Structural Engineering and Mechanics, *Vol. 56, No. 6 (2015) 899-916*
DOI: http://dx.doi.org/10.12989/sem.2015.56.6.899

Eliminating concrete cover separation of NSM strengthened beams by CFRP end anchorage

Md. Akter Hosen, Mohd Zamin Jumaat*, A. B. M. Saiful Islam, Mohamed Kamruzzaman, Md. Nazmul Huda and Mahmudur Rahman Soeb

Department of Civil Engineering, Faculty of Engineering, University of Malaya, 50603, Kuala Lumpur, Malaysia

(Received December 6, 2014, Revised October 3, 2015, Accepted November 3, 2015)

Abstract. Upgrading or strengthening of existing reinforced concrete (RC) infrastructure is an emerging demand nowadays. Near Surface Mounted (NSM) technique is very promising approach for flexural strengthening of RC members. However, premature failure such as concrete cover separation failure have been a main concern in utilizing this technique. In this study, U-wrap end anchorage with carbon fiber reinforced polymer (CFRP) fabrics is proposed to eliminate the concrete cover separation failure. Experimental programs were conducted to the consequence of U-wrap end anchorage on the flexurally strengthened RC beams with NSM- steel. A total of eight RC rectangular beam specimens were tested. One specimen was kept unstrengthened as a reference; three specimens were strengthened with NSM-steel bars and the remaining four specimens were strengthened with NSM-steel bars and U-wrap end anchorage using CFRP fabrics. A 3D non-linear finite element model (FEM) was developed to simulate the flexural response of the tested specimens. It is revealed that NSM-steel (with and without end-anchors) significantly improved the flexural strength; moreover decreased deflection and strains compared with reference specimen. Furthermore, NSM-steel with end anchorage strengthened specimens revealed the greater flexural strength and improve failure modes (premature to flexure) compared with the NSM-steel without end anchorage specimens. The results also ensured that the U-wrap end anchorage completely eliminate the concrete cover separation failure.

Keywords: polymer composites; flexural strengthening; finite element modeling; NSM-steel; debonding; end anchorage; CFRP fabrics

1. Introduction

During the recent eras, strengthening of RC structures has become an important solution to enhance the structural behaviour and their load capacity. Various approaches are offered for strengthening and retrofitting of RC members (Aykac *et al.* 2012, Boukhezar *et al.* 2013, Islam *et al.* 2013, Mini *et al.* 2014). Externally bonded reinforcement (EBR) (Demir *et al.* 2014, Mini *et al.* 2014, Ritchie *et al.* 1991, Saadatmanesh and Ehsani 1991) and near surface mounted (NSM) techniques are attractive for strengthening of RC structures (Laura De Lorenzis *et al.* 2002, De

∗Corresponding author, Ph.D., E-mail: zamin@um.edu.my

http://www.techno-press.org/?journal=sem&subpage=8 ISSN: 1225-4568 (Print), 1598-6217 (Online)

Sena CruzandOliveira de Barros 2004, Novidis *et al.* 2007). The NSM technique demonstrations more attention over the EBR technique in the flexural strengthening of RC members (BadawiandSoudki 2009, Capozucca and Bossoletti 2014). The NSM technique is good for severe environmental conditions; enhances bond performance and offers superior aesthetics over EBR (El-Hacha and Gaafar 2011). However, the NSM method has some limitations. The width of the beam to be strengthened may not be wide enough to provide necessary edge clearance and clear spacing between adjacent NSM grooves (De Lorenzis and Teng 2007).

Numerous experimental studies have examined the bond characteristics of NSM bars or strips in concrete using direct pull out tests (Bilotta *et al.* 2011, Sharaky *et al.* 2013) or beam pull out tests (Cruz and Barros 2004). (El-Hacha and Rizkalla 2004) studied the flexural behaviour of RC beam specimens strengthened with NSM technique utilizing FRP. The variables examined were the number of FRP bars or strips; the form of FRP, either strips or bars; and the type of FRP, either glass or carbon. The results were explained as debonding probably occurring earlier between the CFRP bar and the epoxy interface. (Kishi *et al.* 2005) performed experimental studies of RC beams flexurally strengthened with NSM and externally bonded technique using AFRP bars and sheets, respectively. The tests were conducted using the four-point bending condition. The experimental results indicated that the load capacity increased as the bond length increased and that two types of failure mode occurred in both (EBR and NSM) techniques. One was debonding in the concrete epoxy interface and the other was debonding in the CFRP rod epoxy interface.

Jung *et al*. (2005) investigated the flexural behaviour of NSM CFRP bars and externally bonded reinforcement strengthened RC beams. A total of eight specimens (one control, two strengthened with externally bonded reinforcement, three with NSM CFRP bars and two with NSM and mechanical interlocking grooves) were tested with a shear span by depth ratio of 3.89. The NSM CFRP bars and EB reinforcement strengthened specimens failed by debonding. Al-Mahmoud et al. (Al-Mahmoud *et al.* 2010) assessed the flexural performance of cantilever RC beams that were flexurally strengthened using NSM CFRP bars. The specimens were tested four-point bending condition and the results were compared to the reference specimens. They found that the peeling off failure occurred when some cracks reached to the end.

Soliman *et al*. (2010) studied the responses of reinforced concrete beams flexurally strengthened using NSM FRP bars. Different variables were tension steel reinforcement ratio; type, diameter and bonded length of FRP bar; and groove size were examined in this research. The test results indicated that the application of NSM FRP bars was useful for enhancing the flexural strength of the RC beams. However, all the strengthened beams failed by concrete cover splitting. Sharaky et al. (Sharaky *et al.* 2014) investigated the flexural behaviour of NSM strengthened RC beam specimens using FRP (CFRP and GFRP). A total of eight RC rectangular beams (160 mm×280 mm×2600 mm) were tested, to ensure a shear span/depth ratio of 3.40. The test variables were NSM bar diameter (8 mm and 12 mm), number of NSM bars (1 or 2), FRP bar type (CFRP and GFRP) and epoxy type (Mbrace and Polyfixer EP). Most of the strengthened specimens' failure modes were concrete cover separation.

In this study, extensive experimental and numerical investigation have been carried out to introduce U-wrap end anchorage using CFRP fabrics for eliminating the concrete cover separation of flexurally strengthened RC beams. The cracking, ultimate and failure loads along with midspan deflection and strain data were analysed to comprehend the inclusive behaviours of RC beam elements. The FEM model has been developed to predict the flexural response of the tested specimens with good accuracy.

Table 1 Test matrix

Beams notation	Strengthening materials		End anchorage with CFRP fabrics
	Diameter (mm)	Number of bars	
CB		Unstrengthened	
NS8	8		
NS10	10		-
NS12	12		
NS8U3	8	2	3 layers
NS10U3	10		3 layers
NS12U3	12		3 layers
NS12U4	12		4 layers

Table 2 Properties of Sikadur® 30 and 330

Properties	Sikadur® - 30	Sikadur® - 330
	Strength (MPa)	
Compressive strength	95	-
Tensile strength	31	30
Shear strength	19	-
Modulus of Elasticity	12800	4500

2. Experimental context

The experimental study was composed of eight full size RC rectangular beams in the heavy structure laboratory. The beam specimens were distributed into three groups. One beam was considered as the control specimen (unstrengthened) in first group. The second group were consisted three specimens in strengthened by NSM steel bars and without end anchorage. And, the third group were consisted four specimens in strengthened by NSM steel bars and end anchorage with CFRP fabrics. Table 1 shows the test matrix of this experimental investigation.

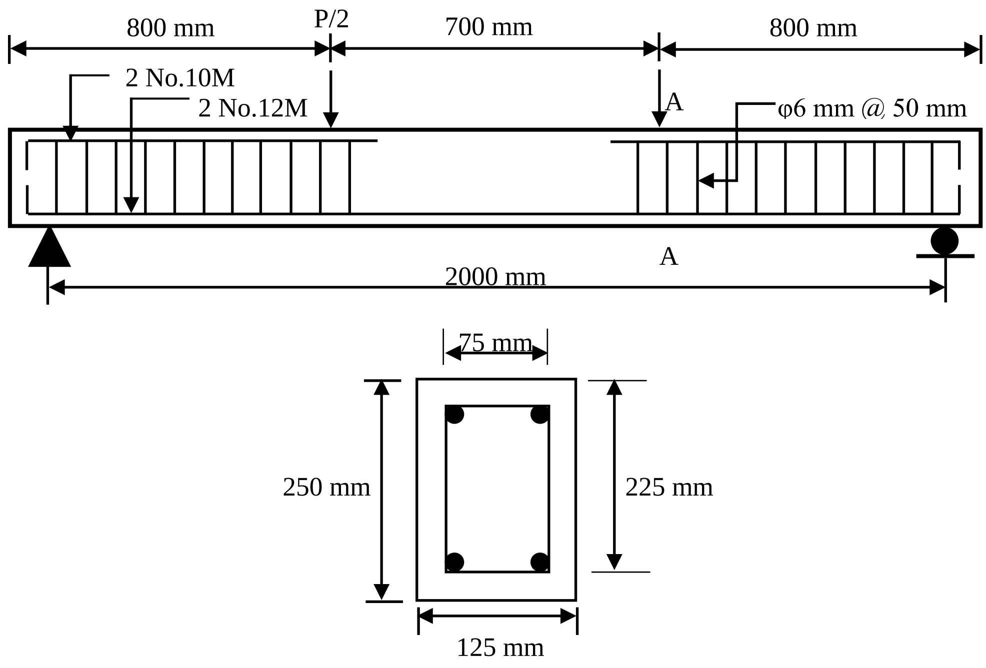
2.1 Materials

Local mining sand was considered as fine aggregate. Crushed granite of maximum size 20 mm was used as coarse aggregate. Fresh tap water hydrated the concrete mix during the casting and curing of the beams, cubes, prisms and cylinders. Ordinary Portland cement was used for casting of the beam specimens. DOE method (Teychenné *et al.* 1997) was followed for mix design of concrete. The 28 days average compressive strength, flexural strength and modulus of elasticity of the concrete was 40 MPa, 4.5 MPa and 29.90 GPa respectively based on tests of concrete three cubes (100 mm×100 mm×100 mm), prisms (100 mm×100 mm×500 mm) and cylinders (150 mm×300 mm). The average yield strength and the ultimate strengths of bars (6 mm, 8 mm, 10 mm and 12 mm) were 520 MPa and 570 MPa respectively. The modulus of elasticity for all steel bars were 200 GPa. The thickness, ultimate strength and modulus of elasticity of CFRP fabrics were 0.17 mm, 4.9 GPa and 230 GPa respectively. Sikadur® 30 and 330, an epoxy adhesive, was used to bond the strengthening bars and CFRP fabrics to the concrete substrate respectively. The

Sikadur® 30 density was 1.65 kg/litre at 23℃ after mixing, and bond strength with steel and concrete is 21 MPa and 4 MPa respectively. The compressive, tensile and shear strength and modulus of elasticity according to manufacturer of adhesives (Sikadur® 30 and 330) shown in Table 2.

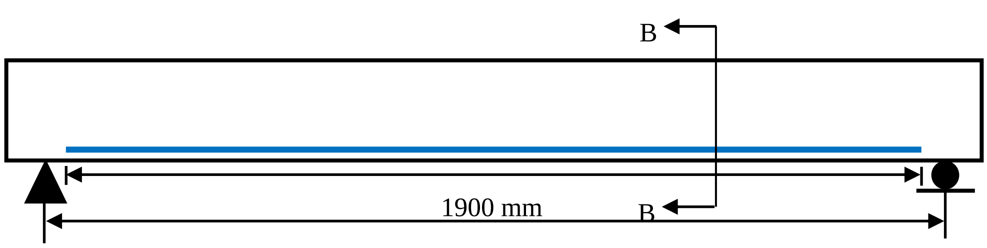
2.2 Preparation of beam specimens

Fig. 1 shows the dimensions and reinforcement details of the prototype specimens. The beam specimens were designed as under reinforced ($\rho=As/bd$=0.0084) beams to initiate failure in flexure, in accordance with the ACI-318 (2011). The cross-sectional dimensions and the length of the beams were 125 mm×250 mm and 2300 mm respectively. The shear-span and effective span length of the beams were 650 mm and 2000 mm respectively. Three types of steel bars (6 mm, 10



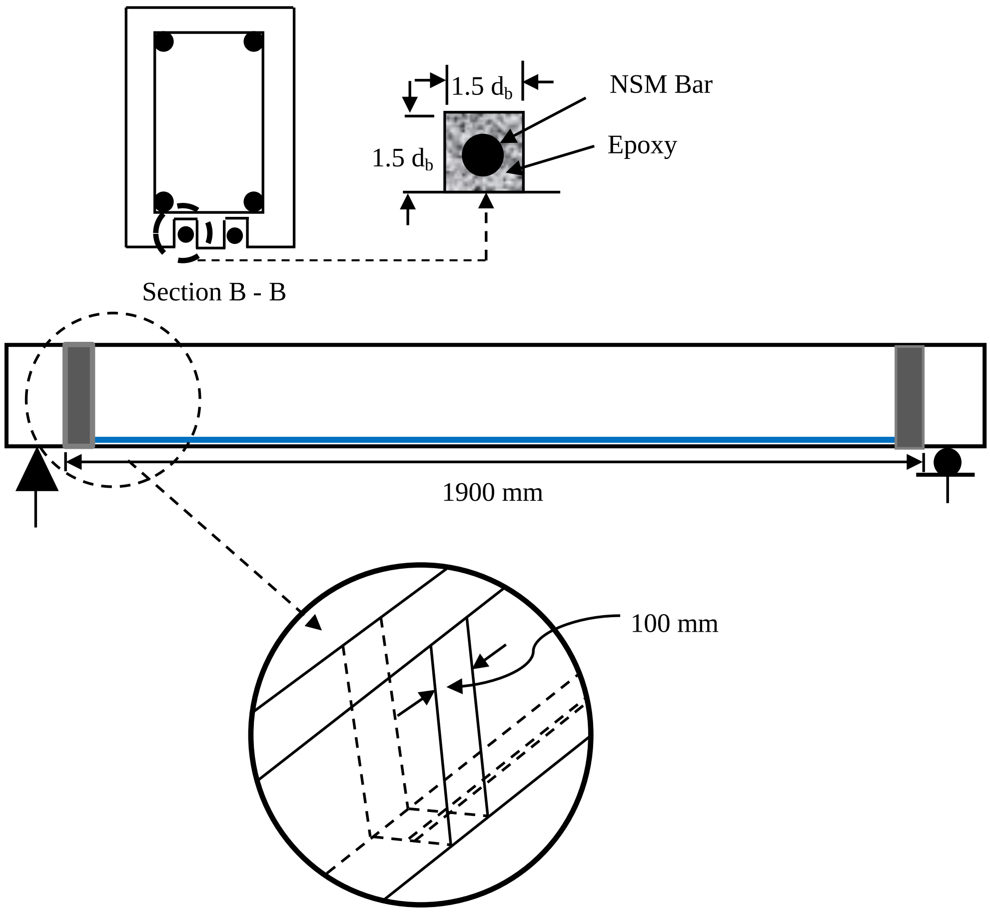
Section A - A

(a)Control beam



(b) NSM-steel strengthen beam

Fig. 1 Beam specimens details



(c) NSM-steel with end-anchorage strengthened

Fig. 1 Continued

mm and 12 mm in diameter) were employed in constructing the beam specimens. Two deformed steel bars (12 mm in diameter) were used as an internal tension reinforcement of all beam specimens, which bent ninety degrees at both ends to fulfil the anchorage criteria. Moreover, two deformed steel bars (10 mm in diameter) were used as hanger bars in the shear span zone. The shear reinforcement comprised of plain steel bars (6 mm in diameter), which distributed along the span length of the beam specimens as shown in Fig. 1.

2.3 Strengthening schemes

The NSM-steel bars were placed into grooves, which cut into the concrete cover of the RC beams and an epoxy adhesive groove filler applied for bonded with concrete substrate. The cutting of grooves into the concrete cover of the beam specimens at the tension face in the longitudinal direction to maintaining the dimensions $1.5d_b \times 1.5d_b$ (where d_b is the diameter of the tension reinforcement), for fixing of the strengthening steel bars. A special concrete saw with a diamond blade was used for making the grooves. To remove any remaining concrete lugs and to roughen the lower surface of the grooves were used a hammer and a hand chisel. A high pressure air jet and a wire brush were utilized for clean the grooves. Before introducing the strengthening steel bars into the grooves were clean with acetone, in order to eliminate any possible dirt. The grooves details are shown in Fig. 1(b). The grooves were half filled with an epoxy adhesive and then the strengthening (steel) bars were placed into the grooves with light pressure. This force was used to flow the epoxy around the inserted steel bars. Adding, essential epoxy to fulfil the grooves and level the surface. The bonded length of the NSM-steel bars were 1900 mm. The beam was kept for one week of curing time to ensure the epoxy achieved full strength.

The concrete surface was prepared after curing period based on manufacturer's instructions for epoxy adhesive (Sikadur® 330) at the curtailment end of NSM-steel bars. The specimens' soffit and two sides (width 100 mm) were prepared for end-anchorage. The end-anchored portion was cleaned with wire brush and high pressure air jet. Lastly, acetone was used to remove the dust or any other materials, which affect the bonding between the CFRP fabrics and concrete substrate. A thin layer of epoxy was used on the concrete surface to make assured the adhesive fully cover the concrete surface. Afterwards, CFRP fabrics layers placed on the required position as like as U (soffit and two sides) and enclosed with epoxy adhesive. Also, the beam was kept one week of curing, for epoxy achieved full strength.

2.4 Test configurations

One vertical linear variable differential transducer (LVDT) was used for measure the deflection at mid-span (Fig. 2) of the beam specimens. TML strain gauges (PFL-20-11-3LT) were used for measuring strains. Two 5 mm strain gauges were attached to the central position of the internal tension bars. A 30 mm strain gauge was placed on the extreme fibre of the beam at mid-span. Demec gauges were attached along the depth of the specimen at central position.

The testing scheme employed four-point bending using an Instron Universal Testing Machine at heavy structural lab. A Dino-Lite digital microscope was used for measure the crack widths on

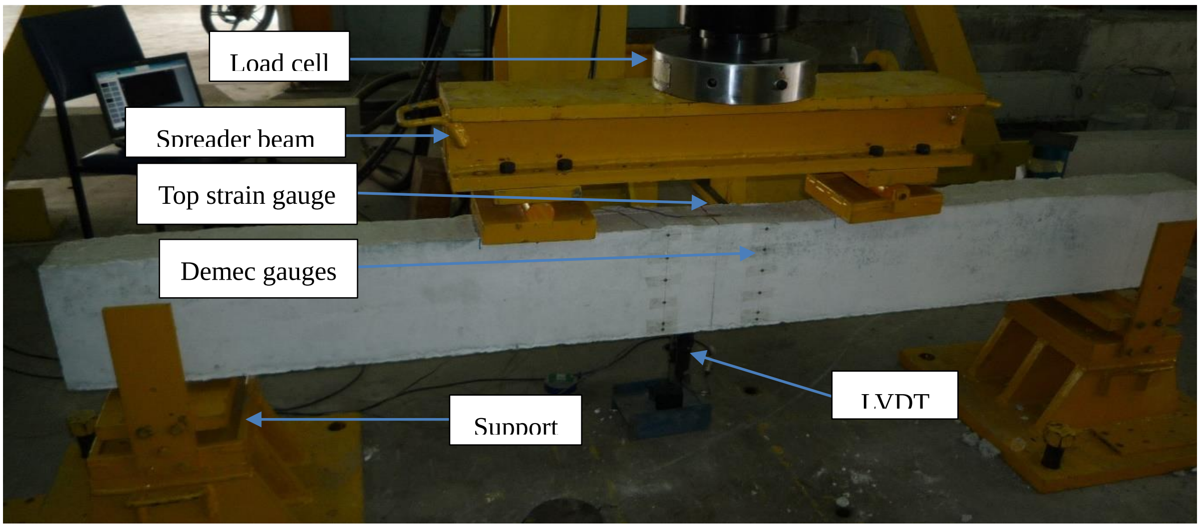


Fig. 2 Experimental set-up

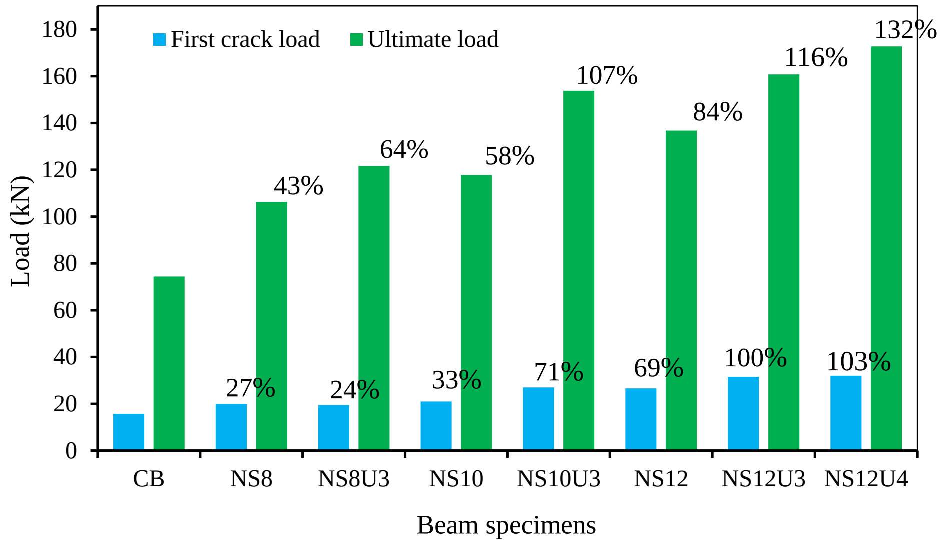


Fig. 3 Load increment using NSM-steel with and without end anchorage

the beams during testing. Two types of controlling techniques were carried out during the experimental test. Firstly, the load control was applied up to the strain hardening of the specimens. Secondly, the displacement control was applied, which commencing from the strain softening region, loading was maintained until failure of the specimens. All test data were logged at 10 second intervals. During the load and displacement control actuator rate was set to 5 kN/min and 1.5 mm/min respectively.

3. Experimental results and discussions

3.1 Behaviour in flexure

The test results revealed that NSM-steel bars significantly enhance the stiffness of the strengthened specimens. The first cracking load of NSM-steel with end anchorage specimens revealed a remarkable increase (till 103%) over the control specimen (Fig. 3). Also, showed that all the strengthened specimens without end-anchored NSM steel bars and those with end-anchored NSM steel bars had higher flexural capacities compared with the control specimen. The ultimate loads of the NSM steel bars and end-anchored specimens were higher (till 49%) compared with the NSM steel bars and without end-anchored specimens. The flexural capacities increase due to important role of end anchorage, which eliminated the concrete cover separation failure of the specimens. The NSM-steel and without end anchorage strengthen specimens failed before the specimens could achieve their full strength by separation of the concrete cover. However, the specimens with NSM steel bars and with end-anchored strengthened had the full strength before failure, which increased the ultimate load carrying capacity.

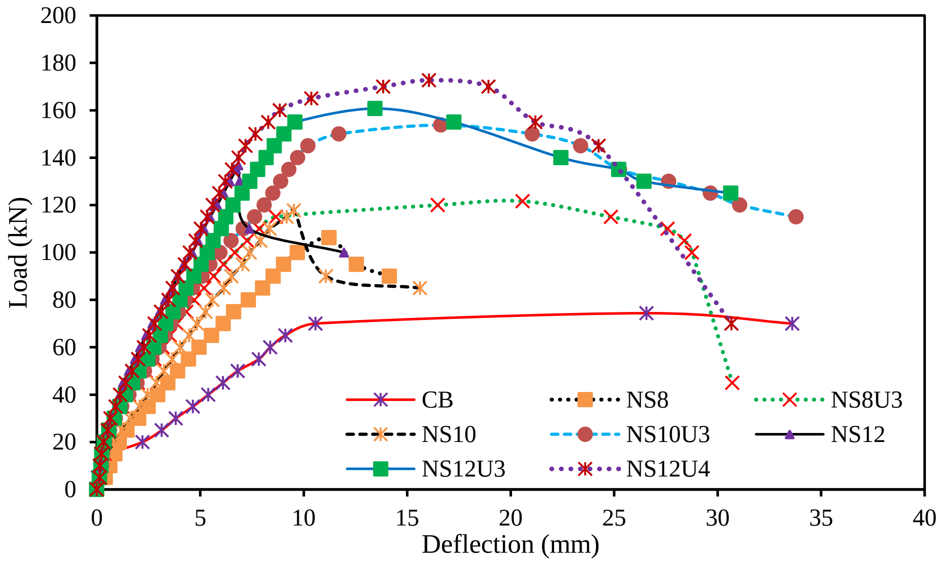


Fig. 4 Load-midspan deflection

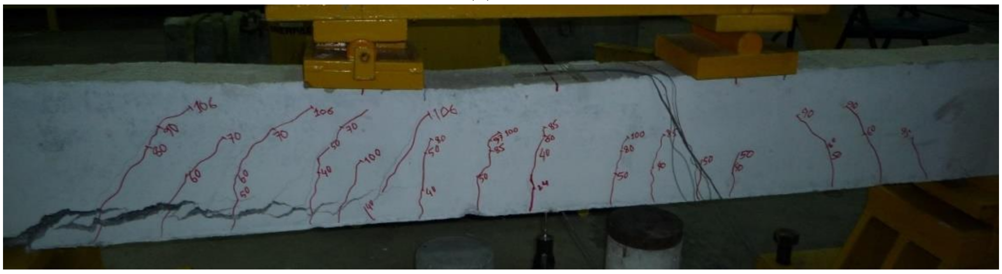
3.2 Behaviour in deflection

The reference, NSM steel bars with end anchorage, and NSM steel bars without end anchorage strengthened specimens load versus midspan deflection curves are shown in Fig. 4. The linear elastic behaviour of deflection revealed at the beginning followed by the first cracking load of the beam specimens. After that, the deflection curve developed nonlinearly due to initiate many flexural cracks in the specimens. The NSM steel bars and end-anchored strengthened specimens revealed less deflections compared with NSM steel bars but not end-anchored strengthened specimens in the elastic region, except the NS12 specimen. At the failure stage, the NSM steel bars and end-anchored specimens strengthened exhibited more deflection compared with the NSM steel bars but not end-anchored specimens strengthened. The main cause being that the NSM steel bars and end-anchored specimens strengthened prevented concrete failure through separation of the cover and improved the ultimate load carrying capacity.

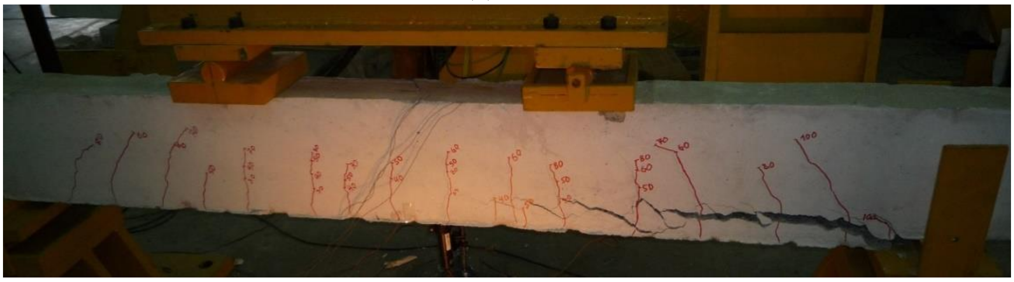
3.3 Failure modes

The control, NSM steel bars without and with end-anchored strengthened beam specimens failure modes are shown in Fig. 5. The results express that the without end anchorage strengthened specimens failed due to separation of concrete cover, which is a brittle modus. By contrast, the NSM steel bars and with end anchorage strengthened specimens failed in flexure in a ductile failure mode. Therefore, all without end anchoring strengthened specimens failed through separation of the concrete cover due to the formation of shear cracks at the curtailment edge of the NSM steel bars. The U-wrap end-anchored (using CFRP fabrics) was decisively attached at the NSM steel bars curtailment end, it’s minimize the risk of the construction of shear cracks at the NSM bars curtailment end. Hence, the failure mode shows ductile characteristics, when concrete cover separation did not occur of the strengthened specimens.

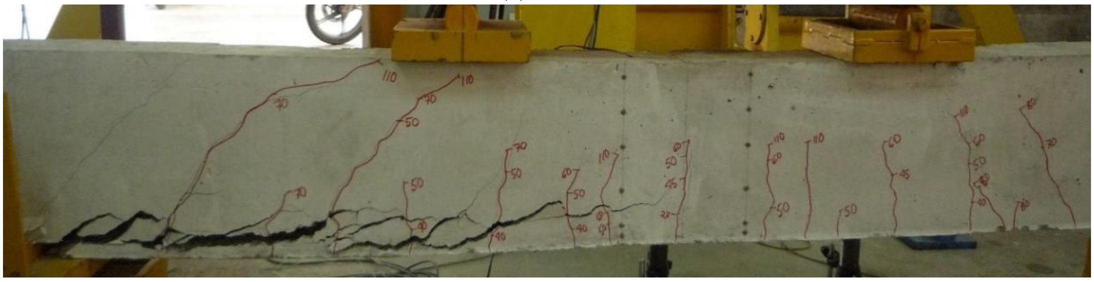
(a) CB



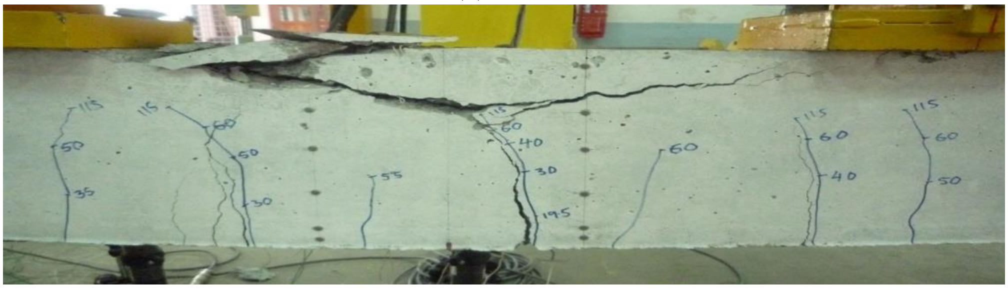
(b) NS8



(c) NS10



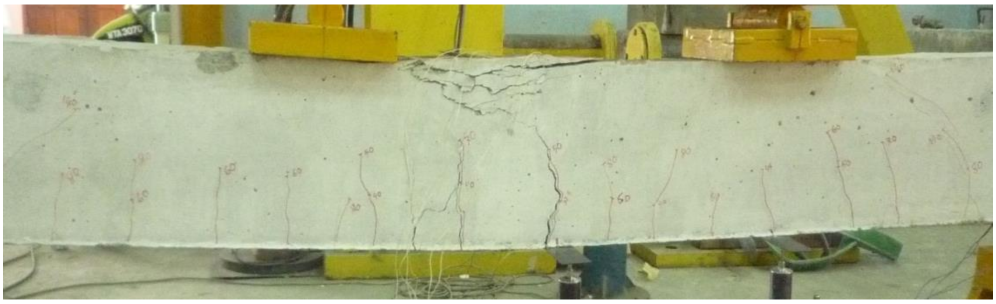
(d) NS12



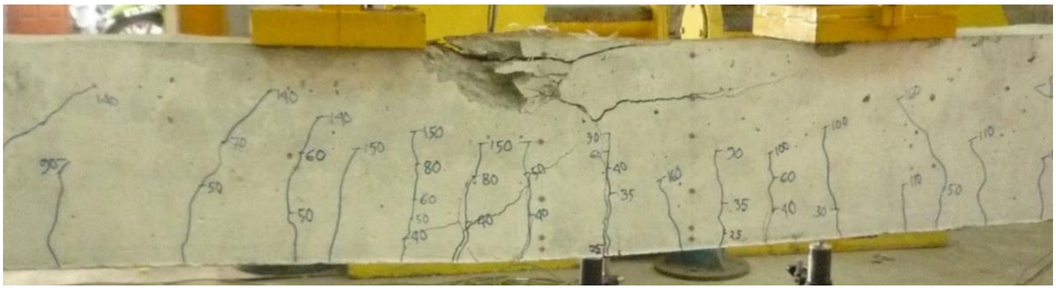
(e) NS8U3

Fig. 5 Failure modes of beam specimens

(f) NS10U3



(g) NS12U3



(h) NS12U4

Fig. 5 Continued

3.4 Compressive strain of concrete

The compressive strain of concrete at the midspan and top fibre of the beams are shown in Fig. 6. The first crack zone of the strengthened beams without end anchorage had similar compressive strains to the concrete of the strengthened beams with end anchorage. The cracking zone of the strengthened beams without end anchorage showed higher compressive strains in the concrete than that of the strengthened beams with end anchorage. However, the strengthened beams with end anchorage showed more compressive strain in the concrete compared to those without end anchorage in the failure phase.

This was because the U-wrap end anchorage prevented failure through separation of the concrete cover

3.5 Tensile strain in rebars

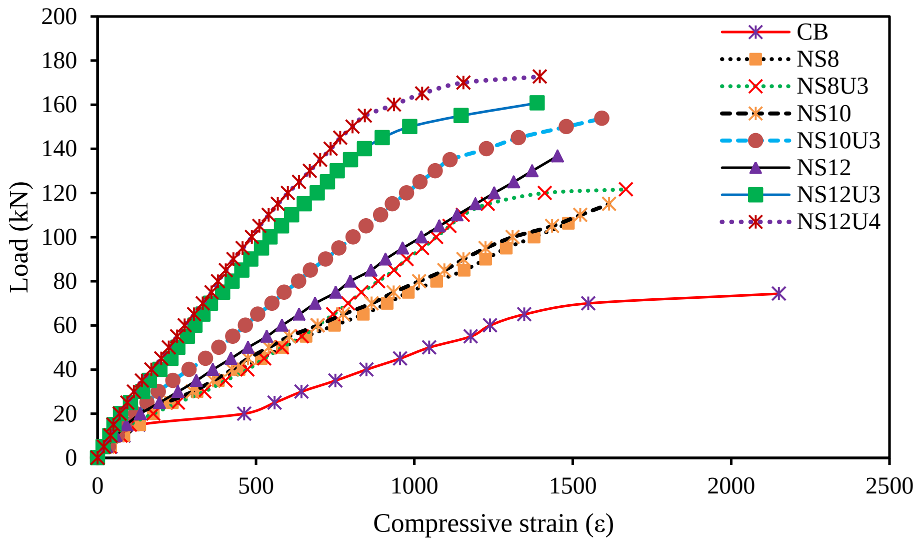


Fig. 6 Load-compressive strain of concrete

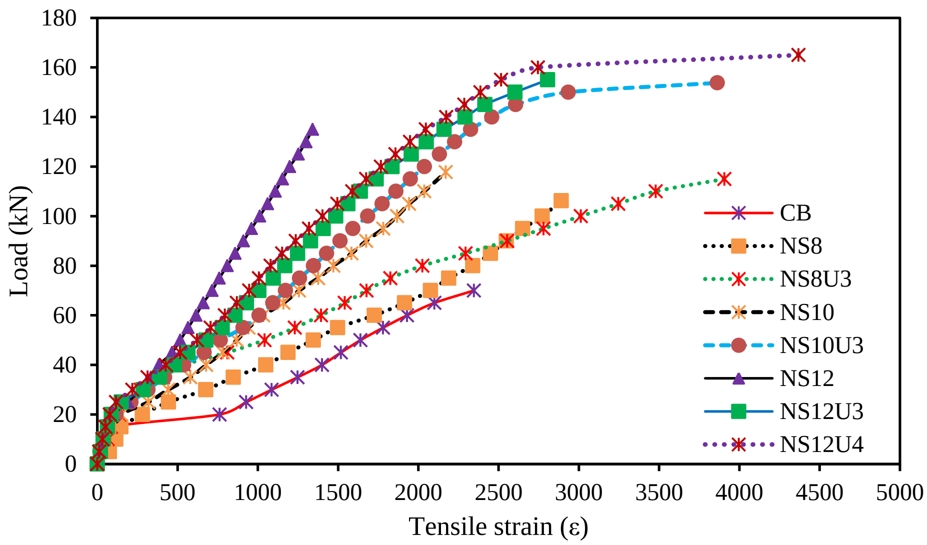


Fig. 7 Load-tensile strain of main reinforcement

3.5.1 Tensile strain of main bars

The main reinforcement tensile strains were logged at the midspan of the specimens, as revealed in Fig. 7. All (without and with end anchorage) strengthened specimens tensile strain were smaller than the control specimen due to greater stiffness. The without end anchorage strengthened specimens showed more tensile strain in the main reinforcement compared to those with end anchorage specimens in the elastic zone, except NS12. At the failure stage, the NSM-steel with end anchorage strengthened specimens exhibited more tensile strain in the main reinforcement compared to those without end anchorage. Since, the strengthened specimens

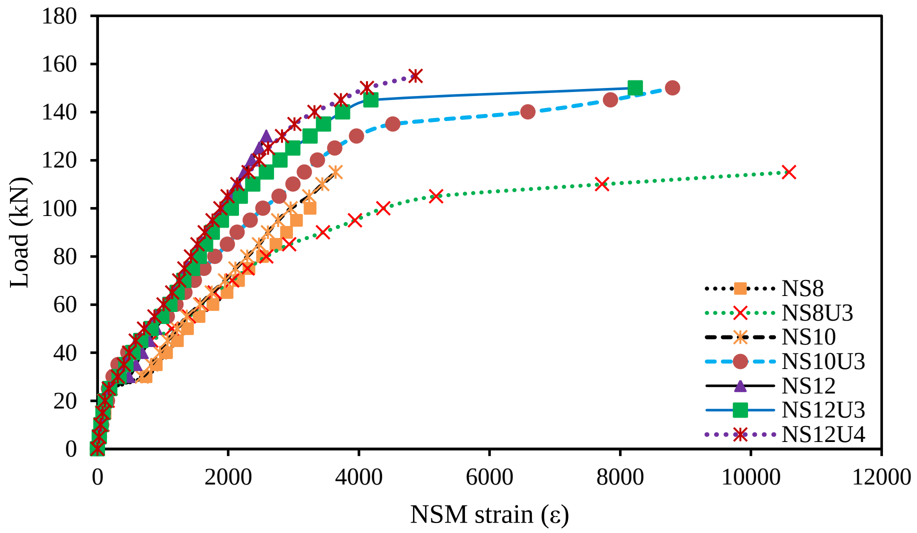


Fig. 8 Load-tensile strain of NSM reinforcement

without end anchorage failed in a brittle manner by separation of the concrete cover, by contrast to the strengthened specimens with end anchorage, which failed in a ductile manner by flexure.

3.5.2 Tensile strain of NSM bars

The tensile strain of the NSM reinforcement for all the strengthened specimens is shown in Fig. 8. The cracking zone of the strengthened specimens without end anchorage showed more tensile strain in the NSM reinforcement compared to those with end anchorage. However, at the failure stage, the specimens strengthened with NSM steel bars and end anchorage had more tensile strain of the NSM reinforcement compared to the specimens strengthened with NSM steel bars but without end anchorage. This is because the strengthened specimens with end anchorage had superior failure loads compared to those without end anchorage.

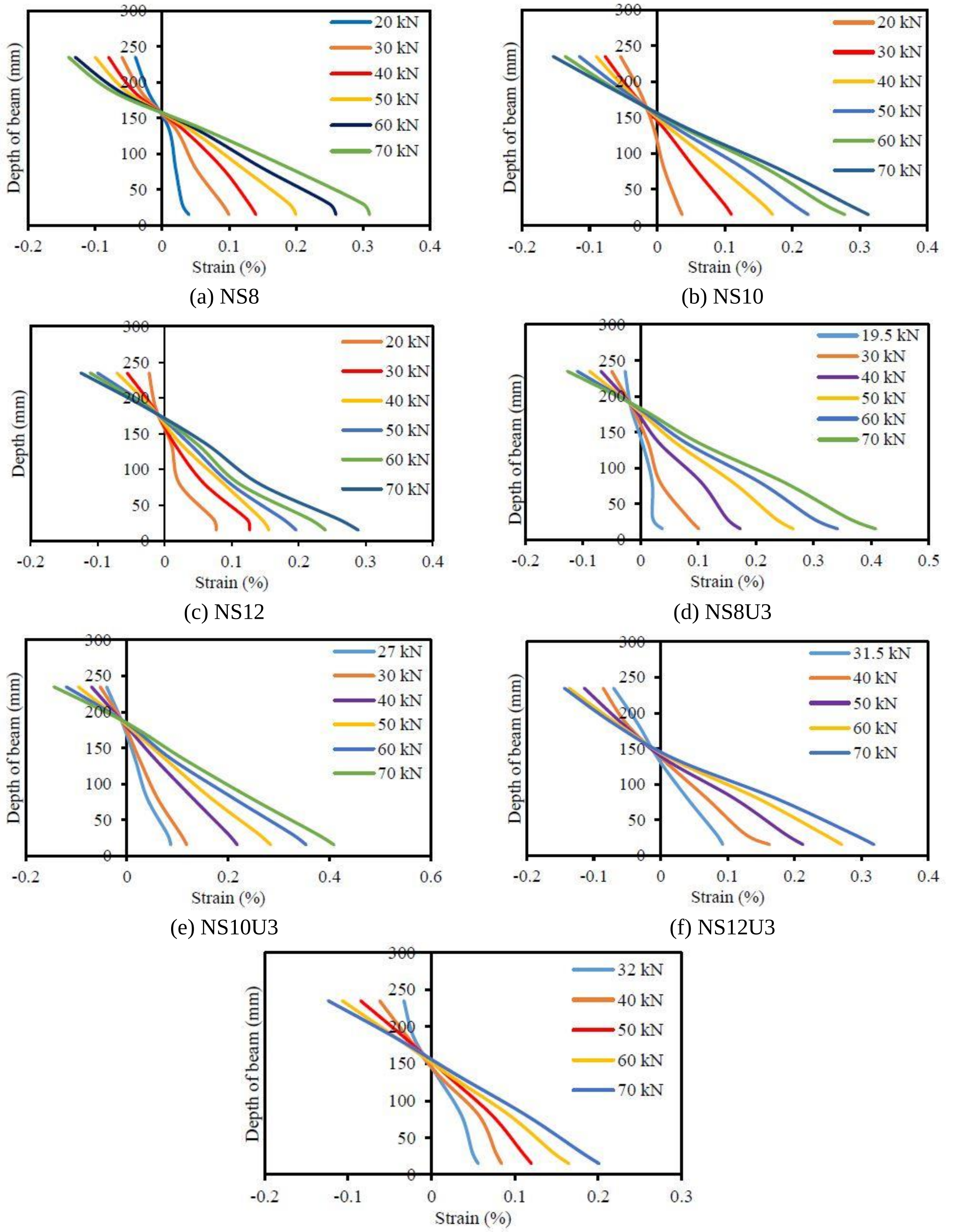
3.6 Sectional strain characteristics

The depth of beam (h) versus strain at the midspan of the beam specimens for various load levels using demec gauge readings for the strengthened specimens with and without end anchorage as shown in Fig. 9. The strengthened specimens with end anchorage showed more sectional strain compared to those without end anchorage at the failure stage due to the strengthened beams without end anchorage failed by separation of the concrete cover, i.e., premature failure, while the strengthened specimens with end anchorage failed in flexure.

4. Numerical analysis

4.1 Geometrical model

The modelling of experimental tested RC beam specimens, it is an imperative that the concrete



(a) NS8 (b) NS10

(c) NS12 (d) NS8U3

(e) NS10U3 (f) NS12U3

(g) NS12U4

Fig. 9 Sectional strain variation at midspan of strengthened beams

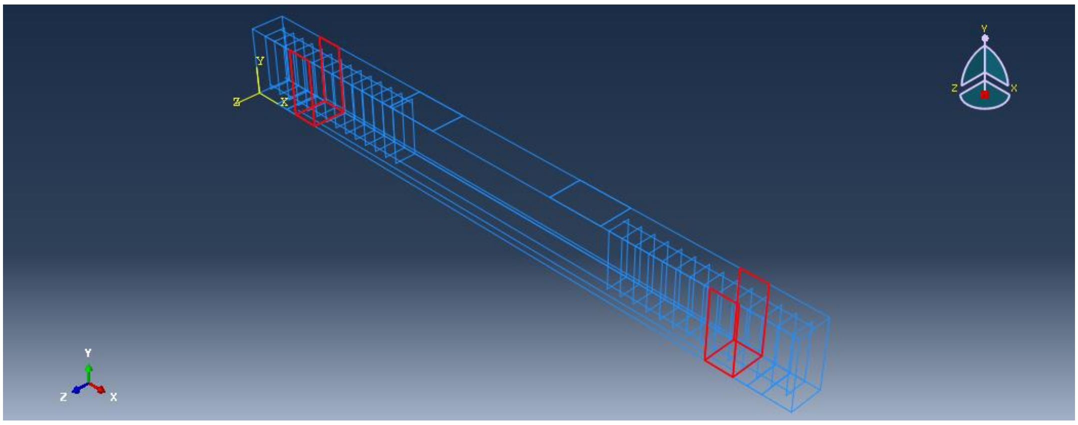


Fig. 10 3D finite element model of reinforcements and end anchorage

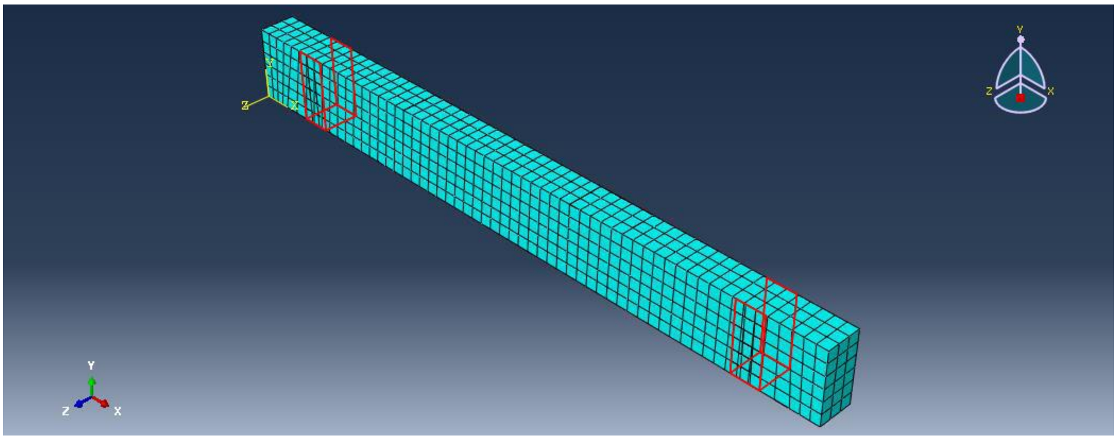
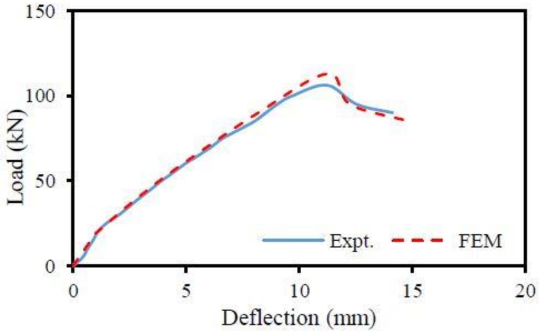


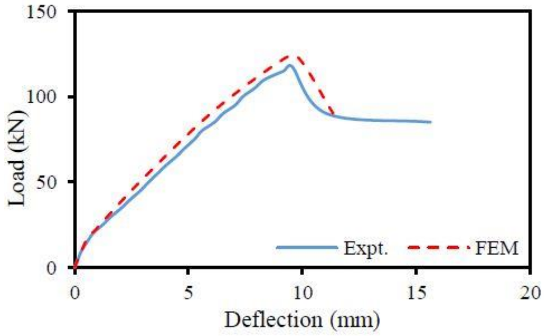
Fig. 11 3D finite element mesh of end anchorage strengthened RC beam specimen

was simulated as 3D solid elements. Hence, 8-node reduced integration solid hexahedron elements were considered to model of concrete. The epoxy adhesive follows similar element definition. These elements have three degrees of freedom at each node.

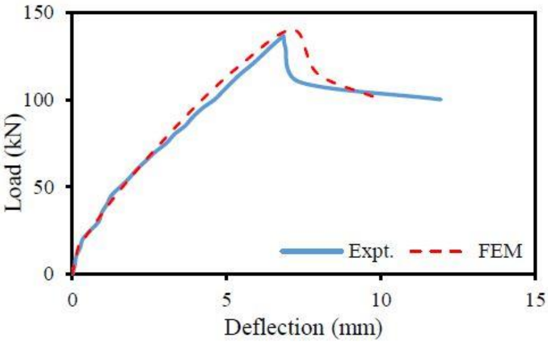
The longitudinal steel, strengthening bars and end anchorage as well as the transverse ties were modeled using 2-node truss elements (Fig. 10). The truss elements have three degrees of freedom at each node, interpretations in *x*, *y*, and *z* directions. The variance between the beam and the truss elements is that the former has stiffness 208 associated with the deformation of the beam's axis while the latter has only axial stiffness. The 8-node solid elements were 1106 in numbers consisting 1784 nodes. The numerical convergence study revealed that further reduction of mesh size has little effect on the numerical results, however leads to the risk of computer memory overflow and substantially increases the computing time. Fig. 11 demonstrates the typical mesh of strengthened specimen, which consists of 1106 solid concrete elements, 19 solid epoxy elements, and 824 truss elements for the reinforcing bars to give a total of 1949 elements. The finite element (FE) analysis was based on perfect bond assumption between steel bars and surrounding concrete, between NSM bars and epoxy adhesive, end anchorages and epoxy, and in between the epoxy adhesive and concrete.



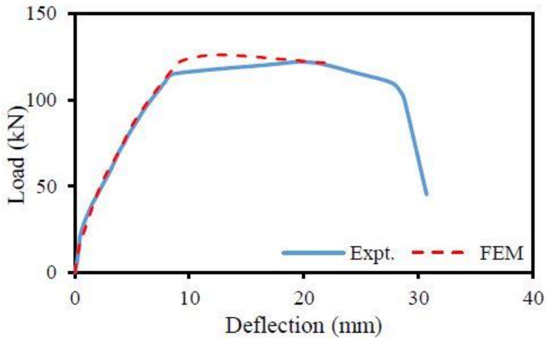
(a) NS8



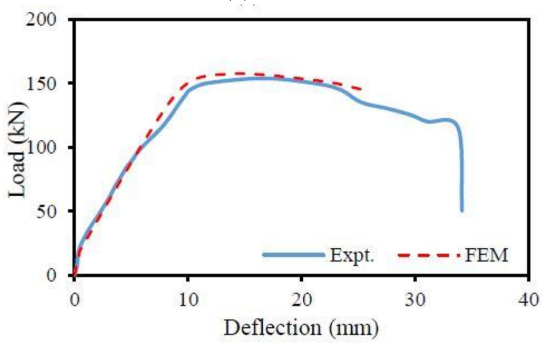
(b) NS10



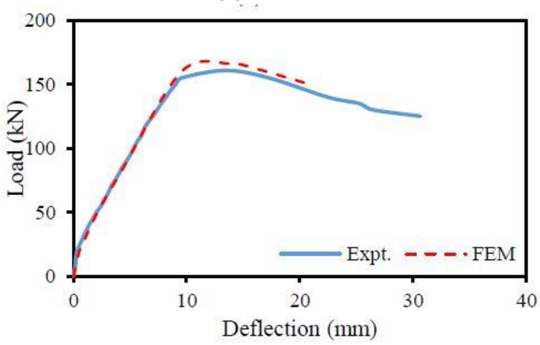
(c) NS12



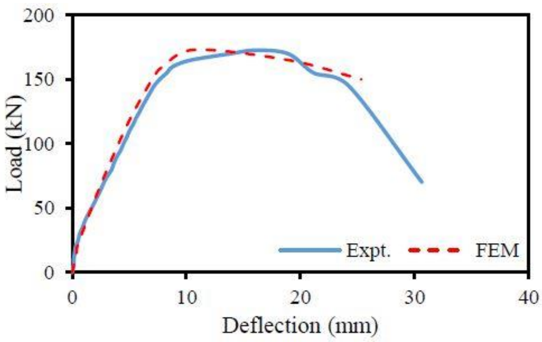
(d) NS8U3



(e) NS10U3

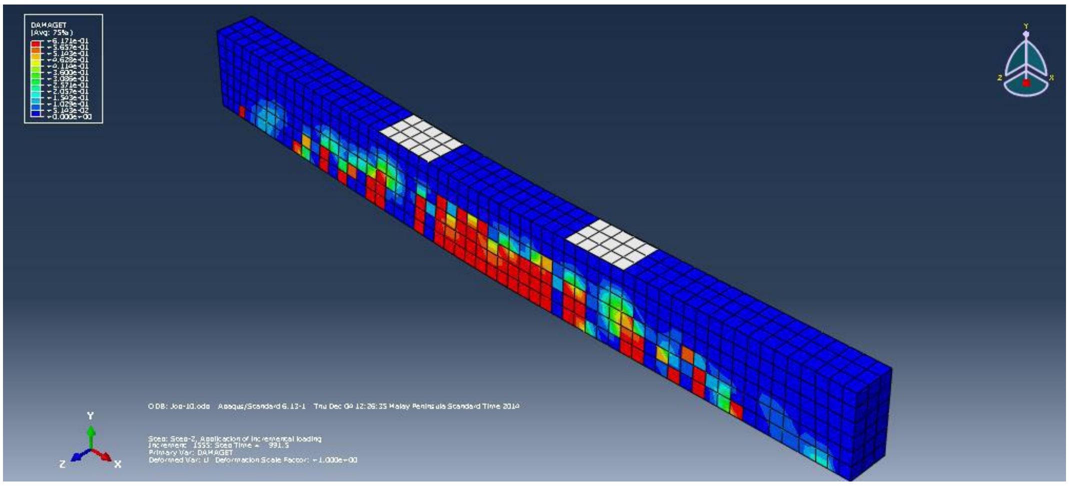


(f) NS12U3

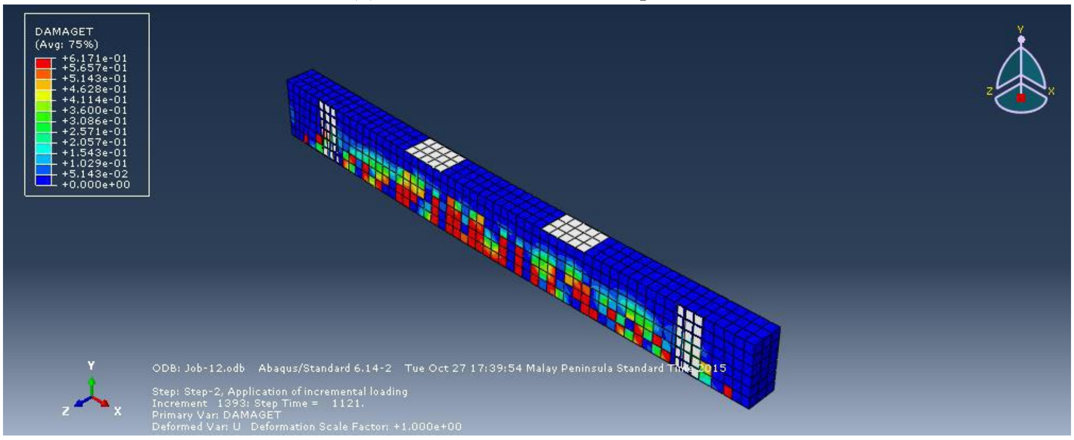


(g) NS124U

Fig. 12 Load-deflection curves comparison of experimental and tested specimens



(a) Without end-anchored specimen



(b) With end-anchored specimen

Fig. 13 FEM failure modes

4.2 Prediction of load-deflection behaviour

Fig. 12 presents the comparison between the load-deflection curves, which achieved from the experimental test and the numerical analysis. The predicted and experimental load-deflection curves shows reasonable agreement.

4.3 Prediction of failure modes

Fig. 13 shows the failure modes of strengthened specimens as observed from the FE analysis. The failure modes of the tested beams predicted from the FE analysis matches well with the experimental testing. The without end anchored specimens failed by concrete cover separation at NSM bar curtailment end, which similar to the experimental observations. The end-anchored specimens failed due to concrete crushing after the creation of flexural cracks in the constant moment region.

5. Conclusions

The experimental and numerical investigations were executed to study, the influence of end anchorage on the NSM-steel bars flexurally strengthened RC beam specimens. The flexural strength, deflection, failure modes, concrete extreme fiber strain, main rebars tensile strain and sectional strain of each of tested were investigated. The subsequent conclusions can be drawn from the experimental and numerical results.

All the strengthened beam specimens enhance the first cracking and ultimate loads, and reduce the displacement at any load level compared with the control beam specimen.

NSM steel bars and with end anchors increase first cracking and ultimate load up to 103% and 132% respectively than the control beam due to used full strength of strengthened materials. Whereas without end anchors, a quite less increase are seen by corresponding 69% and 84%. This eventually ensure the efficacy of end anchorage in sustaining imposed loading.

In case of only NSM-steel bars, the strengthened specimens fail by concrete cover separation and shows brittle behavior.

Proposed U-wrap end anchorage using CFRP fabrics on the NSM-steel strengthened specimens causes failure by flexure. Therefore, end anchorage eliminate the concrete cover separation failure of the specimens.

FE models show good agreement with the experimental study in analyzing RC beams strengthened in flexure with NSM technique (with and without anchors).

Developed numerical simulation can satisfactorily predict the deflection and failure modes of strengthened RC elements.

Acknowledgments

The authors appreciate and are grateful to the financial support from the University of Malaya Research Grant (UMRG) under Account No - RP018/2012A.

References

ACI-318 (2011). *Building Code Requirements for Structural Concrete (ACI 318-11) and Commentary*, First Edition, American Concrete Institute.

Al-Mahmoud, F., Castel, A., François, R. and Tourneur, C. (2010), "RC beams strengthened with NSM CFRP rods and modeling of peeling-off failure", *Compos. Struct.*, **92**(8), 1920-1930.

Aykac, S., Kalkan, I. and Uysal, A. (2012), "Strengthening of reinforced concrete beams with epoxy-bonded perforated steel plates", *Struct. Eng. Mech.*, **44**(6), 735-751.

Badawi, M. and Soudki, K. (2009), "Flexural strengthening of RC beams with prestressed NSM CFRP rods–experimental and analytical investigation", *Constr. Build. Mater.*, **23**(10), 3292-3300.

Bilotta, A., Ceroni, F., Di Ludovico, M., Nigro, E., Pecce, M. and Manfredi, G. (2011), "Bond efficiency of EBR and NSM FRP systems for strengthening concrete members", *J. Compos. Construct.*, **15**(5), 757-772.

Boukhezar, M., Samai, M.L., Mesbah, H.A. and Houari, H. (2013), "Flexural behaviour of reinforced low-strength concrete beams strengthened with CFRP plates", *Struct. Eng. Mech.*, **47**(6), 819-838.

Capozucca, R. and Bossoletti, S. (2014), "Static and free vibration analysis of RC beams with NSM CFRP rectangular rods", *Compos. Part B: Eng.*, **67**, 95-110.

Cruz, J.S. and Barros, J. (2004), “Modeling of bond between near-surface mounted CFRP laminate strips and concrete”, *Comput. Struct.*, **82**(17), 1513-1521.
De Lorenzis, L., Rizzo, A. and La Tegola, A. (2002), “A modified pull-out test for bond of near-surface mounted FRP rods in concrete”, *Compos. Part B: Eng.*, **33**(8), 589-603.
De Lorenzis, L. and Teng, J. (2007), “Near-surface mounted FRP reinforcement: An emerging technique for strengthening structures”, *Compos. Part B: Eng.*, **38**(2), 119-143.
De Sena Cruz, J.M. and Oliveira de Barros, J.A. (2004), “Bond between near-surface mounted carbon-fiber-reinforced polymer laminate strips and concrete”, *J. Compos. Construct.*, **8**(6), 519-527.
Demir, A., Tekin, M., Turali, T. and Bagci, M. (2014), “Strengthening of RC beams with prefabricated RC U cross-sectional plates”, *Struct. Eng. Mech.*, **49**(6), 673-685.
El-Hacha, R. and Gaafar, M. (2011), “Flexural strengthening of reinforced concrete beams using prestressed, near-surface-mounted CFRP bars”, *PCI J.*, **56**(4), 134-151.
El-Hacha, R. and Rizkalla, S.H. (2004), “Near-surface-mounted fiber-reinforced polymer reinforcements for flexural strengthening of concrete structures”, *ACI Struct. J.*, **101**(5), 717-726.
Islam, A.B.M.S., Jameel, M., Jumaat, M.Z. and Rahman, M.M. (2013), “Optimization in structural altitude for seismic base isolation at medium risk earthquake disaster region”, *Disast. Adv.*, **6**(1), 23-34.
Jung, W.T., Park, Y.H., Park, J.S., Kang, J.Y. and You, Y.J. (2005), “Experimental investigation on flexural behavior of RC beams strengthened by NSM CFRP reinforcements”, *ACI Spec. Publ.*, **230**, 795-806.
Kishi, N., Mikami, H., Kurihashi, Y. and Sawada, S. (2005), “Flexural behaviour of RC beams reinforced with NSM AFRP rods”, *Proceedings of the International Symposium on Bond Behaviour of FRP in structures*, BBFS 2005.
Mini, K., Alapatt, R.J., David, A.E., Radhakrishnan, A., Cyriac, M.M. and Ramakrishnan, R. (2014), “Experimental study on strengthening of RC beam using glass fibre reinforced composite”, *Struct. Eng. Mech.*, **50**(3), 275-286.
Novidis, D., Pantazopoulou, S. and Tentolouris, E. (2007), “Experimental study of bond of NSM-FRP reinforcement”, *Constr. Build. Mater.*, **21**(8), 1760-1770.
Ritchie, P.A., Thomas, D.A., Lu, L.W. and Conelly, G.M. (1991), “External reinforcement of concrete beams using fiber reinforced plastics”, *ACI Struct. J.*, **88**(4), 490-500.
Saadatmanesh, H. and Ehsani, M.R. (1991), “RC beams strengthened with GFRP plates. I: Experimental study”, *J. Struct. Eng.*, **117**(11), 3417-3433.
Sharaky, I., Torres, L., Baena, M. and Miàs, C. (2013), “An experimental study of different factors affecting the bond of NSM FRP bars in concrete”, *Compos. Struct.*, **99**, 350-365.
Sharaky, I., Torres, L., Comas, J. and Barris, C. (2014), “Flexural response of reinforced concrete (RC) beams strengthened with near surface mounted (NSM) fibre reinforced polymer (FRP) bars”, *Compos. Struct.*, **109**, 8-22.
Soliman, S.M., El-Salakawy, E. and Benmokrane, B. (2010), “Flexural behaviour of concrete beams strengthened with near surface mounted fibre reinforced polymer bars”, *Can. J. Civil Eng.*, **37**(10), 1371-1382.
Teychenné, D., Franklin, R., Erntroy, H., Hobbs, D. and Marsh, B. (1997), *Design of normal concrete mixes*, 2nd Edition, Building Research Establishment, Watford, UK.

CC