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NUMERICAL SIMULATION OF FLEXURAL RETROFITTING OF T-BEAMS EXPERIENCING FIRST CRACK USING CFRP

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ABSTRACT

Substandard structural maintenance and natural disasters could impair the structure. However, numerous structures could still be utilized even though the safety level and load capacity diminished. Thus, the structure members needed to be strengthened. One of the most widely applied solutions was the use of Carbon Fiber Reinforced Polymeric (CFRP). Therefore, numerical simulation of T-beam strengthened with CFRP in flexural area was important. Because a good agreement results of numerical simulations compared with experimental could reduce cost where numerical simulations could be a tool to carry out further parameter studies without experimental testing. The purpose was to perform a numerical simulation validated by experimental. The idealized components included concrete beams, loads, and supports represented as 3D solid elements. The reinforcing steel was modeled as a truss element and conventional shell element was used for modeling CFRP. Factors such as the strength of reinforcing steel, the number of layers of composite layers, and the interaction between concrete and CFRP were utilized to align the experimental results. The results showed that the difference of yield and ultimate load between numerical simulation and the experimental was less than 5%. Therefore, the result of numerical simulation had a good agreement with the experimental.

Keywords: Numerical simulation, T-Beam, CFRP, Well-validated

ABSTRAK

Pemeliharaan struktur yang tidak memadai serta bencana alam dapat menurunkan kinerja struktur. Meskipun demikian, banyak struktur masih dapat digunakan walaupun tingkat keamanan dan kapasitas bebannya menurun. Oleh karena itu, elemen struktur perlu diperkuat. Salah satu metode yang banyak digunakan adalah Carbon Fiber Reinforced Polymer (CFRP). Simulasi numerik balok T yang diperkuat CFRP pada daerah lentur menjadi penting, karena kesesuaian yang baik antara hasil simulasi dan eksperimen dapat mengurangi biaya serta memungkinkan studi parameter lanjutan tanpa pengujian eksperimental. Penelitian ini bertujuan melakukan simulasi numerik yang divalidasi oleh eksperimental. Komponen yang dimodelkan meliputi balok beton, beban, dan tumpuan sebagai elemen solid tiga dimensi. Tulangan baja dimodelkan sebagai elemen rangka, sedangkan CFRP dimodelkan menggunakan conventional shell. Parameter seperti kuat tarik baja tulangan, jumlah lapisan komposit, serta interaksi beton dengan CFRP divariasikan untuk menyelaraskan hasil demgan eksperimen. Hasil menunjukkan bahwa perbedaan beban leleh dan ultimit antara simulasi numerik dan eksperimental kurang dari 5%, sehingga dapat disimpulkan bahwa simulasi tervalidasi dengan baik dengan hasil eksperimen.

Kata kunci: Simulasi Numerik, Balok T, CFRP, Tervalidasi dengan Baik

1. INTRODUCTION

Earthquakes often happen in Indonesia that is one of a country passed by a ring of fire. It makes structures of building damage. Besides that, poor maintenance can decrease the level of safety of that structure. Thus, the structure needs to be strengthened to increase safety level and load capacity because many buildings still can be reused without changing elements of the structure. Utilizing carbon fiber reinforced polymeric (CFRP) is one of the most often used solutions. Fiber and carbon combine to form CFRP, a material that strengthens and increases load capacity in structures. Consequently, T-beam reinforcement with CFRP added requires numerical simulation, particularly for flexural reinforcement. Since numerical simulations can be used as a tool to conduct more parameter studies without creating additional test objects, they

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can lower the cost of testing when they are well-validated by experimental testing.

Tudjono and Hidayat (2015) conducted experimental testing of T-beams reinforced with fiber-reinforced polymer (FRP). Tests were carried out using a three-point bending test. The results of this study were in the form of failure modes and load-deflection curves. From these results, it could be concluded that the T-beam reinforced with FRP had increased in shear and flexural strength. Mulyanto (2020) conducted a study that aimed to determine the behavior of CFRP-reinforced T-beams in the flexural section. Tests were using four-point bending. The variables analyzed were ductility, flexural stiffness, flexural load capacity, crack, and failure patterns.

Finite element modeling has been widely employed to predict the cracking behavior and ultimite capacity of reinforced concrete (RC) beams. Previous studies demonstrated that ABAQUS is capable of accurately simulating crack patterns and structural responses, with good agreement with experimental results Al hasani et al. (2021). Further developments have integrated numerical and experimental approaches for strengthened RC beams, such as externally prestressed systems and FRP reinforcement, which have been shown to significantly enhance flexural capacity and overall structural performace Ren et al. (2024) and Kashyap et al. (2026). In particular, CFRP strengthening has proven effective in improving strength and stiffness, and its behavior can be reliably captured through numerical simulations Sharifi et al. (2025) and Demir et al. (2021). Moreover, finite element methods have been successfully applied to model complex conditions, including impact, pre-damaged beams, and hybrid strengthening systems, with a high level of accuracy Alshaarbaf et al. (2023), Aslan and Erkan (2025), and Nguyen et al. (2024). However, limitations remain in accurately capturing failure mechanisms and material interactions in detail Jahami and Issa (2023) and Almatrafi et al. (2024).

Most extisting studies simulate structural behavior from the initial loading stage. Therefore, the research gap addressed in this study is the development of a post-cracking numerical simulation, in which the model is initiated after the first crack occurs and subsequently subjected to loading until the ultimate condition. This approach is expected to provide a more realistic representation of structural behavior.

2. MATERIAL AND METHODS

Parameter and properties must be defined for numerical simulation to make the results close from an experimental study. The parameters were the material of concrete, bar steel, CFRP, and epoxy that was the interaction between CFRP and concrete

Concrete

The behavior of compressive strength of concrete was from experimental study that has been carried out by Mulyanto (2020) and modeled according to Mander et al. (1988), and the skeleton curve of compressive behavior of Mander's theory could be seen in Figure 1 and 2. Meanwhile, the tensile strength was modeled using fracture energy. In this approach, the brittle behavior of concrete was defined as a stress-displacement relationship. The alternative of fracture energy could be determined directly as a material property. In this case, the failure stress ($\sigma t0$) was determined as a function of the associated fracture energy. A linear loss of strength after cracking was assumed in this model which is shown in Figure 3 and 4.

Numerical simulation of this research used ABAQUS software. The behavior of concrete material must be idealized damage plasticity. It was shown by Table 1.

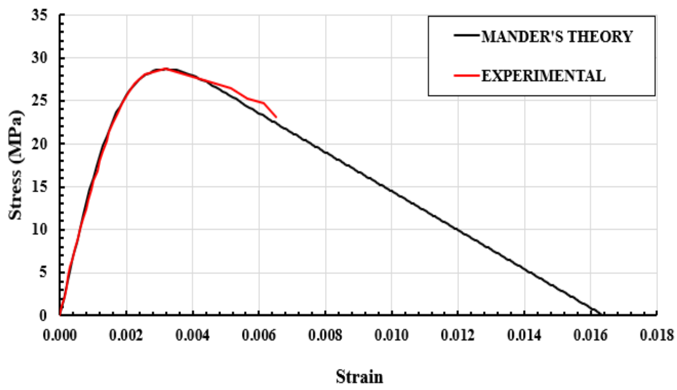

Figure 1. Concrete compressive stress–strain model

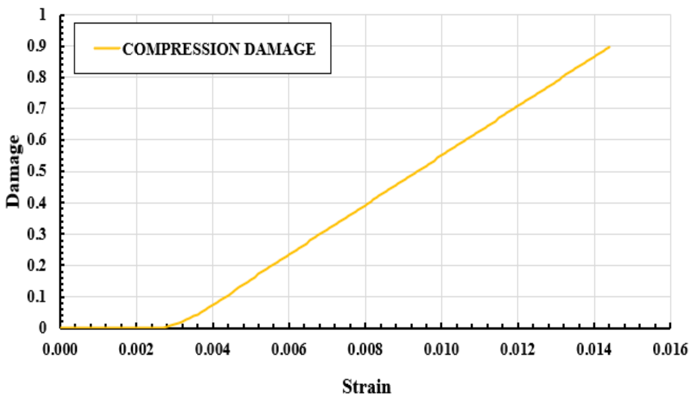

Figure 2. Concrete compressive damage–strain model

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Table 1. Damage Plasticity Parameter (Dassault, 2014)

Dilatation angle ψ	Eccentricity	f_{b0} / f_{c0}	K	Viscosity
30	0,1	1,16	0,67	0,0001

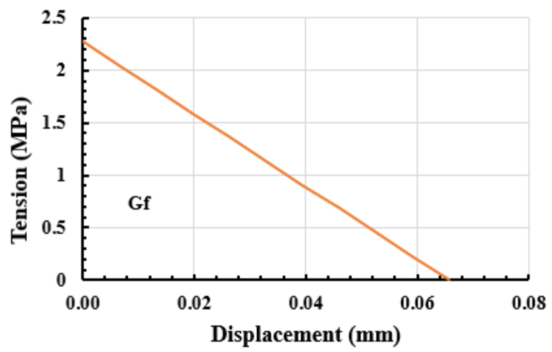

Figure 3. Concrete tensile stress–displacement model

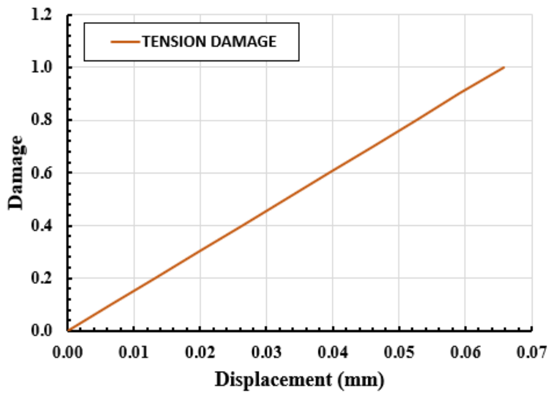

Figure 4. Concrete tensile damage–displacement model

Steel

According to Hastono (2017) that in today's construction world, many manufacturers produced quality reinforcing steel in the field, namely 300, 400, 500, up to 600 MPa. In this study, experimental testing of the quality of reinforcing steel was not carried out so that the quality of reinforcing steel was tried to approach the experimental results, namely 400, 500, and 600 MPa.

In ABAQUS, the material properties of steel were in the form of a stress-strain curve. Therefore, the curve modeling was based on the model proposed by Park and Paulay (1975). The stress-strain relationship model for steel is shown in Figure 5.

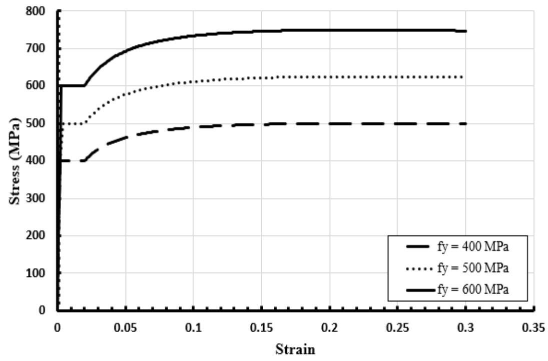

Figure 5. Rebar steel stress–strain model

Epoxy

Epoxy was a material component that was shaped like glue which, had the function to attach two components such as concrete. Epoxy was mostly used to the bond between old and new concrete and was widely used to attach CFRP reinforcement to concrete. In this study, epoxy from Sikadur-330 was used. The characteristics and advantages of using Sikadur–330 were that it is easy to apply with a trowel and an impregnation roller. Details of the mechanical properties contained in the epoxy could be seen in Table 3.

Table 3. Parameter and properties of epoxy (Roman, 2005)

Parameter	Explanation
Density	1,30 kg/liter
Elasticity Modulus	4.563 MPa
Shear Modulus	1.665,3285 MPa
Elongation at break	0,9%
Adhesion compressive strength	> 2 MPa

Kabir et al. (2016) stated that modeling the constitutive behavior of adhesives (epoxy) used a cohesive zone model approach. This cohesive element was practical and realistic for modeling the behavior of the epoxy in ABAQUS. This cohesive law considered the three components of the traction stress, namely one normal component and two shear components. The elasticity behavior could be written as equation 1. Typical traction separation response and mixed-mode based on traction stress could be seen in Figure 6, respectively.

$$\boldsymbol{t} = \begin{Bmatrix} t_n \\ t_s \\ t_t \end{Bmatrix} = \begin{bmatrix} K_{nn} & K_{ns} & K_{nt} \\ K_{ns} & K_{ss} & K_{st} \\ K_{nt} & K_{st} & K_{tt} \end{bmatrix} \begin{Bmatrix} \delta_n \\ \delta_s \\ \delta_t \end{Bmatrix} = \mathbf{K\delta} \qquad (1)$$

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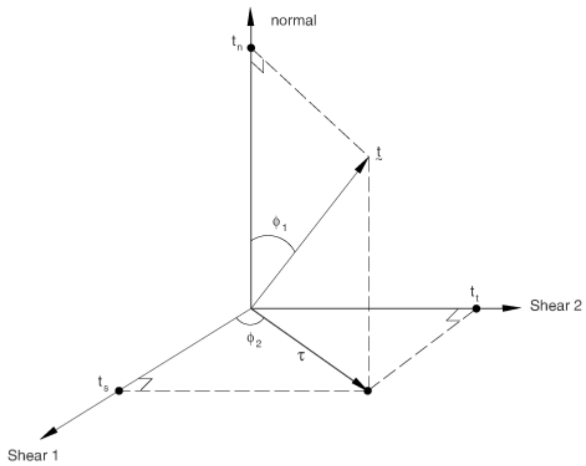

Figure 6. Typical traction separation response and mixed-mode (Dassault, 2014)

K_{nn} could be considered as the initial slope of the bond separation model for mode I. Meanwhile, K_{ss} **and** K_{tt} were also assumed to be equal wherein, the stiffness is the slope for mode II. So, the equations K_{nn}, K_{ss} **and** K_{tt} could be written with equations 2 and 3.

$$K_{nn} = \frac{E_a}{T_0} \quad (2)$$

$$K_{ss} \text{ dan } K_{tt} = 3\left(\frac{G_a}{T_0}\right)^{0.65} \quad (3)$$

Where,

E_a = elasticity modulus of epoxy

G_a = shear modulus of epoxy

T_0 = thickness of epoxy

3. TEST OBJECT MODEL

In this study, the dimensions and sizes of the T-beams followed the experimental tests conducted by Mulyanto (2020). The dimensions of the T-beam are L = 2300 mm, h = 300 mm, b_f = 600 mm, t_f = 100 mm, and b_w = 150 mm. The upper and lower longitudinal reinforcements used were 2D19 and 2D16, respectively. The shear reinforcement used was ϕ6–250. Dimensions, shapes, and variations of T-beam with CFRP are shown in Figure 7 – Figure 9.

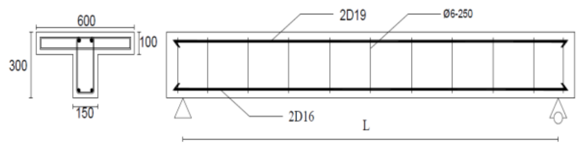

Figure 7. Control beam Mulyanto (2020)

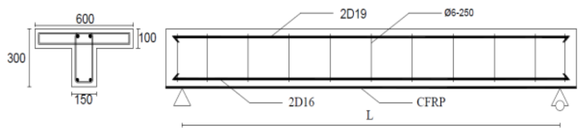

Figure 8. Beam reinforced along the span Mulyanto (2020)

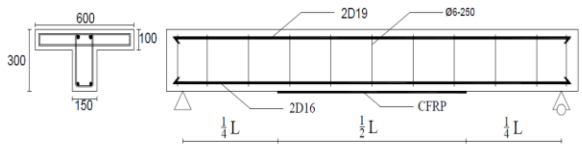

Figure 9. Beam reinforced half of the span Mulyanto (2020)

From the dimensions and shape of the test object above, then the test object was approached with a finite element model with the help of the ABAQUS software. The finite element model of the test object could be seen in Figure 13 – Figure 15. Each of these components was modeled in ABAQUS as follows.

1. Concrete beam, solid steel loads and supports were modeled with 3D solid elements in the form of C3D8R elements (3D continuum, 8–node linear brick, reduced integration).
2. The reinforcing steel modeled with T3D2 truss elements (3D truss, 2–node linear truss) can be seen in Figure 3.6.
3. CFRP was modeled with a three-dimensional conventional shell element in the form of an S4R element (shell, 4-node, reduced integration with hourglass control, finite membrane strains).

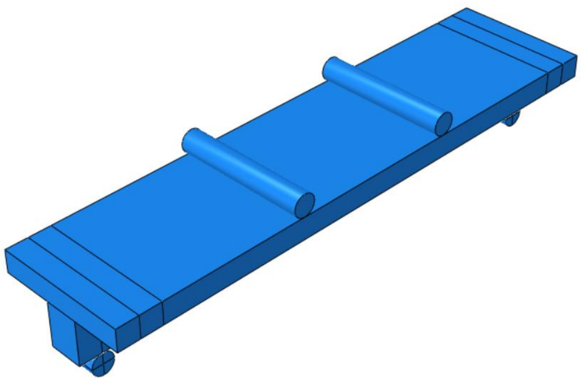

Figure 10. Concrete beam, solid steel loads and supports model

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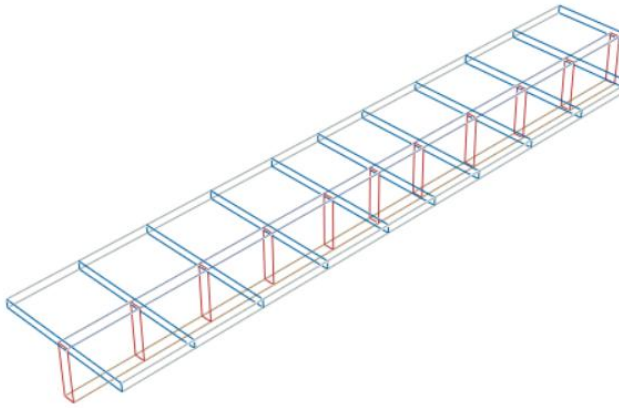

Figure 11. The reinforcing steel model

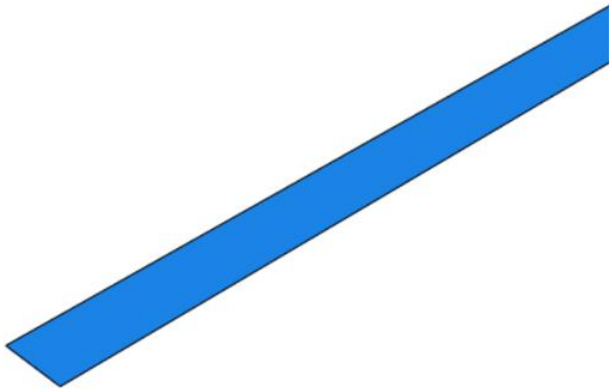

Figure 12. CFRP model

4. LOADING SCHEME

The test object will be given a load up to the first crack and for CFRP reinforced beams, reinforcement was applied after the load is up to the first crack. Then, the loading was continued with repeated loads three times for the control beam and twice for the CFRP reinforced beam. Repeated load of 30% of the design load which represented the live load acting on the structure after the damage occurred to the structure (first crack). Finally, the load will be applied until the beam collapses. The scheme could be seen in Figure 13 - Figure 15.

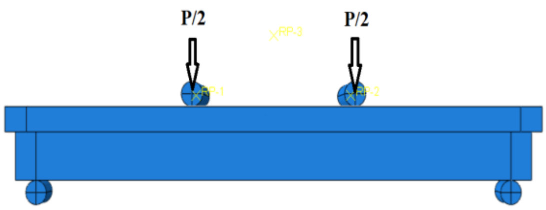

Figure 13. Load until firstcrack

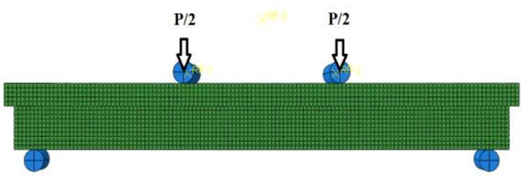

Figure 14. Repeated load

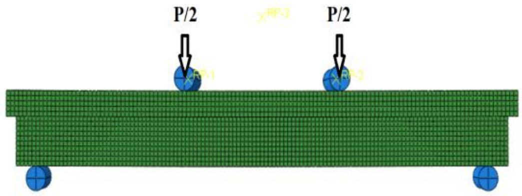

Figure 15. Load until beam collapse

5. RESULT

Convergence test results

In this study, numerical simulations were about to validate the experimental results. The method used was the finite element method in which the test object is given a mesh and then divided into small elements. The mesh also affected the final results of the numerical simulations performed. Therefore, the number of meshes must be appropriate to be able to approach the experimental results. So, mesh convergence needed to be done so that the mesh could be precise. Convergence results were presented in Table 4 to determine the percent difference of each mesh.

Table 4. Convergence results

Mesh	P_u (kN)	The Difference (%)
50	117,093	–
25	124,67	6.4709
20	125,333	0.5318

From the results of the convergence test, it was found that the effective and efficient mesh and able to approach the experimental results was mesh 20. This was because the difference that occurs was below 5%.

Software verification

In this research, the software used in ABAQUS. However, the use of the software needed to verify the results or behavior of the structure being modeled and must have similarity to the behavior of the structure if the modeling used other software. Therefore, verification in this study used two other software, namely RESPONSE2000 and SAP2000. The result or behavior of the structure being compared was a moment-curvature curve where the yield moment (My) and ultimate moment (Mu) could not be more than 5%. The reference and comparison results were the results provided by the RESPONSE2000 software. The comparison of the moment results could be seen in Table 5.

Table 5. The comparison of the moment results

Software	M_y (kNm)	Error (%)	M_u (kNm)	Error (%)

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Response 2000	60,815	–	72,581	–
SAP 2000	62,203	2,282	71,4026	–1,624
ABAQUS	63,312	4,106	70,8561	–2,377

Determination of reinforcing steel quality

Manual calculations (plastic analysis of T-beam cross-section) determined the quality of the reinforcing steel installed in the field. The results of manual calculations could be seen in the load-deflection graph in Figure 16 and numerical calculations were carried out with the help of ABAQUS to determine the quality of reinforcement steel installed in the field presented in Figure 17.

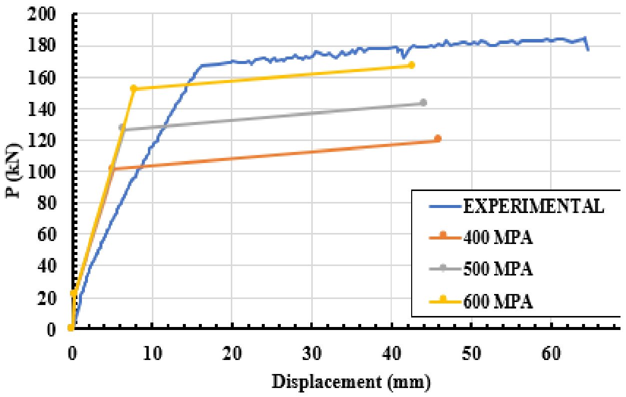

Figure 16. The results of manual calculations

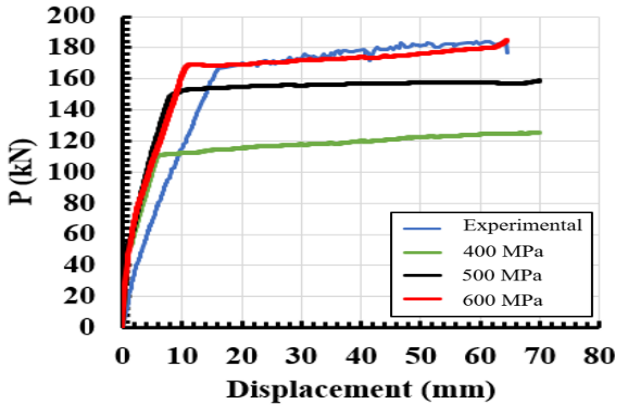

Figure 17. The numerical calculations

From the load-deflection curve above, the quality of the reinforcing steel used in the field is f_y = 600 MPa. Therefore, the analysis and numerical simulation with ABAQUS continued with the quality of the reinforcing steel f_y = 600 MPa.

Load-displacement curve

Figure 18 showed the comparison of load-deflection curves between experimental tests and numerical simulations for control beams. The application of CFRP had several variations to approach the experimental results where the results of the curve were presented in Figure 19 and the comparison of results could be seen in Table 6. The combined curve of all variations could be seen in Figure 20. The results of the load comparison were presented in Table 7 and Table 8. The closest experimental resulted to define and apply CFRP numerically was to use a composite layup with 3 layers with a rotation angle (0/–45/45)˚. The interaction between concrete and CFRP which was close to the experimental results was cohesive behavior. It was proven that the variation had a difference of less than 5% from the experimental results. Variation B– 3PLIES– COH to simplify code naming, the name was changed to code B1.

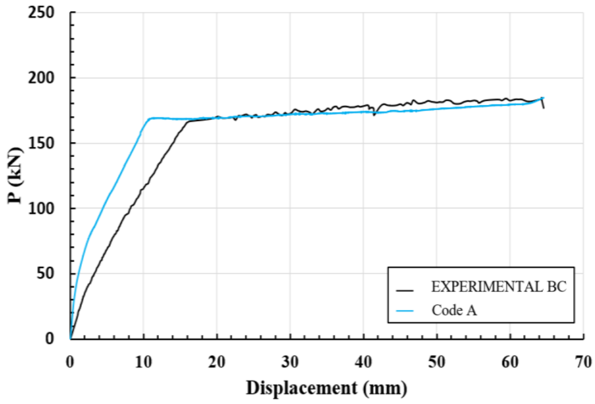

Figure 18. Experimental and control beam (Code A) load-displacement curve

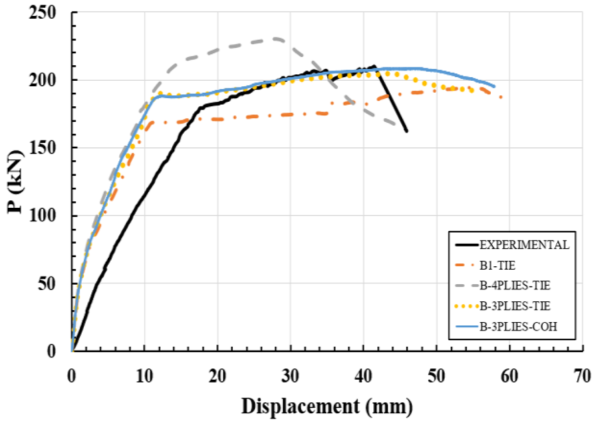

Figure 19. Load-displacement curve of variation of CFRP

Table 6. The result of yield and ultimate load between variations of CFRP

Exp.	Py (kN)	The Difference Py (%)	Pu (kN)	The Difference Pu (%)
Eksperimental B	179,4	–	209,7	–

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B– TIE	169.08	–5,7525	194,627	–7,188
B– 4PLIE S– TIE	205,793	14,7118	230,262	9,8054
B– 3PLIE S– TIE	189,572	5,67	204,816	–2,329
B– 3PLIE S– COH	184,293	2,7274	208,387	–0,626

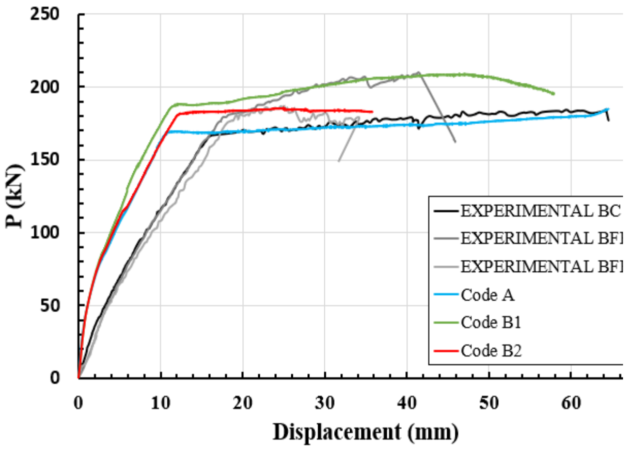

Figure 20. The result and comparison experimental and numerical of load-displacement curve

Table 7. The result and comparison yield load of experimental and numerical

Explanation	Py (kN)	The Difference Py (%)
Experimental BC	164,4	–
A	169,144	2,8856
Experimental BFR1	179,4	–
B1	184,293	2,7274
Experimental BFR2	175,3	–
B2	179,646	2,4792

Table 8. The result and comparison ultimate load of experimental and numerical

Explanation	Pu (kN)	The Difference Pu (%)
Experimental BC	184,8	–
A	184,842	0,0227
Experimental BFR1	209,7	–
B1	208,387	–0,6261
Experimental BFR2	186,7	–
B2	185,191	–0,8082

From these results, the numerical simulation carried out was able to validate the experimental results. This could be seen from the yield load and ultimate load which was compared with the experimental results where the difference between the two was less than 5%. Thus, the results of the numerical simulation were well-validated.

Failure mode

The pattern of cracks and failure which was compared between numerical simulations and experimental tests was the pattern at the time of the last loading until the T-beam collapses. The results of the numerical simulation on the model with code A, B1, and B2 were compared with the results of experimental tests could be seen in Figure 21 – Figure 23. Figure 24 and Figure 25 showed the damage that occurred to CFRP.

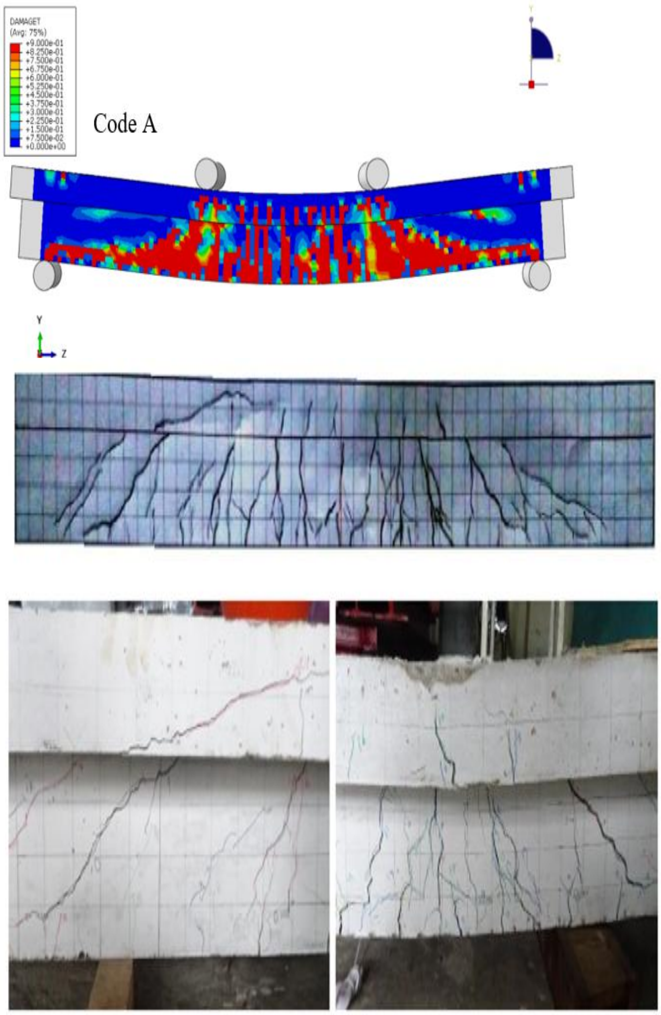

Figure 21. The comparison of failure mode between experimental and numerical code A

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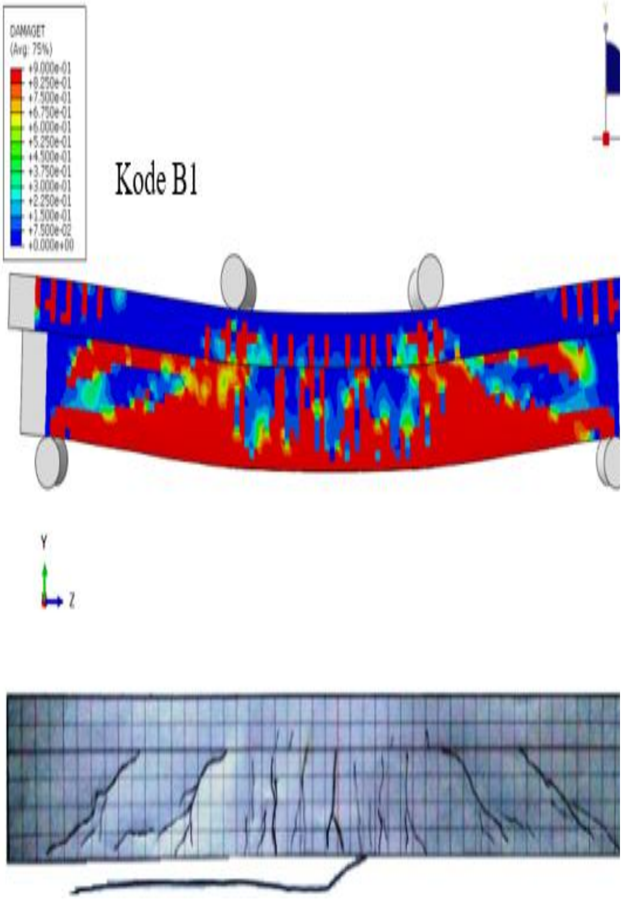

Figure 22. The comparison of failure mode between experimental and numerical code B1

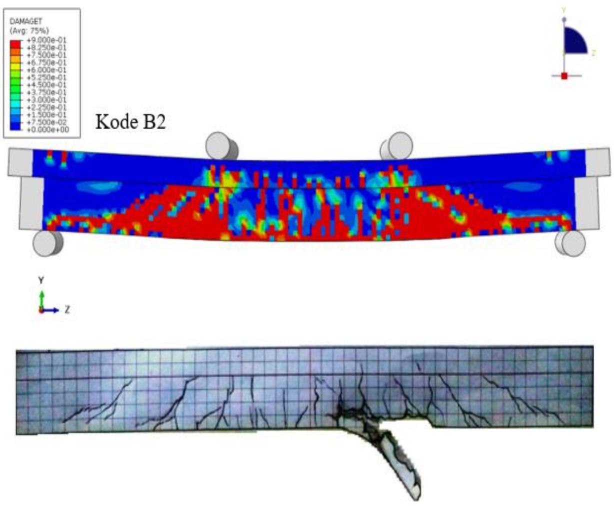

Figure 23. The comparison of failure mode between experimental and numerical code B2

Figure 24. Failure mode of CFRP code B1

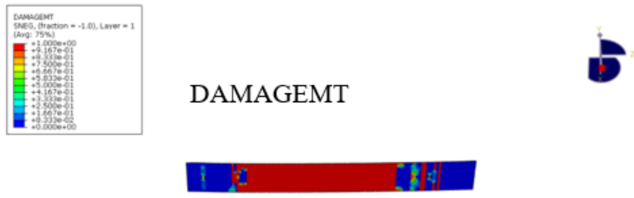

Figure 25. Failure mode of CFRP code B2

6. CONCLUSION

The results of the numerical simulation were well-validated by the experimental results, which were shown by the yield load and ultimate load having a yield difference of less than 5%. The effect of the compressive and tensile strength of concrete and the quality of reinforcing steel could increase or decrease the load capacity depending on the increase or decrease in the material. Further modeling needed to be done so that the numerical simulation results were close to the experimental results without the need to vary the quality of the material used. CFRP modeling to be similar to experimental results was to use Hashin damage and composite layup. The modeling of the interaction between CFRP and beams that produced close experimental results was to use cohesive behavior. Further research needed to conduct a more complete material test for each material so that the behavior of the model could be more similar to the experimental one.

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