International Journal of Technology (2017) 1: 134-144
ISSN 2086-9614

WIRE ROPE FLEXURAL BONDED STRENGTHENING SYSTEM ON RC-BEAMS: A FINITE ELEMENT SIMULATION

Yanuar Haryanto[1*], Buntara Sthenly Gan[2], Agus Maryoto[1]

[1]*Department of Civil Engineering, Jenderal Soedirman University, Purwokerto 53122, Indonesia*
[2]*Department of Architecture, College of Engineering, Nihon University, Koriyama 963-8642, Japan*

(Received: December 2015 / Revised: December 2016 / Accepted: January 2017)

ABSTRACT

We conducted a finite element simulation by using a computer program, ATENA, to verify the behavior of T-section reinforced concrete beams strengthened by bonded wire ropes in the negative moment region with a pretensioned initial prestressing force; we compared this behavior with that in experimental tests. The simulation was performed on five models consisting of one unstrengthened beam and beams strengthened by wire ropes with initial prestressing forces of 0%, 10%, 20%, and 30%. We found that the capacity of a flexural load had the ratios to the experimental results close to 1 — that is, 1.25, 1.16, 1.12, 1.01, and 1.10, for UB, SB1, SB2, SB3, and SB4, respectively. The ratios of effective stiffness, as the result of the simulation, to the experimental results were 1.45, 1.08, 1.76, 2.13, and 2.46 for UB, SB1, SB2, SB3, and SB4, respectively. We also observed that crack propagation developed in the finite element simulation indicated that all models underwent flexural failure.

Keywords: ATENA; Finite element simulation; Reinforced concrete; Strengthened; Wire rope

1. INTRODUCTION

Structural elements need to be strengthened; one example is using wire rope to improve their structural capacity so that the possibility of collapse due to an additional load can be prevented. Although wire rope does not grip the structural element, Raoof and Davies (2003) stated that such rope was a little more flexible axially than a spiral strand but considerably more flexible in bending. Such flexibility is why wire ropes are used as tractive elements in pulleys, winch drums, and fairleads in mines and cable cars (among others). The potential of using wire ropes in concrete structures is based on the idea of utilizing their advantages, including high tensile strength. Previous studies have shown that a larger rope diameter and higher concrete strength lead to a higher modulus of elasticity of the concrete steel-wire ropes (Avak & Willie, 2005). A study by Yang et al. (2011) proved that beams with spiral-type wire ropes developed a higher shear capacity than control beams with closed stirrups, showing that the shear capacity of beams increased with the increase in the number of wire ropes.

Yang et al. (2009a) proposed a relatively simple column-strengthening procedure using unbonded wire rope and T-shaped steel-plate units. The measured axial load capacities of all strengthened columns were higher than the predictions obtained from ACI 318-05, indicating that the ratio of the measured and predicted values increased with the increase of the volume ratio of wire ropes and flange width of T-shaped steel plates. Yang et al. (2009b) also tested a series of reinforced concrete continuous T-beams externally strengthened with unbonded wire

*Corresponding author's email: yanuar_haryanto@yahoo.com, Tel./Fax. +62-281-630696
Permalink/DOI: https://doi.org/10.14716/ijtech.v8i1.2734

ropes and concluded that the ultimate shear capacity of beams strengthened with closed-type wire ropes increased with the increase in the amount and prestressing force of wire ropes, whereas that of beams with U-type wire ropes was little influenced by the amount and prestressing force of wire ropes. Wire ropes were also previously tested as flexural strengthening materials, and it was shown that if the stiffness of wire ropes was not improved, their contribution was suboptimal (Haryanto, 2011; Atmajayanti et al., 2013; Galuh, 2015). A follow-up study to improve the effectiveness of using them by applying the initial prestressing force was also conducted (Haryanto et al., 2013).

The finite element simulation was able to verify the experimental results (Han et al., 2016). In this study, we conducted a finite element simulation by using a computer program, ATENA, to verify the behavior of T-section reinforced concrete beams strengthened by bonded wire ropes in the negative moment region with a pretensioned initial prestressing force; we compared this behavior with that in experimental tests. A study using a finite element simulation can overcome the constraints related to time, cost, and tools. Studies applying a finite element simulation to the behavior of concrete structures have also been conducted previously by Maryoto and Shimomura (2015), and Maryoto et al. (2015). ATENA (Cervenka et al., 2014) is one of the finite element simulation programs used by many researchers (Pangestuti & Effendi, 2010; Sukarno et al., 2011; Jati, 2013) and is considered to give results that are very close to the results of experimental tests. A simulation in this paper was performed by modeling the experimental test specimens by Haryanto (2011) and Haryanto et al. (2013) by using the demo versions of GiD 7.4 and ATENA 2.1.10 as a preprocessor and a postprocessor, respectively.

2. METHODOLOGY

The basis of the concrete constitutive model in ATENA used the concept of smeared cracking and the approach of fracture mechanics with strain reactions that occurred based on the fracture concept of the uniaxial stress-strain law. The law explains that concrete fractures due to monotonic loading with peak tension are determined based on the biaxial failure surface, as shown in Figure 1 (Cervenka et al., 2014). The steel constitutive model in ATENA used a multilinear law, as shown in Figure 2 (Cervenka et al., 2014). Meanwhile, the wire rope constitutive model assumed to be linear.

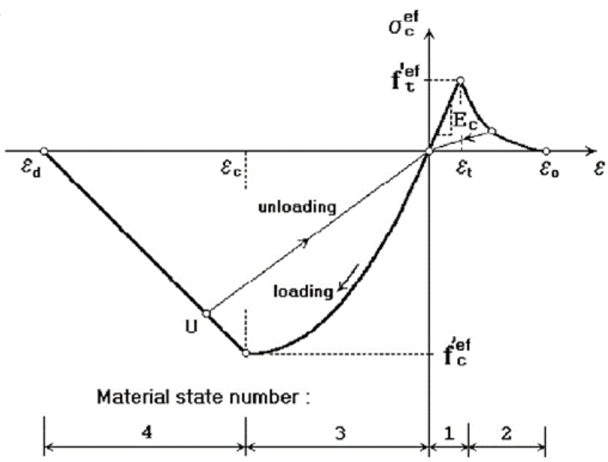


Figure 1 Uniaxial constitutive law for concrete (Cervenka et al., 2014)

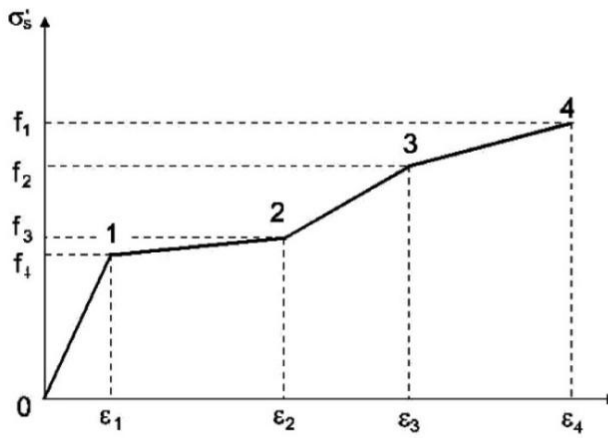


Figure 2 Multilinear constitutive law for steel (Cervenka et al., 2014)

The model simulated in this paper referred to the experimental test specimens (Haryanto, 2011; Haryanto et al., 2013). The wire rope consisted of six typical strands laid helically over a central core — which may itself consist of a smaller independent wire ropes (IWRC), as seen in Figure 3 — were used as a flexural bonded strengthening system. Specifications of the experimental test specimens are presented in Table 1, and the sections are presented in Figure 4. The simulation was done for half of a symmetrical beam, as seen in Figure 5. This was done due to the limited meshing that can be carried out by the demo version of ATENA, that is, a maximum of 200 elements. An 8-noded solid element, *CC3DnonLinCementitous2*, was used to simulate the concrete and mortar. Longitudinal reinforcement and wire ropes were simulated using *CCReinforcement* elements. Two nodes were required for this element. Loading and support plates were simulated using the 8-noded solid element *CC3DElastIsotropic*. The concrete with stirrups was simulated using the 8-noded *CCCombinedMaterial* element. The materials and type of elements used in this simulation are summarized in Table 2.

Table 1 Specifications of experimental test specimens (Haryanto et al., 2013)

Codes	L (mm)	bf (mm)	tf (mm)	bw (mm)		Longitudinal reinforcement		Stirrup		Wire rope	Prestressing force (%)
						Top	Bottom	Edge of span	Center of span		
UB	2400	400	75	150	175	3D13	2P8	P8-40	P8-100	–	–
SB1	2400	400	115	150	175	3D13	2P8	P8-40	P8-100	2ϕ10	0
SB2	2400	400	115	150	175	3D13	2P8	P8-40	P8-100	2ϕ10	10
SB3	2400	400	115	150	175	3D13	2P8	P8-40	P8-100	2ϕ10	20
SB4	2400	400	115	150	175	3D13	2P8	P8-40	P8-100	2ϕ10	30

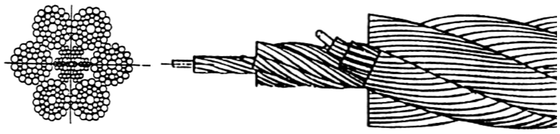
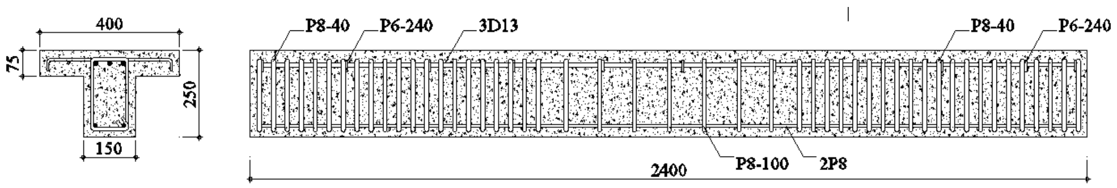
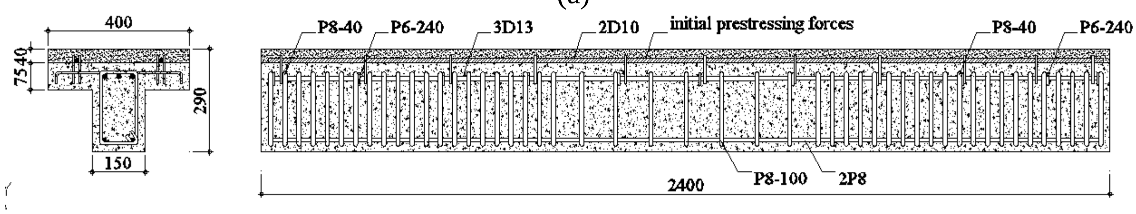


Figure 3 An independent wire rope core (IWRC) (Lee, 1991; Raoof & Davies, 2003)



(a)



(b)

Figure 4 Experimental test specimens: (a) unstrengthened beam; (b) strengthened beam (Haryanto, 2011; Haryanto et al., 2013)

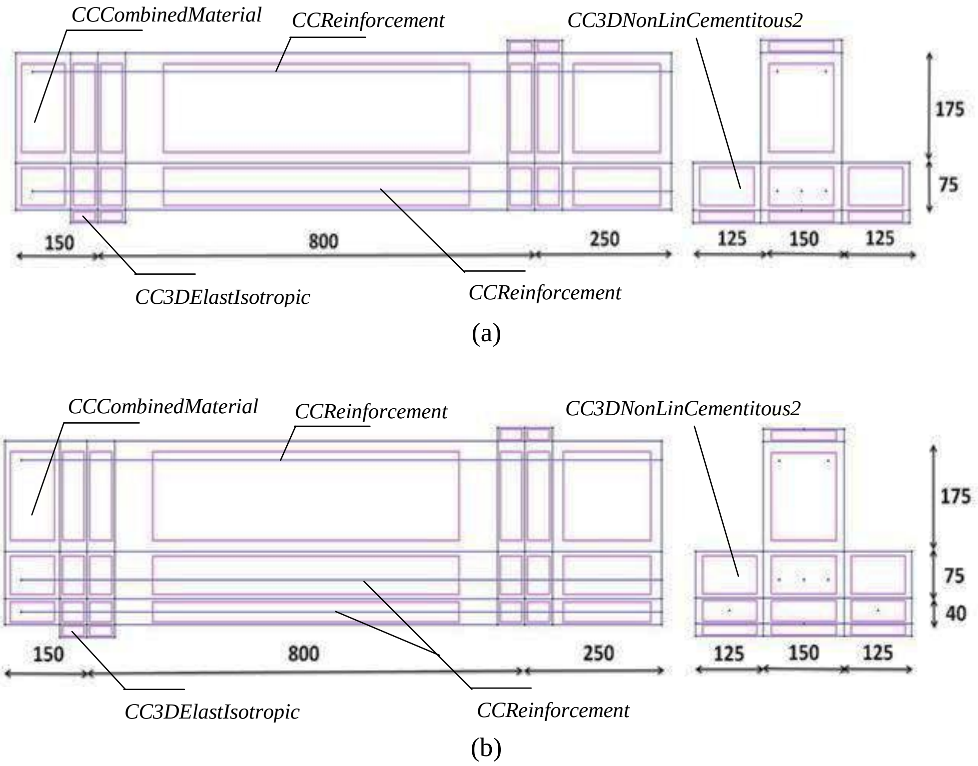


Figure 5 Models of finite element simulation for half of a section: (a) unstrengthened beam; (b) strengthened beam

The application of constraint conditions in the simulation 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 using *constraint for surface* to the surface. This application was because the simulation was done for only half of the section. The constraint conditions applied can be seen in Figure 6.

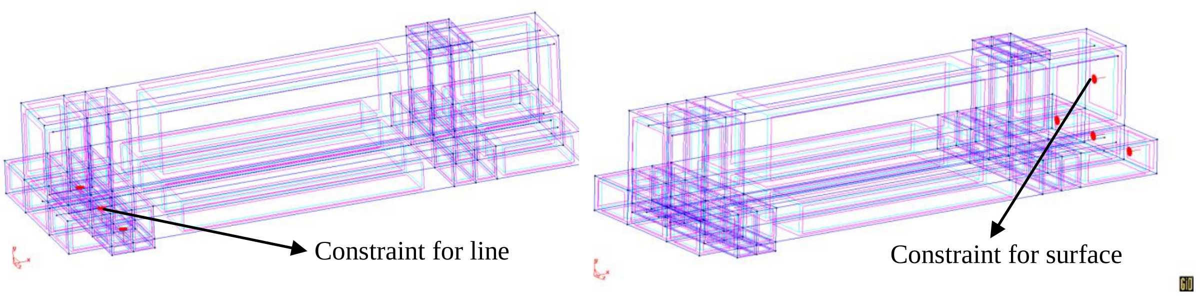


Figure 6 The application of constraint conditions

Table 2 Materials and types of elements

Materials	Element type	Properties	Data
Concrete	*CC3DnonLinCementitous2*	Compression strength	37.54
		Young's modulus, E_c	27545.489
Mortar	*CC3DnonLinCementitous2*	Compression strength	48.52
		Young's modulus, E_c	30025.891
Reinforcement P8	*CCReinforcement*	Young's modulus, E_s	201624
		Ultimate stress, f_u	525.33
		Yield stress, f_y	373.85
		Area of reinforcement, A	0.00005024
Reinforcement D13	*CCReinforcement*	Young's modulus, E_s	197664
		Ultimate stress, f_u	742.52
		Yield stress, f_y	479.71
		Area of reinforcement, A	0.000132665
Wire rope	*CCReinforcement*	Young's modulus, E_s	32568
		Ultimate stress, f_u	743.73
		Yield stress, f_y	-
		Area of reinforcement, A	0.0000785
Concrete stirrup P8-40	*CCCombinedMaterial*	Area of shear reinforcment, A_v	0.0008038
		Ratio of direction x reinforcement (1)	0.0032154
		Ratio of direction y reinforcement (2)	0.0053589
		Ratio of direction z reinforcement (3)	0
Concrete stirrup P8-100	*CCCombinedMaterial*	Area of shear reinforcment, A_v	0.0003517
		Ratio of direction x reinforcement (1)	0.0014067
		Ratio of direction y reinforcement (2)	0.0023445
		Ratio of direction z reinforcement (3)	0
Loading and support plates	*CC3DElastIsotropic*	Young's modulus, E_s	200000
		Poisson's ratio, v	0.3

A convergence study by Al Faridi (2010) concluded that the optimal number of elements in ATENA is 1056. Since the demo version of ATENA provided a maximum of only 200 elements for the 3-D analysis, the meshing had to be done thoroughly so that the number of elements made did not exceed the limit of a maximum number of meshing elements. The plan of meshing the unstrengthened beam and strengthened beam models, shown in Figures 7 and 8, exceeded the total number of 197 and 193 elements, respectively. To discover the response that occurred in the model, 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.

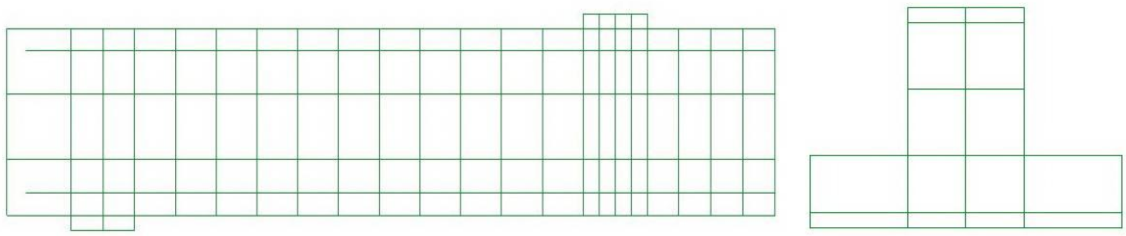


Figure 7 The plan of meshing in the unstrengthened beam model

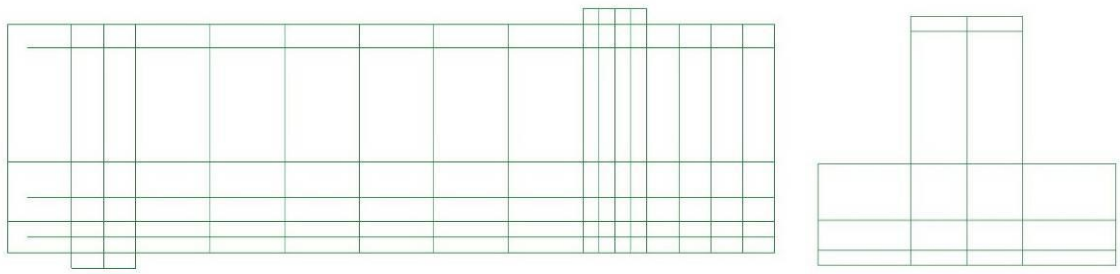


Figure 8 The plan of meshing in the strengthened beam model

3. RESULTS AND DISCUSSION

3.1. Load-displacement Relationship

From the results of the finite element simulation carried out using ATENA, graphs of the load-displacement relationship could be made and were then compared with the results of the experimental tests. The load-displacement relationship resulting from the finite element simulation behaved similarly to the results of the experimental test. The study by Hidayat et al. (2015) previously proved that, in reality, a concrete member is not uniform and does not possess homogeneous strength throughout its depth. Since the properties of materials were homogeneous in all segments in the simulation, there was a consistent difference in its slope between the results of finite element simulation and the results of the experimental test. The graphical comparison of the load-displacement relationship for the unstrengthened beam is presented in Figure 9, and that of the load-displacement relationship for the strengthened beams is presented in Figure 10.

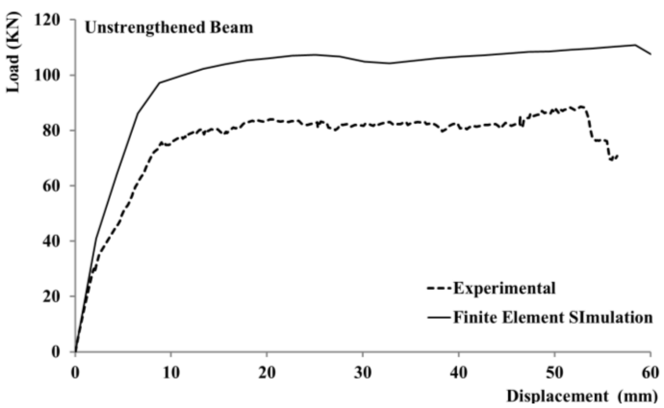


Figure 9 Load-displacement relationship of unstrengthened beam

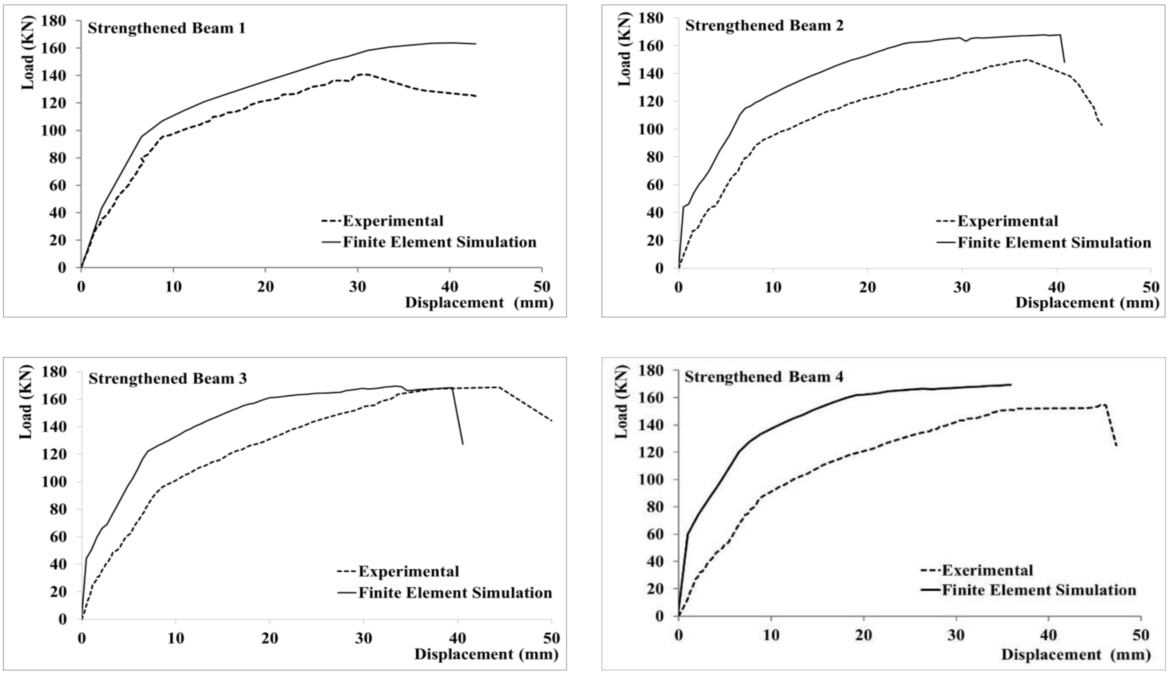


Figure 10 Load-displacement relationship of strengthened beams

3.2. Flexural Load Capacity

The comparison of the flexural load capacity resulting from the finite element simulation and the experimental test is shown in Figure 11. It can be seen that the flexural load capacity resulting from the finite element simulation is higher than that resulting from the experimental test, but the resulting ratios were close to 1 — that is, 1.25, 1.16, 1.12, 1.01, and 1.10 for UB, SB1, SB2, SB3, and SB4, respectively. The difference can be affected by the assumed perfect bond among materials, so the simulation worked well, and no slip occurred during the experimental tests.

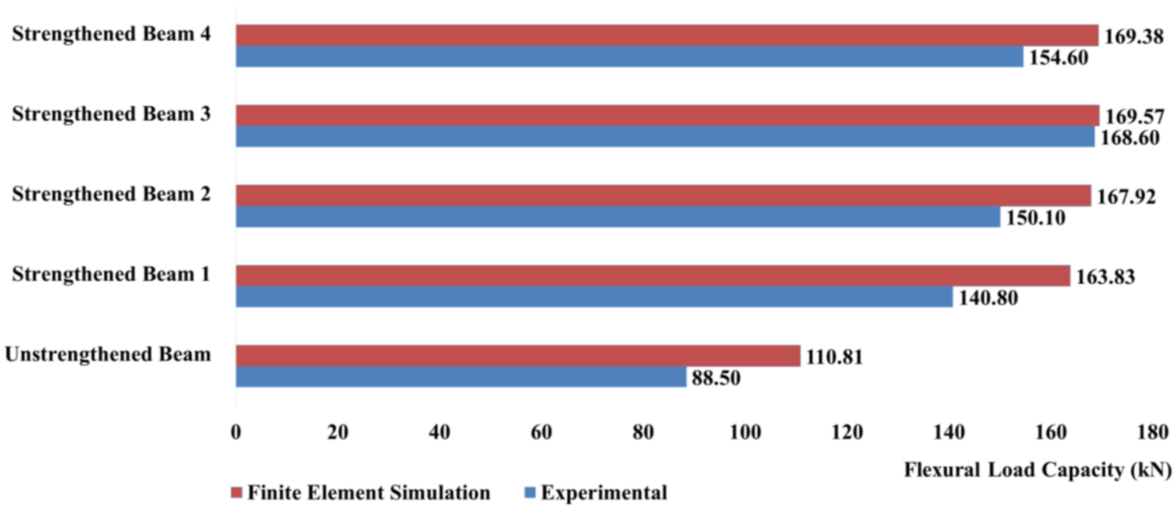
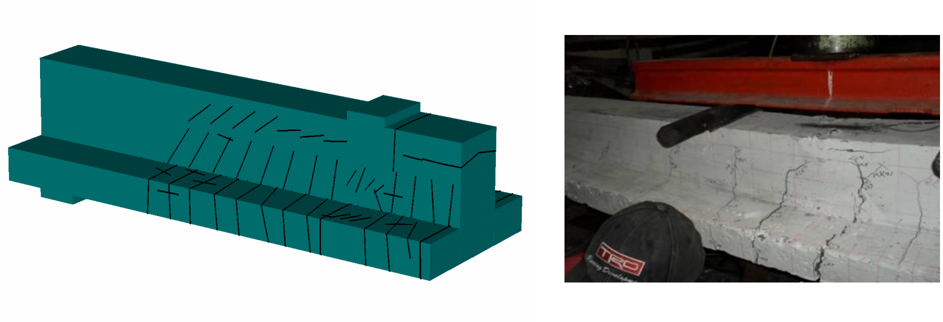
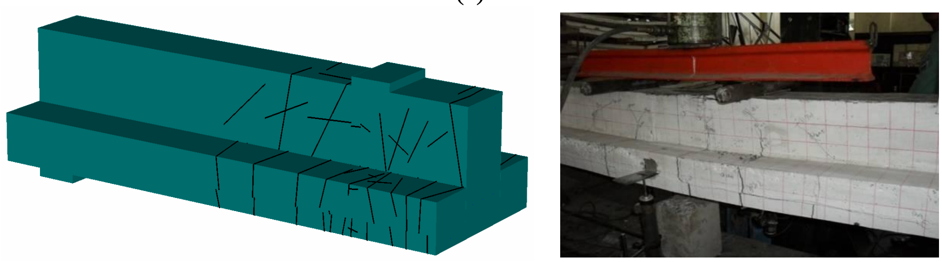


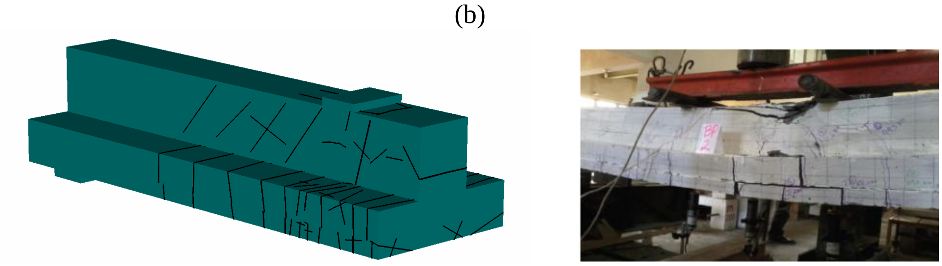
Figure 11 Comparison of flexural load capacity



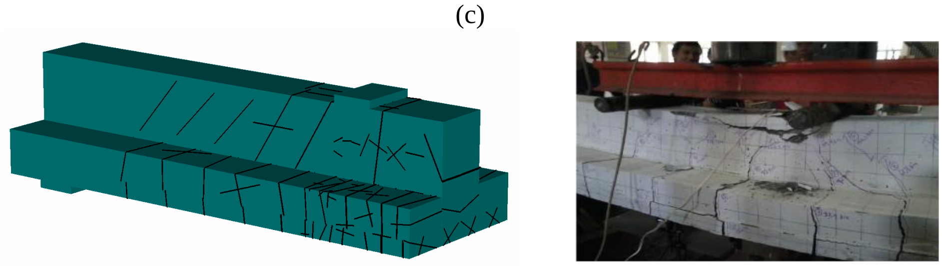
(a)



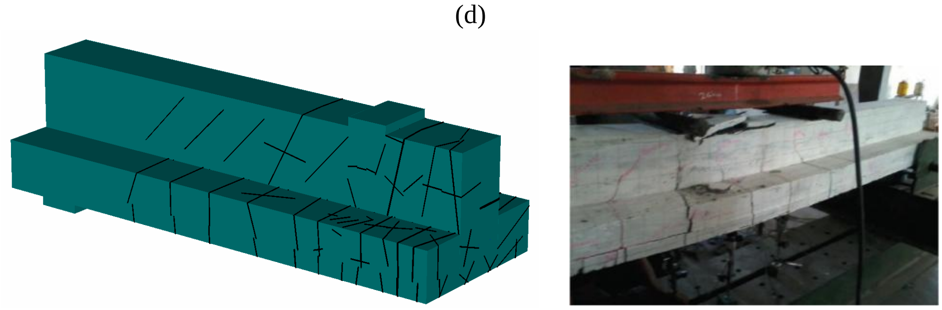
(b)



(c)



(d)



(e)

Figure 12 The cracking patterns: (a) unstrengthened beam; (b) strengthened beam 1; (c) strengthened beam 2; (d) strengthened beam 3; (e) strengthened beam 4 (Haryanto, 2011; Haryanto et al., 2013)

3.3. Stiffness

The comparison of effective stiffness resulting from the finite element simulation and experimental test can be seen in Table 3. It shows that the ratios of effective stiffness resulting from the finite element simulation to the effective stiffness resulting from the experimental test were 1.45, 1.08, 1.76, 2.13, and 2.46 for UB, SB1, SB2, SB3, and SB4, respectively. It was found that the behavior obtained from the finite element simulation was stiffer with an average of 77.60%, relatively high in the context of this study — because there was no bond slip of wire ropes — than that obtained by the experimental test. In addition, Shaker and Kamonna (2016) confirmed that the application of prestressing force resulted in the development of the stiffness of the beams.

Table 3 Comparison of effective stiffness

Codes	Prestressing forces (%)	Results of experimental test	Results of finite element simulation	Ratio
UB	–	9039.84	13139.05	1.45
SB1	0	7963.80	8620.82	1.08
SB2	10	7188.69	12628.08	1.76
SB3	20	7060.30	15044.86	2.13
SB4	30	6751.09	16590.70	2.46

3.4. Cracking Pattern

The first crack in the unstrengthened beam occurred in the area around midspan when the load reached 40.98 kN with a deflection of 2.18 mm. The maximum load of 110.81 kN was achieved with the corresponding deflection of 58.45 mm. Strengthened beam 1 had the first crack at a load of 43.29 kN with a deflection of 2.22 mm. The maximum load of 163.83 kN was achieved with the corresponding deflection of 40.37 mm. The first crack in the strengthened beam 2 occurred when the load reached 44.04 kN with a deflection of 0.51 mm at midspan. The maximum load of 167.29 kN was reached with the corresponding deflection of 31.62. Strengthened beam 3 had the first crack at a load of 44.06 kN with a deflection of 0.48 mm. The maximum load of 169.57 kN was achieved with the corresponding deflection of 33.40 mm. The first crack in the strengthened beam 4 occurred under a load of 60.02 kN with a deflection of 0.96 mm at midspan. The maximum load of 169.38 kN was achieved with the corresponding deflection of 35.91 mm. It was observed that crack propagation developed from the finite element simulation indicated that all models underwent flexural failure. The cracking patterns can be seen in Figure 12.

4. CONCLUSION

It was found that the load-displacement relationship resulting from the finite element simulation behaves similarly to that resulting from the experimental test and had higher accuracy in flexural load capacity, but there was a consistent difference in stiffness between the the results of finite element simulation and the results of the experimental test. The difference can be affected by the assumed perfect bond between materials, so the simulation worked well, and no slip occurred under experimental conditions. Another factor that could affect the difference was that the properties of materials were homogeneous in all segments in the simulation, whereas they could differ in the experimental tests. It was also observed that crack propagation developed in the finite element simulation indicated that all models underwent flexural failure. While the study modeled the beams, it used only the parameters identical to those in the experimental test results. Therefore, the different strength and modulus of elasticity of the materials should be analyzed using finite element simulation for merit further study. Different types of elements and a higher number of meshing elements are candidates for future work.

5. ACKNOWLEDGMENT

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

6. REFERENCES

Al Faridi, S., 2010. Analisis Non-linier Elemen Hingga Struktur Balok Beton Prategang Dua Bentangan. *Master's Thesis*, Gadjah Mada University, Yogyakarta [in Bahasa]

Atmajayanti, A.T., Satyarno, I., Saputra, A., 2013. *Pengaruh Penggunaan Wire Rope Sebagai Perkuatan Lentur Terhadap Kekuatan dan Daktilitas Balok Beton Bertulang Tampang T.* Konferensi Nasional Teknik Sipil 7, Universitas Sebelas Maret, Surakarta, Indonesia [in Bahasa]

Avak, R., Willie, F., 2005. Experimental Investigations and Modeling of Bond between Round Strand Ropes and Concrete. *In*: Proceedings of the 11th International Conference on Fracture (ICF), Turin, Italia

Cervenka, V., Jendele, L., Cervenka, J., 2014. *Atena Program Documentation Part 1*. Theory, Cervenka Consulting, Prague, Czech Republic

Galuh, D.L.C., 2015. The Effectiveness of the Use of Wire Rope Flexural as the Negative Moment Reinforcement in T-sectional Reinforced Concrete Beam. *In*: Proceedings of International Conference on Quality in Research, Lombok, Indonesia

Han, A., Gan, B.S., Pratama, M.M.A., 2016. Effects of Graded Concrete on Compressive Strengths. *International Journal of Technology*, Volume 7(5), pp. 732–740

Haryanto, Y., 2011. Efektifitas *Wire Rope* Sebagai Perkuatan Pada Daerah Momen Negatif Balok Beton Bertulang Tampang T. *Jurnal Dinamika Rekayasa*, Volume 7(2), pp. 36–42 [in Bahasa]

Haryanto, Y., Wariyatno, N.G., Sudibyo, G.H., 2013. Pengaruh Gaya Prategang Awal Terhadap Efektifitas *Wire Rope* Sebagai Perkuatan Daerah Momen Negatif Balok Beton Bertulang Tampang T. *Seminar Nasional Teknik Sipil IX*, Institut Teknologi Sepuluh November, Surabaya, Indonesia [in Bahasa]

Hidayat, A., Purwanto, Puspowadojo, J., Aziz, F.A., 2015. The Influence of Graded Concrete Strength on Concrete Element. *Procedia Engineering*, Volume 125, pp. 1023–1029

Jati, D.G., 2013. Analisis Lentur Pelat Satu Arah Beton Bertulang Berongga Bola Menggunakan Metode Elemen Hingga Non Linier. *Konferensi Nasional Teknik Sipil 7*, Universitas Sebelas Maret, Surakarta [in Bahasa]

Lee, W.K., 1991. An Insight into Wire Rope Geometry. *International Journal of Solids and Structures*, Volume 28(4), pp. 471–490

Maryoto, A., Shimomura, T., 2015. Prediction of Crack Width due to Corrosion of PC Tendon in Prestressed Concrete Structures. *Civil Engineering Dimension*, Volume 17(2), pp. 67–75

Maryoto, A., Hermanto, N.I.S., Haryanto, Y., Waluyo S., Anisa, N.A., 2015. Influence of Prestressed Force in the Waste Tire Reinforced Concrete. *Procedia Engineering*, Volume 125, pp. 638–643

Pangestuti, E.K., Effendi, M.K., 2010. Perilaku Lentur Balok-L Beton Bertulang Berlubang Ditinjau Secara Eksperimental dan Analisis Numerik Memakai *Software* GID-ATENA. *Jurnal Teknik Sipil dan Perencanaan*, Volume 12(2), pp. 121–130 [in Bahasa]

Raoof, M., Davies, T.J., 2003. Simple Determination of the Axial Stiffness for Large Diameter Independent Wire Rope Core or Fibre. *The Journal of Strain Analysis for Engineering Design*, Volume 38, pp. 577–586

Shaker, Q.M., Kamonna, H.H., 2016. Nonlinear Analysis of Reinforced Concrete Beams Strengthened Prestressed CFRP Sheets under Static Loads. *Jordan Journal of Civil Engineering*, Volume 10(1), pp. 93–106

Sukarno, P., Muslikh, Sulsityo, D., 2011. Analisis Lentur Balok Penampang T Berlubang Memanjang Menggunakan Metode Elemen Hingga Non-linier. *Jurnal Ilmiah Semesta Teknika*, Volume 14(1), pp. 1–14 [in Bahasa]

Yang, K.H., Ashour, A.F., Lee, E.T., 2009a. Axial Behaviour of Reinforced Concrete Short Columns Strengthened with Wire Rope and T-shaped Steel Plate Units. *Magazine of Concrete Research*, Volume 61(2), pp. 143–154

Yang, K.H., Byun, H.Y., Ashour, A.F., 2009b. Shear Strengthening of Continuous Reinforced Concrete T-beams using Wire Rope Units. *Engineering Structures*, Volume 31, pp. 1154–1165

Yang, K.H., Kim, G.H., Yang, H.S., 2011. Shear Behavior of Continuous Reinforced Concrete T-beams using Wire Rope as Internal Shear Reinforcement. *Construction and Building Materials*, Volume 25, pp. 911–918