhibit an energy absorption capacity which is from 45% to 80% higher than those of ordinary RC deep beams. The trend of growth of energy absorption with shear span to effective depth ratio is approximately a linear relationship.
- CFRP sheet proportionally contributes more in high shear span to effective depth ratio compared to those of the lower ratios.
- As the shear span to effective depth ratio of both ordinary RC deep beams and CFRP-strengthened RC deep beams increases, the mid-span deflection increases and ultimate shear strength decreases. However, the rate of growth of mid-span deflection of CFRP-strengthened RC deep beams is higher than those of the ordinary RC deep beams.

This research is confined to the ordinary RC deep beams strengthened with one layer of CFRP sheet with two-side wet lay-up system. Various exploitations may merit further numerical research for modeling of energy absorption of CFRP-strengthened deep beams as well as investigation of unloading branches in load-deflection curves to assess structural energy absorption.

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Symbols

a	:	shear span of deep beams (mm)
d	:	effective depth of deep beam (mm)
$P_{u\text{-control}}$	:	ultimate shear strength of ordinary deep beam from experiment (kN)
$P_{u\text{-CFRP}}$	:	ultimate shear strength of CFRP-strengthened deep beam from experiment (kN)
Δ_{ordinary}	:	mid-span deflection of ordinary RC deep beam corresponding to the ultimate shear strength (mm)
$\Delta_{\text{CFRP-strengthening}}$	:	mid-span deflection of CFRP-strengthened RC deep beam corresponding to the ultimate shear strength (mm)
R_E	:	ratio of energy absorption of CFRP-strengthened RC deep beam to that ordinary