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Nonlinear finite element analysis of traditional flexural strengthening using betung bamboo (*Dendrocalamus asper*) on concrete beams

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Abstract. Structural failure, which can be caused by design miscalculation or changes in the building's function, can be dangerous if left untreated. Consequently, structural strengthening is done by providing steel plates, fiber-reinforced-polymer, or in the traditional way using bamboo fibers. In this study, a numerical calculation for bamboo strengthening using the FEM method is conducted. Bamboo strengthening was installed on concrete beams and attached using mortar. The analysis was carried out with ATENA software dealing with beam specimens, namely Control Beam (BC) and Bamboo-strengthened Beam using M13 and M20 mortar (BB13 and BB20). The materials used are CC3DNonLinCementitious2 and CCD3DBiLinearSteelVonMises for concrete and bamboo, respectively. The concrete and mortar use the fracture concept of a uniaxial stress-strain law and the constitutive model of the bamboo is based on a linear stress-strain law. The results of comparing the numerical and experimental results for the load-carrying capacity ratio are 0.96, 0.90, 0.77 for BC, BB13, and BB20, respectively. The crack pattern of the specimens shows that collapse is by flexural cracking starting from the mid-span. This is in accordance with previous laboratory results. In conclusion, the analyses using ATENA program and experimental methods show the appropriate results.

1. Introduction

Nowadays structural damage is increasingly common in buildings. This damage may be caused by a change in the building's function or by a miscalculation in the previous design. Aside from these factors, the seismic design regulations in Indonesia have changed from Indonesian Code 03-1726-2002 to the new 2012 Indonesian Code, something which must be taken into account [1]. The new provision modifies the Indonesian earthquake zone mapping, the seismic design criteria, and the calculation of the spectrum response [2]. These parameters were not mentioned in the old seismic code. With these new parameters for seismic load-carrying calculations, all the structural members designed based on the previous code must be reviewed [3–7]. The earthquake force results in an additional burden on the structure of the building, so that it is necessary to strengthen the building so that it can withstand this additional load. Therefore, there is a need for strengthening structural elements to avoid or anticipate the failure of the elements themselves. Furthermore, considerations of efficiency and budgetary constraints make the alternative of strengthening preferable to replacement with a new structure [8]. However, experimental research in the laboratory requires more complicated steps and needs a long time to prepare the specimens. An alternative to this is an analysis using the method of Finite Element Analysis (FEA).

FEA with computer programs will produce an approach to analyzing the structural behavior. One of the FEA-based software programs used to analyze concrete structural behavior is ATENA. Numerical analysis based on FEA using ATENA has been conducted by Haryanto *et al.* [9–11], Jati [12], and Jirawattanasomkul *et al.* [13]. The basics of the concrete constitutive model in ATENA use the concept of smeared crack and fracture mechanics with stress reactions occurring based on the concept of uniaxial stress–strain law damage. This law explains that concrete failure due to monotonic loading with peak stress is determined based on the biaxial failure surface [14].

This research is focused on analyzing the behavior of concrete strengthened with betung bamboo (*Dendrocalamus asper*), attached using mortar cement. This mortar is used as the bonding agent to replace epoxy on the concrete and betung bamboo fiber replaces fiber reinforced polymer as the strengthening material. The strengthening method is carried out by coating the existing concrete beams with mortar layers and betung bamboo fibers which are then re-coated with mortars [15, 16].

Haryanto *et al.* [10] investigated the flexural strengthening of RC beams by using the Near Surface Mounted (NSM) method of bamboo reinforcement, through both FEM Analysis and experimental tests. The results of the experiments and the FEA are similar. The flexural strength of beams with NSM bamboo strengthening increased by 41.7% and the ductility index was reduced by 21.55%. The crack pattern and failure mode observed in both simulation and experiment also show the same result: it was a flexural failure.

Pamuji [16] carried out an experimental investigation of bamboo strengthening on flexural beams by using mortar cement as the bonding agent to investigate the behavior of bamboo-strengthened beams. The increase of flexural strength as an effect of the bamboo strengthening was about 30%, compared to the control beams. The crack pattern that occurred on all beam specimens showed damage of the outer fiber concrete on the middle span.

2. Finite element analysis

The analysis program is based on previous experimental research on the laboratory [16]. This data is in the form of physical properties (cross-sectional area and the length) and material characteristics (the concrete's stress–strain diagrams and compressive strength, the compressive strength of the mortar, and the tensile strength of the bamboo). FEA was performed by using a limited version of ATENA, which can be used to carry out a numerical modeling with up to 200 elements [9–11, 14, 17]. The material properties of each material in the concrete beam specimens are shown in table 1. It is used as a comparison to the results of numerical analysis by ATENA.

All of the specimens (figure 1 and figure 2) that were used included one control beam and two samples of bamboo-strengthened beams, one each using M13 and M20 mortar. The modeling was carried out with the concept of three-dimensional coordinates using GID 7.4 as the pre-processor. Two variants of the models were used: a quarter-span model and a half-span model, due to the symmetry of the concrete beam specimens.

All components of the specimens were assumed to have a perfect bond condition. The plan of meshing of the specimens could not exceed a total number of 200 elements, since the student version of ATENA only provides a maximum number of meshing elements of 200 for 3-D analysis. This is shown in figure 3. The concept of smeared cracking and the fracture mechanics approach was used in the basic constitutive model of concrete in ATENA. Figure 4 explains the fracture of the concrete under monotonic loading; this is based upon the fracture concept of a uniaxial stress–strain law. The constitutive model of the bamboo is based on a linear law, as shown in figure 5.

An 8-node solid element, of the material type CC3DNonLinCementitious2, was used to model the concrete and mortar. This element assumes a hardening region before the compressive strength of the material is reached but only a purely incremental formulation is used, therefore it can be used in creep calculations or with changing material properties during the analysis process [14]. However, in modeling the bamboo material, CCD3DBiLinearSteelVonMises was used as the constitutive model in the program.

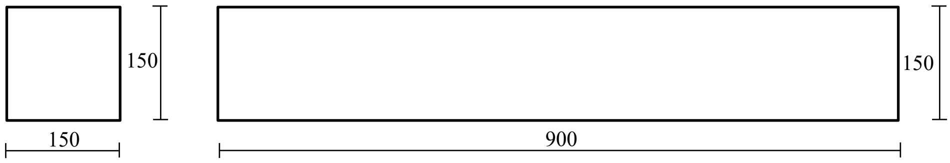


Figure 1. Control Beam (BC).

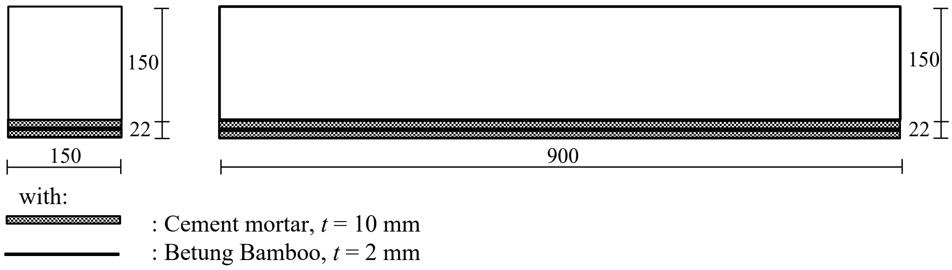
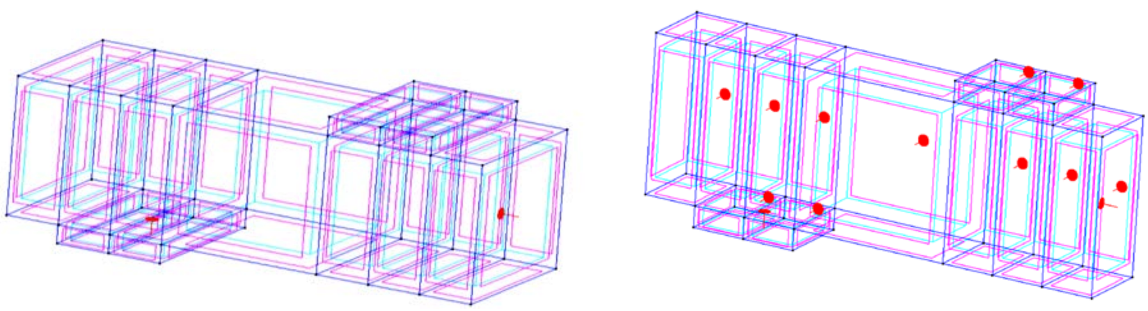


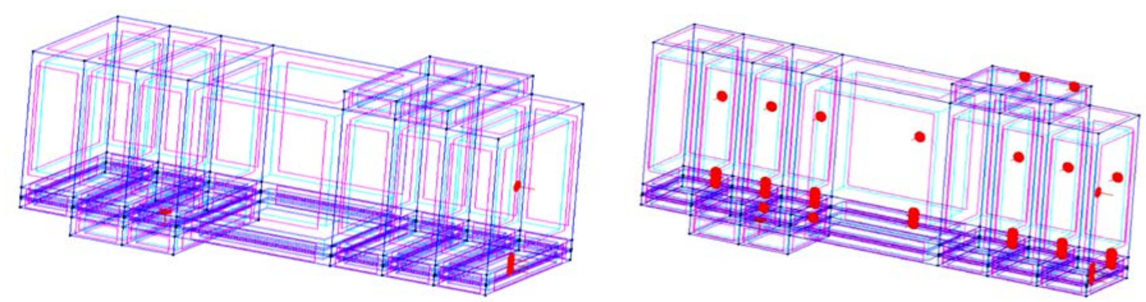
Figure 2. Bamboo-strengthened Beam (BB13 and BB20).

Table 1. Material properties of each component.

Parameters	Concrete	Mortar M13	Mortar M20	Bamboo	Unit
Compressive strength, f_c	20.13	13.12	20.81		MPa
Modulus of elasticity, E	21795.67	18925.551	22045.16	2000	MPa
Poisson's ratio, υ	0.2	0.2	0.2		
Tensile strength, f_t	2.24	1.811	2.28	152	MPa
Fracture energy, G_f	5.61 x 10^{-5}	4.527 x 10^{-5}	5.7 x 10^{-5}		MN/m
Fixed crack	0.7	0.7	0.7		
Plastic strain, ε_{cp}	-0.000924	-0.000693	-0.000944		
Onset of crushing, f_{cu}	6.039	3.936	6.243		MPa
Critical compressive displacement, w_d	-0.0005	-0.0005	-0.0005		M
Eccentricity, e	0.52	0.52	0.52		
Density, γ	0.024	0.024	0.024		MN/m^3
Thermal expansion, α	0.000012	0.000012	0.000012		



(a) BC with half-span model (b) BC with quarter-span model



(c) BB with half-span model (d) BB with quarter-span model

Figure 3. Application of boundary conditions.

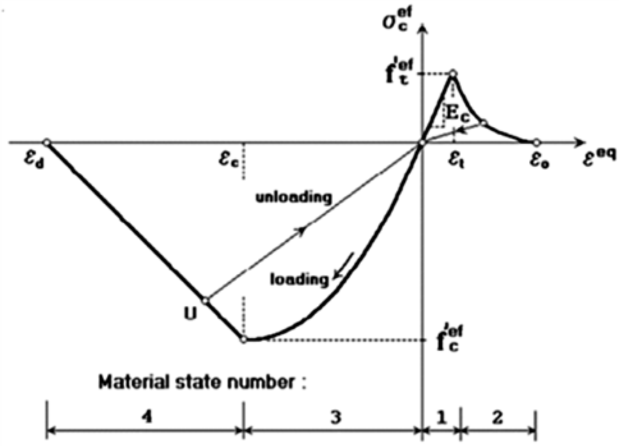


Figure 4. Uniaxial stress–strain law for concrete.

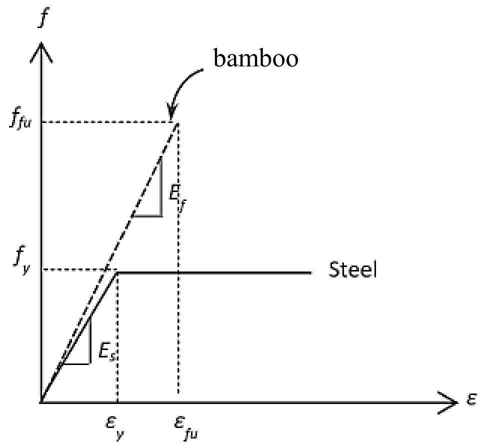


Figure 5. Linear stress–strain law for bamboo.

3. Results and analysis

3.1. The load–displacement (P–Δ) relation

Based on the results from the FEA conducted using ATENA, a graph for the load versus mid-span displacement could be made, then compared with the results from experimental tests. A graphical comparison of the control beam is shown in figure 6, and for the bamboo-strengthened beam with mortars M13 and M20 as the bonding agent, is shown in figure 7. It can be observed that the numerical calculations provided behavior similar with that of the experiments. However, the graph from the numerical analysis shows a slightly lower ultimate load compared to the experimental graph.

Under real conditions, the strength of a concrete member is not homogeneous through the member's depth [9–11, 18]. There were some slope differences between FEA and experimental results, since in the numerical analysis, all segments possess homogenous material properties [9–11]. The differences may also be caused by the material bonding assumption in the numerical method, which was that of being perfectly attached with a perfect bond, however, a slip may occur in the experimental tests. Also, the uniformity in the material does not occur in the experimental specimens, nevertheless, the concrete, mortar, and bamboo fiber were assumed to be uniform in material quality for each specimen.

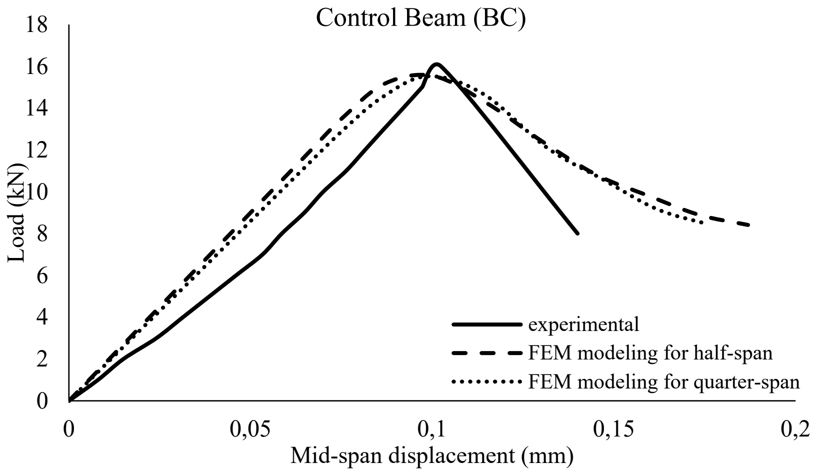
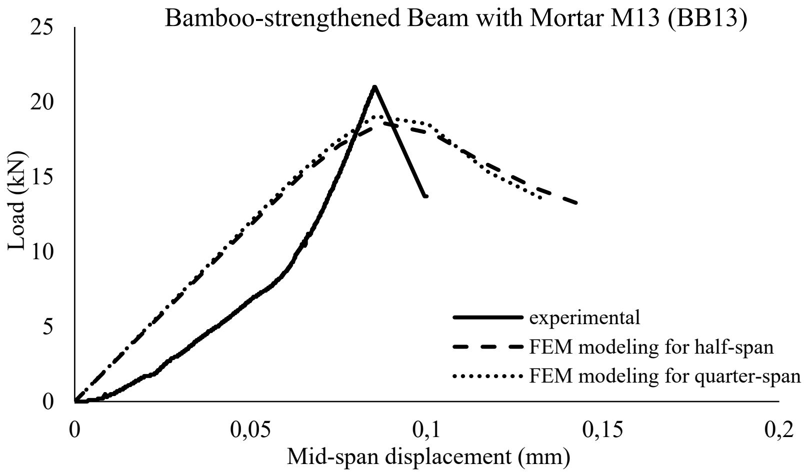
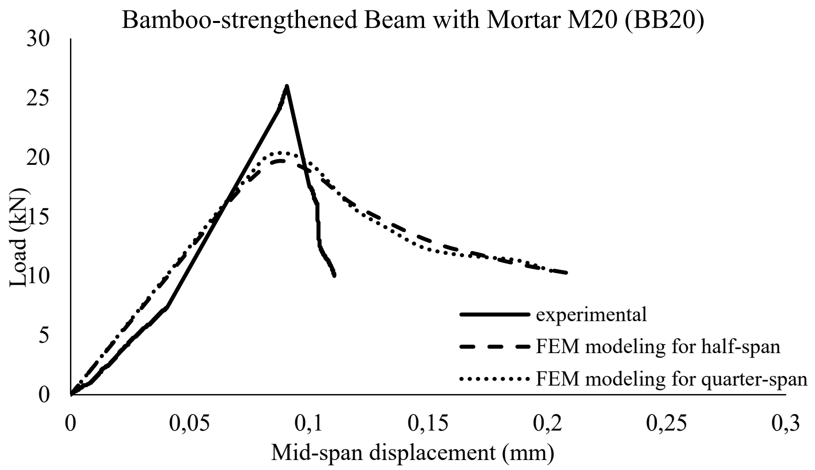


Figure 6. Load–displacement relationship of control beam.



(a)



(b)

Figure 7. Load–displacement relationship of bamboo-strengthened beam: (a) with mortar M13 (BB13); (b) with mortar M20 (BB20).

Table 2 shows the comparison of the experimental test results with the results of the FEA conducted with ATENA. It can be seen that in the experimental results, the presence of a bamboo strengthening system with mortars M13 and M20 could increase the ultimate load by up to 28.57% and 60.25%, compared to the control beam, respectively. The bamboo fibers caused an increase in the tensile component in the beam cross-section, then this causes an increase in the moment capacity of the beam cross-section, which means it also causes an increase in the load capacity. However, in the results of the numerical analysis, a smaller percentage value of the ultimate load increment was obtained: 19.71% and 22.70% for the half-span and quarter-span models of BB13 and 26.64% and 30.56% for BB20, respectively. It can be observed from table 2 that the ultimate load average ratios between the FEM analysis and the experimental test results are 0.96, 0.90, and 0.77 for BC, BB13, and BB20, respectively.

Table 2. Ultimate load *Pu* of the beams.

Codes	Experimental		FEM Analysis					
			Half-span model			Quarter-span model		
	Ultimate Load *Pu* (kN)	% *Pu*	Ultimate Load *Pu* (kN)	% *Pu*	Ratio	Ultimate Load *Pu* (kN)	% *Pu*	Ratio
BC	16.10	–	15.53	–	0.965	15.53	–	0.964
BB13	20.70	28.57	18.59	19.71	0.898	19.05	22.70	0.920
BB20	25.80	60.25	19.67	26.64	0.762	20.27	30.56	0.786

3.2. Crack and failure modes

The failure mode of the BC, BB13, and BB20 beam specimens in experimental program and FEA modeling can be seen in figures 8–11. The cracking behavior of each beam was similar, for both the experiments and the numerical calculations. For the beam specimens of a normal concrete that has no steel reinforcement, the beam experienced cracks at the maximum load. The beam collapse with flexural cracking started from the middle span of the beam then spread towards the loading as the external loading increased. These cracks are in line with the increase of the displacement at the mid-span of the beams.

(a) Control beam (BC)

(b) Beam bamboo with mortar M13 (BB13)

(c) Beam bamboo with mortar M20 (BB20)

Figure 8. Crack patterns for beam specimens in experimental tests.

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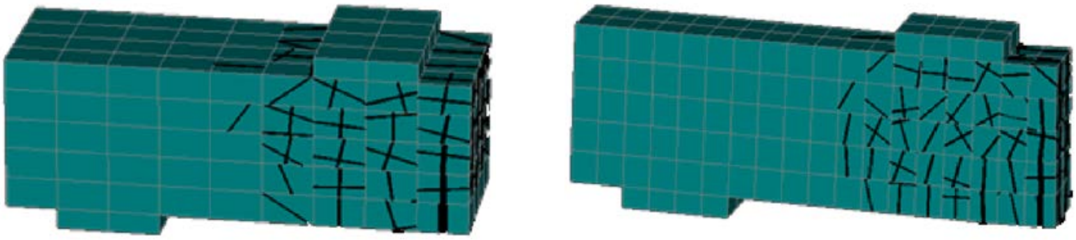
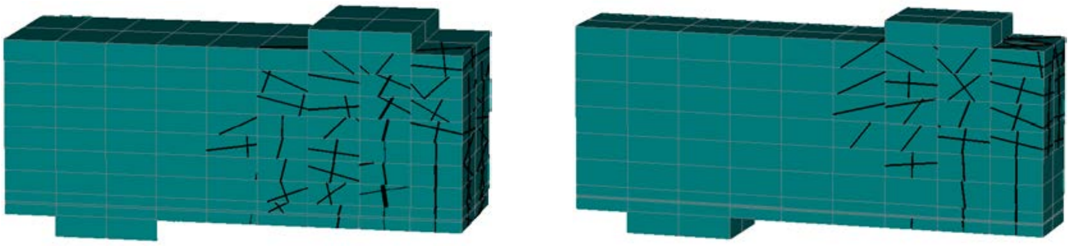
Moreover, the failure of the strengthened beams (BB13 and BB20) occurred after the concrete beam had cracked and there was a de-bonding of the mortar from the concrete beams. Despite the de-bonding, the betung bamboo fibers were still attached to the mortar and were able to hold together the concrete beams that had collapsed. In the final results, the bamboo-strengthened beam specimens had narrower cracks than the control beam, due to the greater stiffness of the strengthened beam specimens. This is in accordance with the results of Haryanto *et al.* [10].



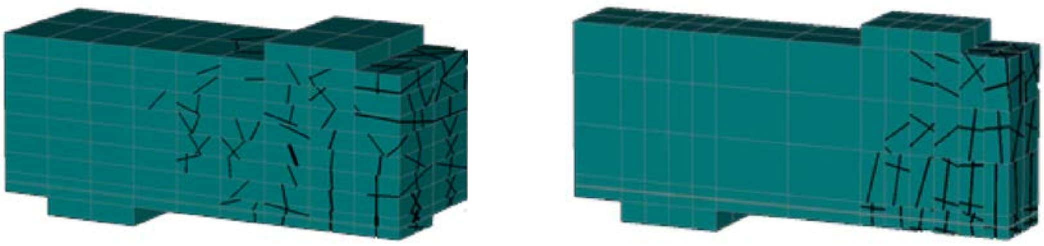
(a) Half-span model (b) Quarter-span model

Figure 9. Crack patterns for control beams (BC) in numerical calculations.



(a) Half-span model (b) Quarter-span model

Figure 10. Crack patterns for bamboo-strengthened beams with mortar M13 (BB13) in numerical calculations.



(a) Half-span model (b) Quarter-span model

Figure 11. Crack patterns for bamboo-strengthened beams with mortar M20 (BB20) in numerical calculations.

4. Conclusion
Based on the experimental and numerical results, some conclusions may be drawn:

- The presence of bamboo can increase the load-carrying capacity by up to 28% and 60% for BB13 and BB20 compared to BC in the experimental results. Meanwhile, in the FEM analysis, the ultimate load could only increase by up to 22% and 30% for BB13 and BB20, compared to BC.

- The failure modes shown in both the experimental results and the numerical calculations was a flexural failure, starting from the mid-span of the beams and spreading towards the loading position as the external loading increased.
- The crack patterns found by FEA were similar to those from the experiments.

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References
[1] Tudjono S, Han A L and Hidayat B A 2015 *Proc. Eng.* vol 125 pp 1070–5
[2] Tudjono S, Han A L and Gan B S 2017 *Proc. Eng.* vol 171 pp 1123–8
[3] Tudjono S, Han A L, Hidayat A and Purwanto 2017 *Proc. Eng.* vol 171 pp 1116–22
[4] Haryanto Y, Sudibyo G H and Effendi F C A 2017 *Proc. Eng.* vol 171 pp 1025–34
[5] Haryanto Y, Gan B S., Wariyatno N G, and Indriyati E W 2017 *ARPN JEAS* **12** 4858–66
[6] Haryanto Y, Gan B S., Wariyatno N G and Indriyati E W 2018 *MATEC Web of Conf.* vol 192
[7] Widyaningrum A, Haryanto Y and Hermanto N I S 2018 *MATEC Web of Conf.* vol 195
[8] Yanuar Y, Gan B S, Widyaningrum A, Wariyatno N G and Fadli A 2018 *J. Teknol. (Sci. and Eng.)* **80** 145–54
[9] Haryanto Y, Gan B S and Maryoto A 2017 *Int. J. Tech.* **8** 134–44
[10] Haryanto Y, Gan B S, Widyaningrum A and Maryoto A 2017 *J. Teknol. (Sci. and Eng.)* **79** 233–40
[11] Haryanto Y, Hu H T, Han A L, Atmajayanti A T, Galuh D L C and Hidayat B A 2019 *J. Teknol. (Sci. and Eng.)* **81** 143-154
[12] Jati D G 2013 *Konferensi nasional teknik sipil 7 Proc.* (Surakarta, Indonesia: Sebelas Maret University)
[13] Jirawattanasomkul T, Kongwang N, Jongvivatsakul P and Likitlersuang S 2018 *Composites Part B* **154** 33–42
[14] Červenka V, Jendele L and Červenka J 2018 *ATENA Program Documentation Part 1: Theory* (Prague, Czech Republic: Cervenka Consulting)
[15] Haryanto Y, Wariyatno N G and Sudibyo G H 2013 *Konferensi nasional teknik sipil 7 Proc.* (Surakarta, Indonesia: Sebelas Maret University) pp S149–55
[16] Pamuji A Y 2013 *Perilaku lentur balok beton dengan perkuatan bambu petung dan perekat berbahan dasar semen* Undergraduate thesis (Purwokerto, Indonesia: Jenderal Soedirman University)
[17] Al Faridi S 2010 *Analisis non-linie elemen hingga struktur balok beton prategang dua bentang* Master thesis (Yogyakarta, Indonesia: Gadjah Mada University)
[18] Hidayat A, Purwanto, Puspowardojo J and Aziz F A 2015 *Proc. Eng.* vol 125 pp 1023–9