Jurnal
Teknologi

Full Paper

NEAR SURFACE MOUNTED BAMBOO REINFORCEMENT FOR FLEXURAL STRENGTHENING OF REINFORCED CONCRETE BEAMS

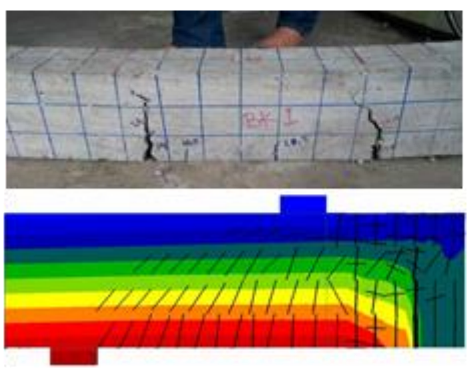
Article history
Received
28 March 2017
Received in revised form
17 June 2017
Accepted
10 August 2017

Yanuar Haryanto[a*], Buntara Sthenly Gan[b], Arnie Widyaningrum[a], Agus Maryoto[a]

[a]Department of Civil Engineering, Faculty of Engineering, Jenderal Soedirman University, Purwokerto, Indonesia
[b]Department of Architecture, College of Engineering, Nihon University, Koriyama, Japan

*Corresponding author
yanuar_haryanto@yahoo.com

Graphical abstract



Abstract

Near Surface Mounted (NSM) is a technique performed for the installation of strengthening material into grooves cut into the concrete cover of reinforced concrete (RC) beams bonded using a bonding agent. This technique is becoming more widely recognized because of its efficiency, effectiveness, and ease of application. We investigated flexural strengthening of RC beams with the NSM technique using bamboo reinforcements, through both experimental tests and a finite element analysis (FEA). The experimental tests were carried out on three RC beams, one consisting of a control beam, and the other two strengthened by the NSM technique with two steel reinforcements, and four bamboo reinforcements. From the experimental tests, we found that the flexural strength of the beam with NSM bamboo reinforcements was increased by 41.7% and the deflection ductility index was reduced by 21.55%. The mode of failure observed in all the strengthened beams was a flexural failure. Finally, the result of FEA behaved similarly to the results of the experimental test.

Keywords: Bamboo reinforcement, flexural strength, finite element analysis, near surface mounted

1.0 INTRODUCTION

Reinforced concrete structures all over the world require rehabilitation or strengthening at some time in their life span for various reasons, such as mechanical damage, environmental effects, increased service loads, and errors in the design and construction [1]. On the other hand, some elements of the structures may also have been weakened due to corrosion of steel rebars [2-5]. This paper presents an investigation on the flexural strengthening of reinforced concrete (RC) beams with the Near Surface Mounted (NSM) technique using bamboo reinforcements through both experimental tests and a finite element analysis (FEA). In the NSM technique, strengthening materials are placed into grooves cut into the concrete cover of the RC beams and bonded using a bonding agent. This technique has many potential advantages because it can improve and enhance the flexural strength of reinforced concrete beams without the need for additional dimensions, and it is becoming more widely recognized because of its efficiency, effectiveness, and ease of application [6]. The other advantages of this technique include: less risk of debonding from the concrete substrate, better protection against accidental impacts and unchanged aesthetic features [7, 8].

The use of bamboo as the strengthening materials of RC beams was previously reported [9-11]. Bamboo is a source of building materials that are renewable and widely available in Indonesia. Of the approximately 1,250 species of bamboo in the world, 140 species or 11% of them are native to Indonesia. Gonzales *et al.* [12] state that the high potential of bamboo and its versatile characteristics have opened a wide area of study. Bamboo can be used in manufacturing value-added products because of its excellent tensile strength [13]. Furthermore, the moisture content and shrinkage of bamboo are very important, as they effect its dimensional stability and strength [14]. Bamboo's moisture content is influenced by age and place of growth. The shrinkage is calculated from the air-dried density of bamboo because it is considered as a state approaching bamboo applications in the field [15].

Many studies on the use of the NSM technique for flexural strengthening of RC beams have been conducted. Rancovic *et al.* [16] performed an experimental investigation on the flexural behavior of RC beams strengthened with NSM GFRP reinforcement. FRP bars with G-rod Ø10 mm were used. It was found that the NSM strengthened specimen achieved 73% higher maximum load. Zhang *et al.* [17] presented a bond strength model for applying NSM CFRP strip to concrete interfaces. The predictions of the proposed model were compared with the results of 51 test specimens collected from 7 existing studies as well as the predictions of the only existing bond strength model. They reported that the proposed bond strength model, due to its accuracy, simplicity, and applicability to a wide range of real-world cases, can be readily incorporated in design codes and guidelines. Husain *et al.* [18] conducted a study on the strengthening of reinforced concrete beams using NSM FRP. They found that, in general, as the bond length of NSM FRP bars increases, the initial stiffness, ultimate load capacity, and deformation capacity increase. The increase is more significant with a bond length not less than 48 times the diameter of the bar.

2.0 METHODOLOGY

2.1 Beams Design

For the experimental program, a total of three series of specimens, consisting of 1000 mm long RC beams with a rectangular cross-section of 100 x 150 mm, were conceived. The tension and compression reinforcements used were steel bars with 6 mm diameter. The shear reinforcement, designed to induce flexural failure, consisted of steel stirrups of 6 mm nominal diameter spaced at 50 mm. The first beam specimen was the control beam with no strengthening (CB), and the remaining beam specimens were strengthened with different numbers of steel and bamboo bars (NSM1 and NSM2). The specimen dimensions and reinforcement details are shown in Figure 1.

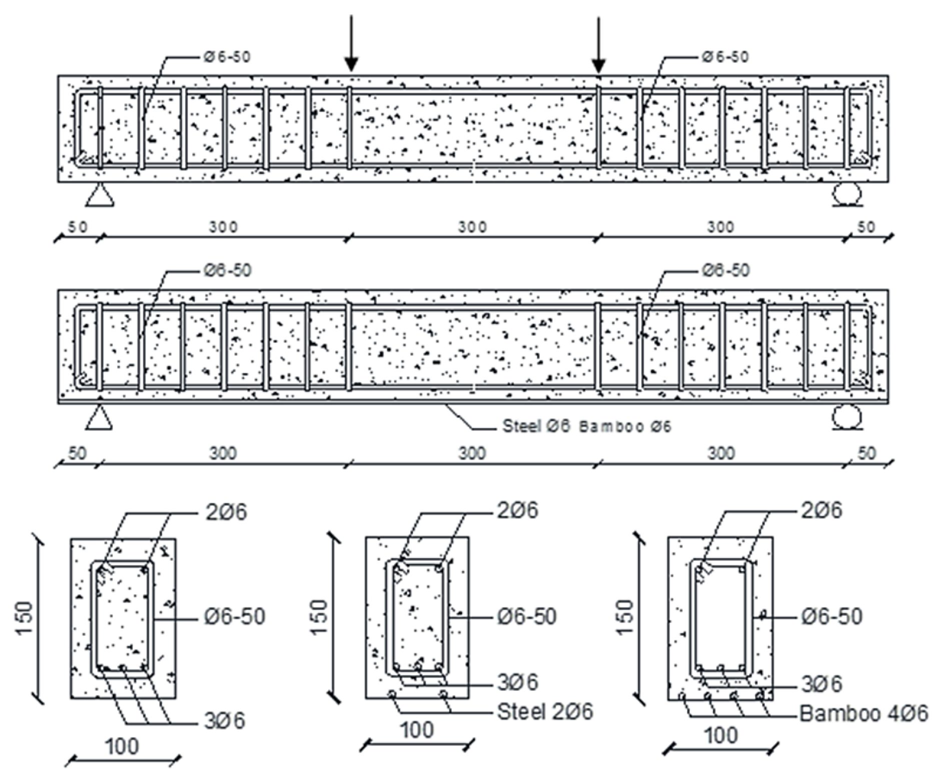


Figure 1 Details of the specimens

2.2 Material Properties

All beam specimens were cast using normal concrete. Figure 2 shows the casting process. Crushed stone was used as coarse aggregate, and the maximum size of the coarse aggregate was 20 mm. Natural river sand was used as fine aggregate. Fresh tap water was used to hydrate the concrete mix during the casting and curing of the beams and cylinders. The concrete consisted of 205 kg/m^3 of water, 510 kg/m^3 of fine aggregate, 1,135 kg/m^3 of coarse aggregate and 477 kg/m^3 of cement, with a 0.43 water/cement ratio. The 28 days average compressive strength of the concrete was 18.30 MPa based on tests of three 150 mm diameter and 300 mm high concrete cylinders. On average, the yield and ultimate strength of the 6 mm steel bar were 240.39 MPa and 510.46 MPa respectively. The average ultimate strength of the bamboo was 688.88 MPa. The results of tensile tests of the steel bar and bamboo, in an example of one specimen, are presented in Figure 3.

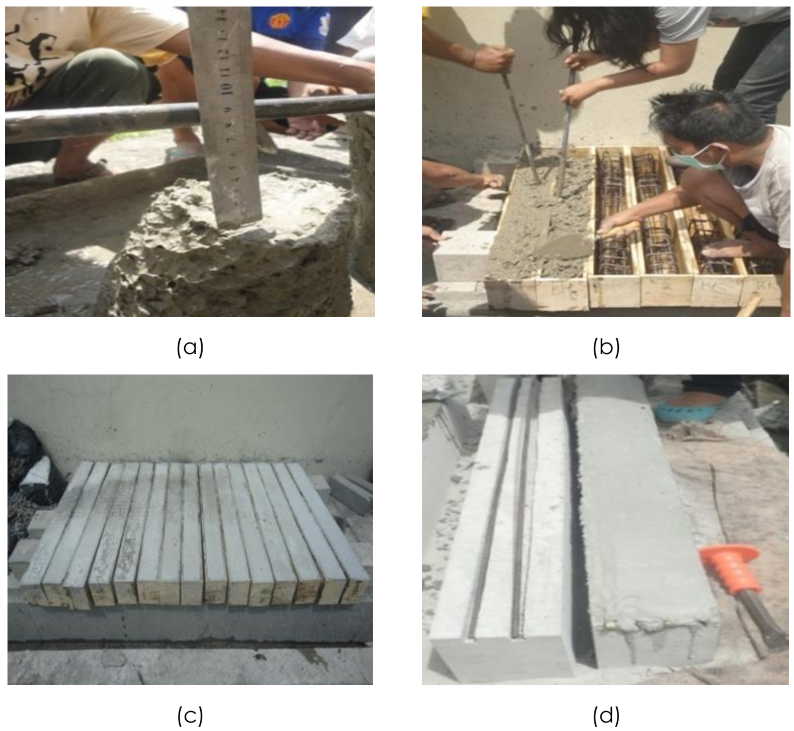


Figure 2 Casting process: (a) slump test, (b) pouring the fresh concrete, (c) unstrengthened beams, (d) strengthened beams

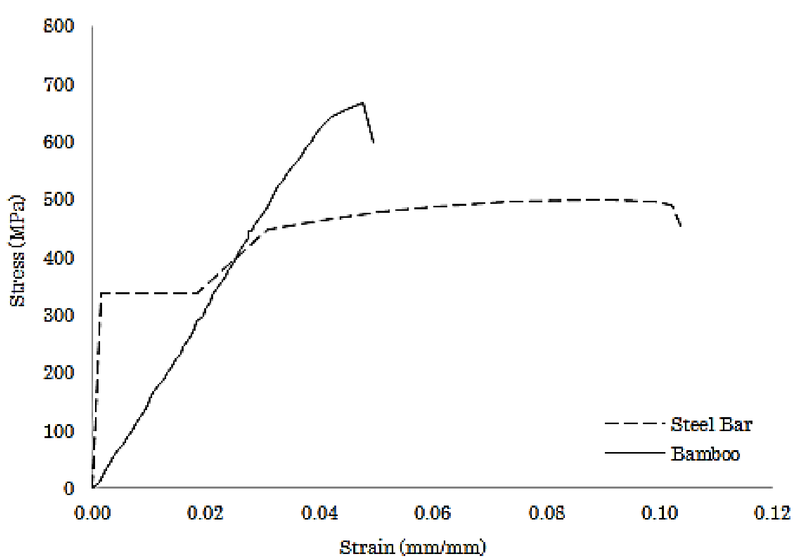


Figure 3 The result of tensile tests of steel bar and bamboo

2.3 Finite Element Analysis

Finite element analysis (FEA) was also performed here using a limited version of a program named ATENA, which can model up to 200 elements [19-21]. An 8-noded solid element, *CC3DnonLinCementitious2*, was used to model the concrete. The longitudinal steel reinforcement and bamboo were modeled using *CCReinforcement* elements. Two nodes were required for this element. Loading and support plates are modeled using the 8-noded solid element *CC3DElastIsotropic*. The concrete with stirrup was modeled using the 8-noded *CCCombinedMaterial* element. The material properties which are the results of a test on one specimen, and the types of elements used in this analysis, are summarized in Table 1. The finite element analysis (FEA) was performed based on just a quarter section as shown in Figure 4.

Table 1 Materials and the type of the elements

Materials	Element Type	Properties	Unit	Data
Concrete	*CC3DnonLinCementitous2*	Compresion strength	MPa	11.30
		Young's modulus, E_c	MPa	17850.33691
Reinforcement P6	*CCReinforcement*	Young's modulus, E_s	MPa	195000
		Ultimate stress, f_u	MPa	495.49
		Yield stress, f_y	MPa	338.75
		Area of reinforcement, A	m^2	0.0000283
Bamboo	*CCReinforcement*	Young's modulus, E_s	MPa	20000
		Ultimate stress, f_u	MPa	644.44
		Yield stress, f_y	MPa	666.67
		Area of reinforcement, A	m^2	0.0000283
Concrete with stirrup P6-40	*CCCombinedMaterial*	Area of Shear reinforcement, A_v	m^2	0.0000283
		Ratio of direction x reinforcement (1)	-	0
		Ratio of direction y reinforcement (2)	-	0.005652
		Ratio of direction z reinforcement (3)	-	0.003768
Loading and support plates	*CC3DElastIsotropic*	Young's Modulus, E_s	MPa	200000
		Poisson's Ratio, *v*	-	0.3

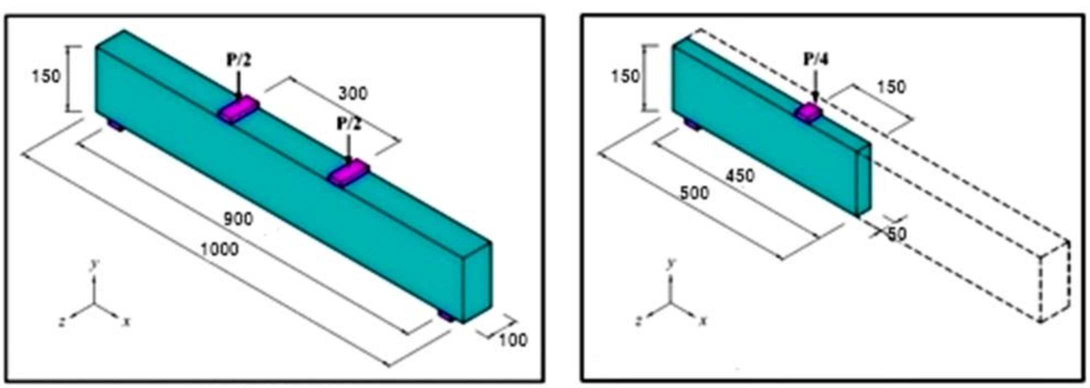
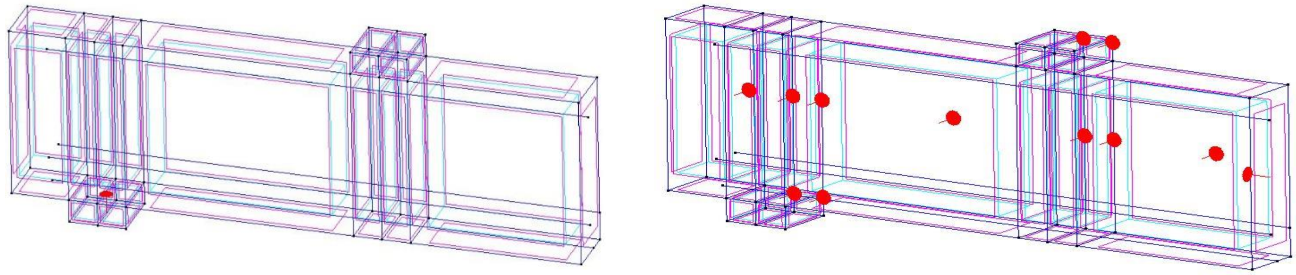


Figure 4 Model of finite element analysis at a quarter section

The application of constraint conditions in the FEA consisted of a support constraint condition and a surface constraint condition. The support constraint condition was applied in the simulation to represent support in the experimental test specimens. It was applied by giving the displacement value of zero in the Y direction using *constraint for line*. The value was applied to a line in the middle part of the support steel plates in the model. In addition to the support line, the constraint condition was also applied to the surface that does not undergo displacement by using *constraint for surface*. This was because the simulation was only done for half of the section. The constraint condition applied can be seen in Figure 5. The plan of meshing of the beam with NSM bamboo reinforcement shown in Figure 6 exceeded the total number 200 elements, consisted of 196 volume elements and 4 line elements, respectively. To find out the response that occurred in the FEA, the load observation and flexural observation points for the Y direction were applied. The observations were carried out by using *monitor for point* with output *displacements* to measure the deformation and using the output of *compact external forces* to measure the load.



(a) Constraint for line (b) Constraint for surface

Figure 5 The application of constraint conditions

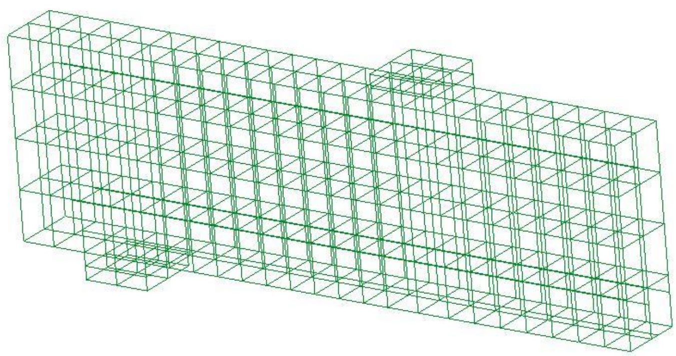
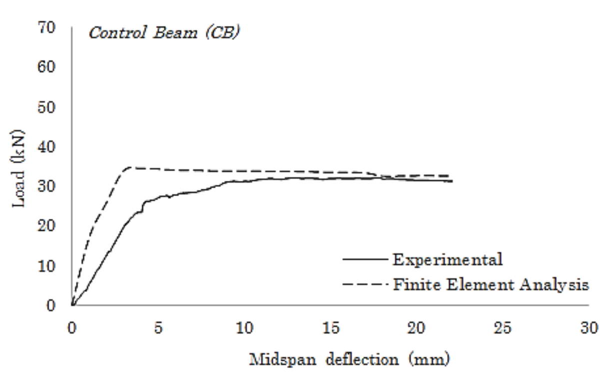


Figure 6 The plan of meshing of the beam with NSM bamboo reinforcement

3.0 RESULTS AND DISCUSSION

3.1 Load-Deflection Curve

Figure 7 shows the load versus midspan deflection for all beam specimens. As can be seen from the figure, the curves exhibit a tri-linear response defined by elastic, concrete cracking to steel yielding and steel yielding to failure stages. The load–displacement curve resulting from the FEA behaved similarly to the results of the experimental test. The study by Hidayat *et al.* [22] previously proved that in reality a concrete member is not uniform and does not possess a homogeneous strength throughout its depth. Since the properties of materials were homogeneous in all segments in the FEA, there was a reasonable difference in its slope between the two [21]. The experimental result shows that the use of NSM strengthening increased the ultimate load of the strengthened beams by 12.46% and 41.74%. Table 2 shows the results of FEA by using the NSM strengthening increased the ultimate load of the strengthened beams by 75.46% and 86.39% for NSM1 and NSM2, respectively over the control beam. It is observed that the ultimate load ratios from the FEA results against experimental results are 1.08, 1.56, and 1.31 for CB, NSM1, and NSM2, respectively.



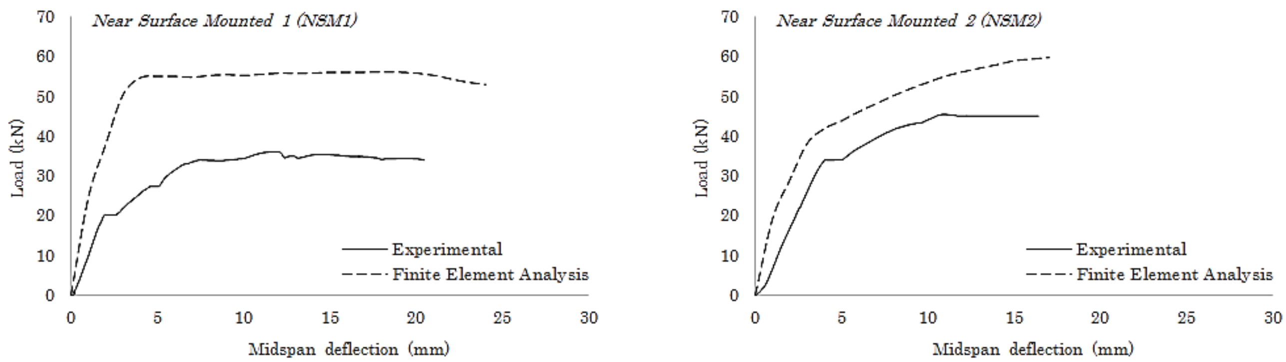


Figure 7 Load-midspan deflection of beams

Table 2 Ultimate load of the beams

Codes	Experimental		Finite element analysis		*Ratio
	Ultimate Load, Pu (kN)	%Pu	Ultimate Load, Pu (kN)	%Pu	
CB	32.10	-	34.56	-	1.08
NSM1	36.10	12.44	56.32	75.46	1.56
NSM2	45.50	41.74	59.83	86.39	1.31

*Finite element analysis result to the experimental result

3.2 Ductility

In this study the displacement deflection index was examined, with the results as presented in Table 3. The deflection ductility index is expressed as the ratio between the deflection at ultimate load (Δu is the mid-span deflection at ultimate load) and the yield load (Δy is the midspan deflection at yield load). Compared with the control beam, the deflection ductility index was reduced by 15.65% and 21.55% in the experimental test result, and it was reduced by 7.96% and 23.90% in the FEA result, for NSM1 and NSM2 respectively. The overall reduction in ductility of the strengthened beams was most likely due to the increased tension reinforcement ratio (strengthened bars).

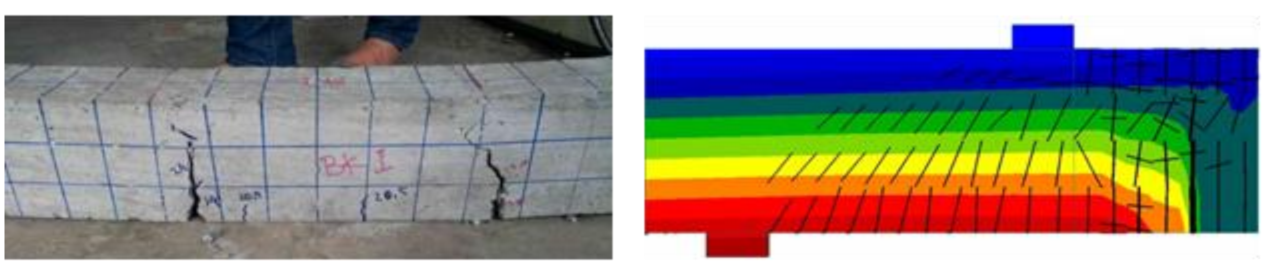
Table 3 Ductility of the beams

Codes	Experimental			Finite element analysis			*Ratio
	Δy (mm)	Δu (mm)	μd	Δy (mm)	Δu (mm)	μd	
CB	5.39	22.06	4.09	3.00	22.34	7.45	1.82
NSM1	5.92	20.44	3.45	3.21	22.00	6.85	1.98
NSM2	5.10	16.39	3.21	3.00	17.00	5.67	1.77

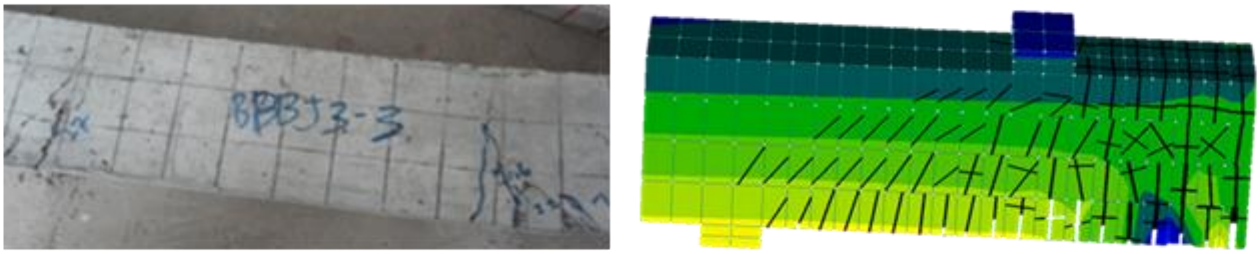
*Finite element analysis result to the experimental result

3.3 Mode of Failure

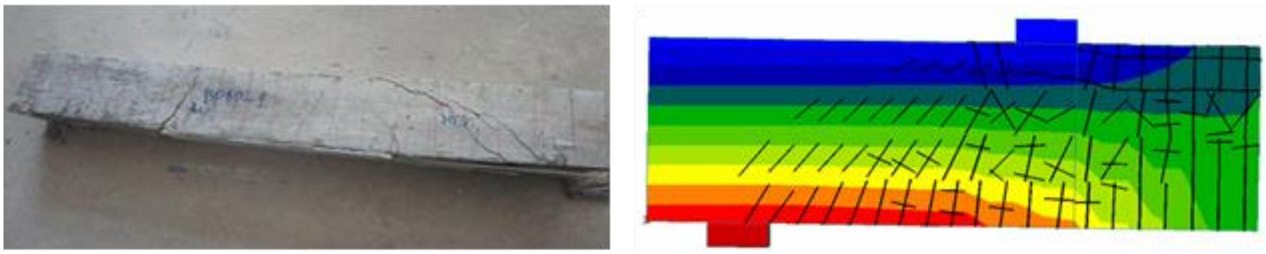
The failure modes of all the beams are shown in Figure 8. The cracking pattern was similar for all the beams, in the results of both the experimental test and the FEA. At first, a fine flexural crack developed at the midspan of the beam. As the external load increased, additional cracks developed at the neutral axis or beyond the neutral axis, with a notable increase in the deflection of the beam. However, all the strengthened beam specimens showed narrower and finer cracks compared to the control beam. The results are due to the greater stiffness of the strengthened beam specimens.



(a)



(b)



(c)

Figure 8 Failure modes of the beams: (a) CB; (b) NSM1; (c) NSM2 [11]

4.0 CONCLUSION

The following conclusions can be derived from the experimental and finite element analytical results:

a. The experimental result shows that the use of NSM strengthening increased the ultimate load of the strengthened beams by 12.46% and 41.74%, while the results of FEA when using the NSM strengthening increased the ultimate load of the strengthened beams by 75.46% and 86.39% for NSM1 and NSM2, respectively, compared with the control beam.
b. The deflection ductility index was reduced by 15.65% and 21.55% in the experimental test results, and it was reduced by 7.96% and 23.90% in the FEA results, for NSM1 and NSM2, respectively, compared with the control beam.
c. The mode of failure observed in all the strengthened beams was a flexural failure.
d. The results of finite element analysis behaved similarly to those of the experimental test.

Acknowledgements

The authors express their gratitude and appreciation to the Research and Public Services Institution (LPPM) of Jenderal Soedirman University for funding this study through the Institutional Research Scheme, and to Rahmat Agung Triono and Agung Aryandi who provided assistance so that this study accomplished its goals. The authors also thank the anonymous reviewers, whose comments greatly improved the paper.

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