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Performance Analysis of Reinforced Concrete Beam with GFRP Using Finite Element Method

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Abstract. Structural strengthening is required when structures suffer from minor damage or strength degradation. Structural strength degradation can be caused by incorrect initial design, structural age, environmental factors, or changes of building functions. One of the strengthening solutions is Glass Fiber Reinforced Polymer (GFRP) due to its easy application and good mechanical properties such as. This research discussed the effect of externally bonded GFRP sheets on the flexural capacity of reinforced concrete beams. The concrete specimens had dimensions of 150×250×3300 mm and were simply supported beams tested using two point symmetrical loading. Flexural strengthening was done by applying GFRP sheets to the bottom side of the beams (bottom wrapping). Flexural capacity analysis was done using finite element method with the help of MIDAS FEA program and shows 27,915-70,521% flexural capacity increasement for each GFRP layer addition for bottom wrapping models. Finite element analysis results are close to the theoretical calculation based on ACI 440.2R-17 with the biggest difference of ±3% and gives a conservative approach in predicting laboratory test results. Finite element modelling is also able to show the failure process of specimens properly.

INTRODUCTION

Reinforced concrete beam is one of the structure elements that often undergoes damage or capacity degradation due to structural age, changes of building functions, or incorrect design [1]. If it is not handled properly, it could lead to structural failure which causes fatalities. In order to avoid that, we could replace the entire old structure with the new one or use external reinforcement. Replacing the entire structure costs a lot, and therefore structural reinforcement or strengthening is often chosen. One of the strengthening methods is using Finite Reinforcement Polymer (FRP) which has been widely used for column, beam, and slab reinforcement. FRP has good mechanical properties such as high tensile strength, lightweight, corrosion-resistant, and ease of application. FRP material which is often used is Glass Fiber Reinforced Polymer (GFRP) in the form of sheet. GFRP is a fiber reinforced polymer made of a plastic matrix reinforced by fine fibers of glass. Fiberglass is usually way cheaper than carbon fiber and aramid fiber [2].

Laboratory experiments are necessarily required for relatively new material like GFRP. Direct experiments in the laboratory, however, are expensive and time consuming and often slows down the research progress. Limitation of resources and testing equipment also reduce the possibility of structure that can be tested. This situation has strongly inspired the development of advanced analytical methods such as finite element method (FEM) which is capable of representing the behavior of concrete structures internally and (or) externally reinforced by composite materials under all possible loading conditions [3].

The data used in this research is acquired from previous research done by Sultan et al. [4] called "Pengaruh Perkuatan GFRP-S terhadap Kapasitas Lentur Balok Beton Bertulang". In this research, the variation of bottom wrapping models were added using up to 3 layers of GFRP. Analysis was carried out using finite element method and compared with experimental results and theoretical calculations based on ACI 420.2R-17 in order to know which of the models provide the best performance. It is hoped that this research will encourage external strengthening using GFRP to be widely used in Indonesia and give an alternative solution to physical experiments in the laboratory.

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Flexural Strength of Reinforced Concrete Beam

According to ACI 440.2R-17 [5], flexural nominal strength of reinforced concrete strengthened by GFRP could be determined based on strain compatibility, internal force equilibrium, and the controlling mode of failure. Nominal flexural moment of bottom wrapping models are determined by calculating moment contribution of steel reinforcement and GFRP as indicated by the following equations.

$$M_{ns} = A_s f_s \left(d - \frac{\beta_1 c}{2} \right) \tag{1}$$

$$M_{nf} = A_f f_{fe} \left(d_f - \frac{\beta_1 c}{2} \right) \tag{2}$$

$$M_n = M_{ns} + M_{nf} \tag{3}$$

With M_{ns} = contribution of steel reinforcement to nominal strength (kNm), A_s = area of steel reinforcement (mm^2), f_s = stress of steel reinforcement (MPa), d = effective depth of beam (mm), β_1 = ratio of depth of equivalent stress block to depth of the neutral axis, M_{nf} = FRP contribution to nominal strength (kNm), A_f = area of FRP (mm^2), f_{fe} = effective stress of FRP (MPa), d_f = effective depth of FRP (mm), and M_n or M_{max} = nominal flexural strength or maximum bending moment (kNm). Meanwhile, maximum loading capacity is determined using basic statics principle.

$$P_{max} = \frac{M_n - M_{DL}}{a/2} \tag{4}$$

With P_{max} = maximum loading capacity (kN), M_{DL} = maximum bending moment caused by dead loads (kNm), and a = distance between loading and support (mm).

Finite Element Method

Finite element method (FEM) is a numerical method which is often used to solve mathematical or engineering problems. For problems involving complicated geometries, loading and material properties, it is generally not possible to obtain analytical mathematical solutions. Hence we need to rely on numerical methods, such as the finite element method in order to get acceptable solution [6]. In this research, analysis was done using a finite element method with MIDAS FEA.

Interface

To model composite relationships between reinforced concrete, epoxy and GFRP sheet, the interface function that is commonly used is bond slip. This interface modeling aims to depict debonding mode of failure which often occurred in FRP strengthening systems. Non linear relationships between local shear stress and associated slip could be determined by equations developed by Lu et al. [7] and illustrated in Fig. 1.

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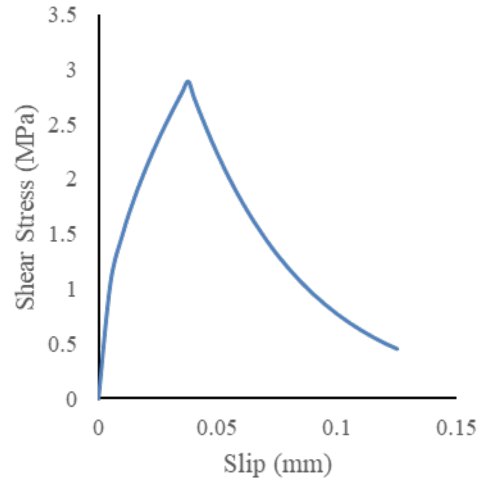

FIGURE 1. Bond Stress-Slip Relationships for FRP and Concrete

METHODOLOGY

Research data used were obtained from laboratory tests done by Sultan et al. Test beams were reinforced with two No.14 longitudinal bars in the tension zone, two No.6 longitudinal bars in the compressive zone, and 10 mm stirrup bars. Concrete compressive strength was 25,1 MPa. Control beam specimen is presented in Fig. 2.

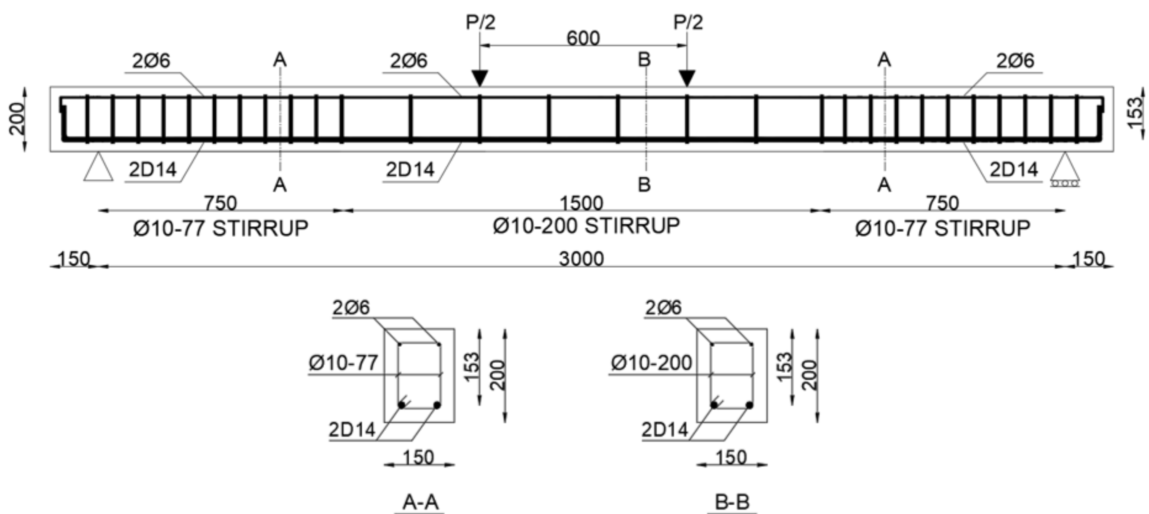

FIGURE 2. Illustration of Control Beam Model

Glass Fiber Reinforced Polymer and Epoxy

GFRP sheets used are Tyfo SEH-51A produced by Fyfe Co. LLC. GFRP specifications in the form of dry fiber include 3,24 GPA tensile strength, 72,4 GPa tensile modulus, and 0,36 mm thickness. Whereas, GFRP in composite form has 460 MPa tensile strength, 20,9 GPA tensile modulus, and 1,3 mm thickness. Epoxy Tyfo S produced by Fyfe Co.LLC is used as adhesive to hold GFRP and reinforced concrete together with specifications of 72,4 MPa tensile strength and 3,18 GPA tensile modulus.

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Model Variation

There are two types of test models as shown in Table 1 which consist of a conventional reinforced concrete beam without GFRP strengthening and GFRP bottom wrapping beams as shown in Fig. 3 up to 3 layers of GFRP.

TABLE 1. Model Variation

Wrapping Pattern	Code	GFRP Layers	Width of GFRP (mm)
-	BK	-	-
Bottom Wrapping	BB-1	1	150
	BB-2	2	150
	BB-3	3	150

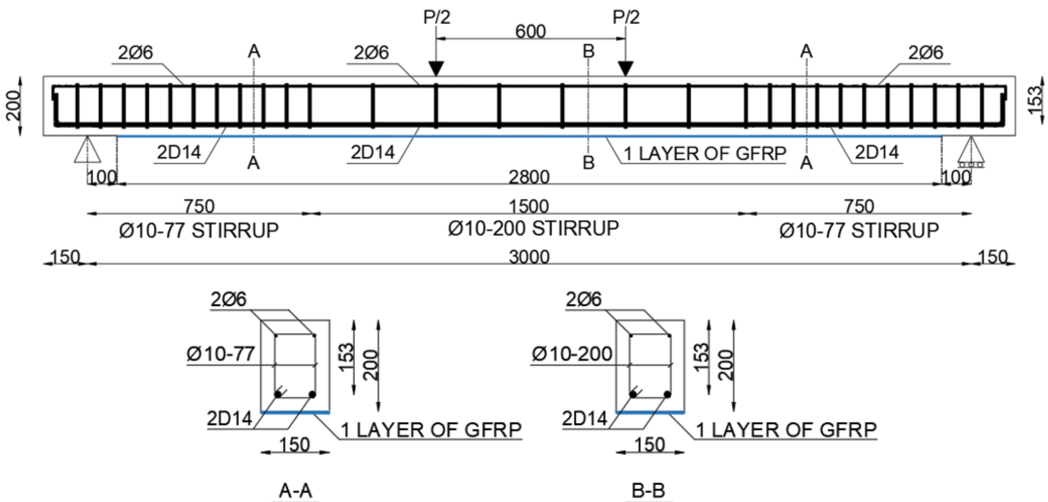

FIGURE 3. Illustration of BB-1 Model

Steps of Finite Element Analysis

Finite element method analysis is done by the MIDAS FEA program. Concrete beam and GFRP sheets are modeled using solid geometry, while steel bars are modeled using reinforcement bars in solid option and interface option for epoxy as shown in Fig. 4.

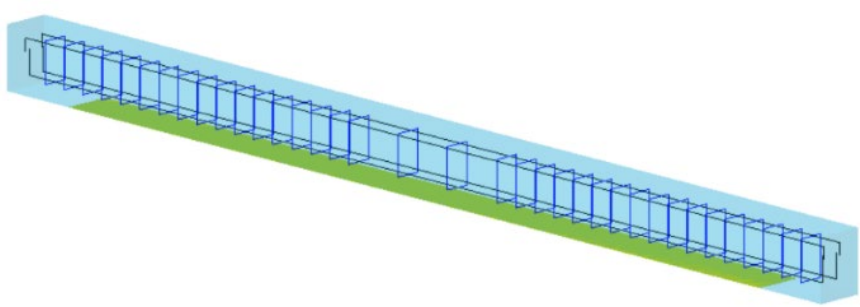

FIGURE 4. Geometrical Model of BB-1 in MIDAS FEA

Structure materials are modeled by assigning the function of each material. Concrete modeling uses total crack function with brittle function representing tensile behavior and thorenfeldt function for compressive behavior. Whereas, reinforcement bars use hardening function and GFRP uses brittle function and is assumed to be isothropic.

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After that, meshing needs to be done to combine all these materials and geometries together as a whole beam as shown in Fig. 5.

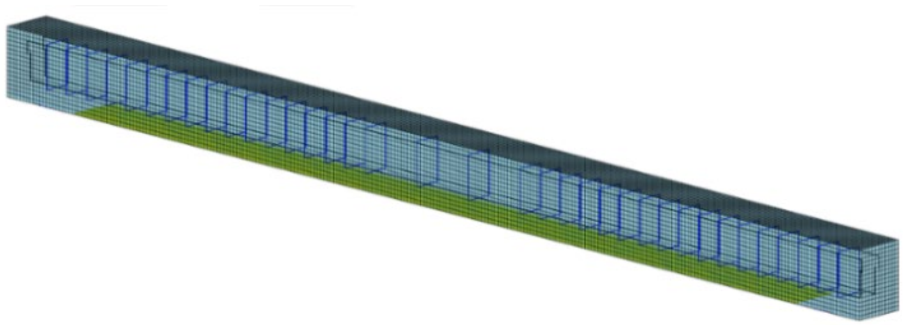


FIGURE 5. Meshing of BB-1 in MIDAS FEA

Interface element modeling between GFRP and beams uses a bond slip parameter with multilinear hardening function and constant function for relationship between GFRP and GFRP. Meanwhile, the bond of reinforcement bars is assumed to be plain rebar and modeled using a reinforcement bar in solid option. Support of the beam is designed using the constraint option and is made into simply supported beams by assigning its degree of freedom. Two point loads are given to the beams by load displacement option. Then nonlinear analysis will be done for each model.

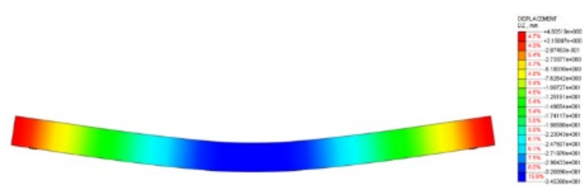
RESULT AND DISCUSSION

Nonlinear analysis results of all models using MIDAS FEA will be compared to theoretical calculation based on ACI 440.2R-17. Specially for control beam and beams reinforced with one layer of GFRP will also compared with experimental results.

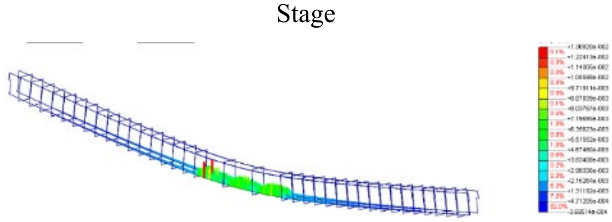
Control Beam

Finite element analysis shows an under reinforced type of failure with longitudinal rebars in the tension zone has yielded before concrete crushed. It can be seen from longitudinal rebars whose strain has reached 0,002 while concrete strain has not reached its maximum value (0,003). Control beam analysis result is shown in Fig 6.

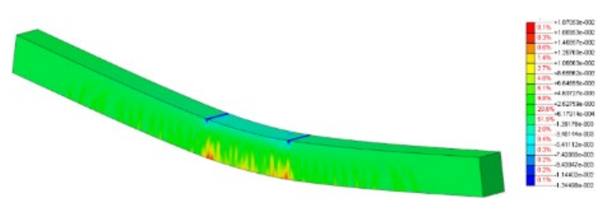
(a) Crack Pattern of Control Beam at The Ultimate Stage



(b) Deflection of Control Beam at The Ultimate Stage



(c) Strain of Steel Reinforcement at The Ultimate Stage



(d) Strain of Concrete at The Ultimate Stage

FIGURE 6. Result Analysis of Control Beam Using Finite Element Method

MIDAS FEA analysis gives a similar result compared with laboratory test and theoretical calculation as can be

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seen in Table 2 and Table 3.

TABLE 2. Flexural Capacity of Control Beam

Code	FEM		Theoretical		Experiment	
	P_{max} (kN)	M_{max} (kNm)	P_{max} (kN)	M_{max} (kNm)	P_{max} (kN)	M_{max} (kNm)
BK	27,140	16,284	27,368	16,421	26,740	16,044

TABLE 3. Comparison of Control Beam Analysis

Kode Balok	FEM vs Theoretical (%)	FEM vs Experiment (%)	Experiment vs Theoretical (%)
BK	0,833	1,497	2,350

It is shown in Fig. 7, that the finite element graph shows a similar trend near maximum load capacity point especially compared to the BN-1 beam from the laboratory test. Maximum deflection value from finite element analysis (34,511 mm) is also similar to BN-1 with 34,59 mm. Numerical analysis which doesn't give the same result can be caused by imperfect test models created in the laboratory.

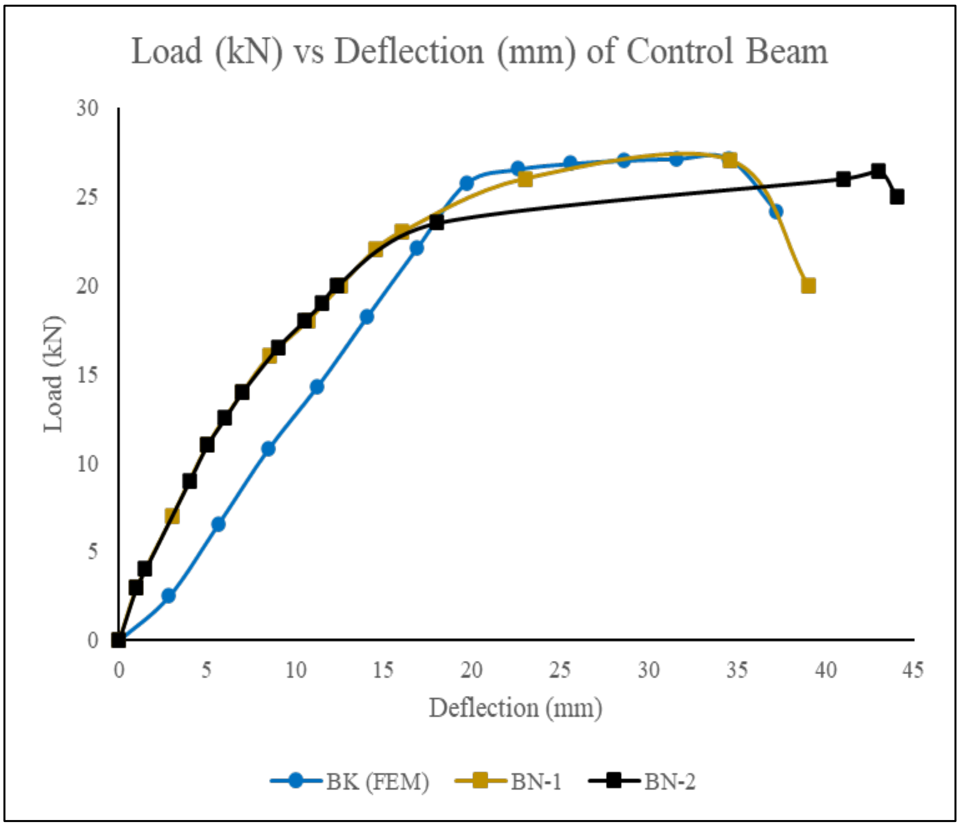

FIGURE 7. Load vs Deflection Graph Comparison of Control Beam

Bottom Wrapping Beams

All bottom wrapping beams tested show concrete crushing type of failure and not debonding. It is shown by concrete strain which has surpassed 0,003 while GFRP strain hasn't surpassed its ultimate value (0,045) when beams reached its failure. Bottom wrapping analysis results can be seen from Fig 8, Fig. 9, and Fig 10.

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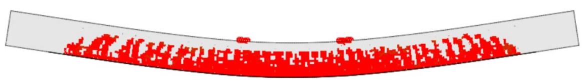
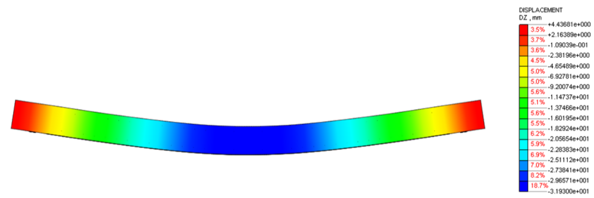
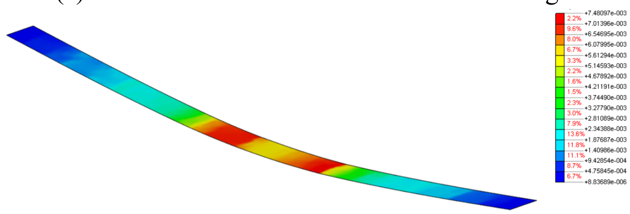


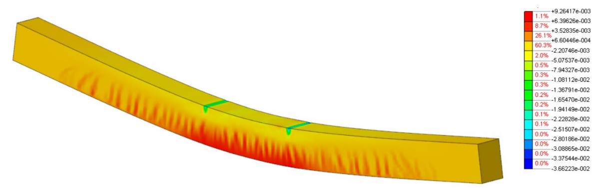
(a) Crack Pattern of BB-1 at The Ultimate Stage



(b) Deflection of BB-1 at The Ultimate Stage

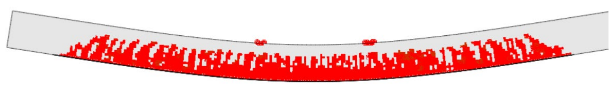


(c) Strain of GFRP at The Ultimate Stage

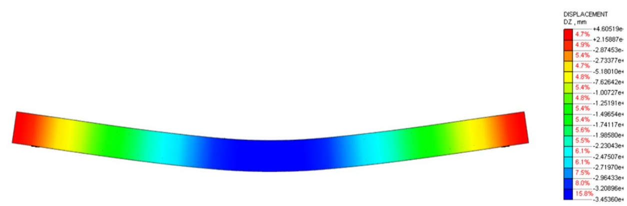


(d) Strain of Concrete at The Ultimate Stage

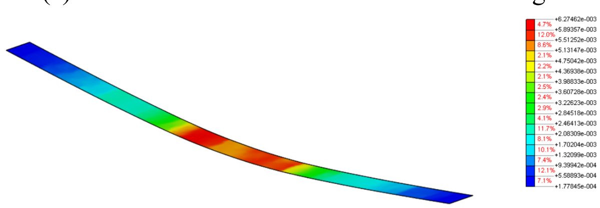
FIGURE 8. Result Analysis of BB-1 Using Finite Element Method



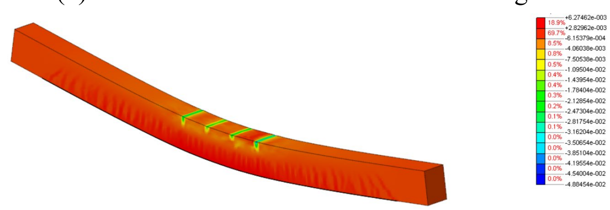
(a) Crack Pattern of BB-2 at The Ultimate Stage



(b) Deflection of BB-2 at The Ultimate Stage

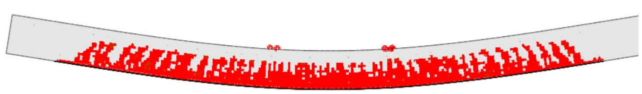


(c) Strain of GFRP at The Ultimate Stage

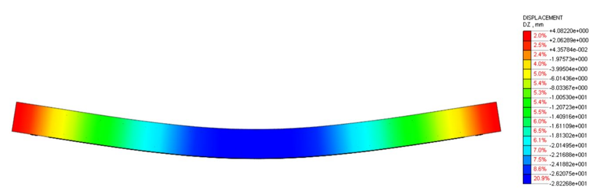


(d) Strain of Concrete at The Ultimate Stage

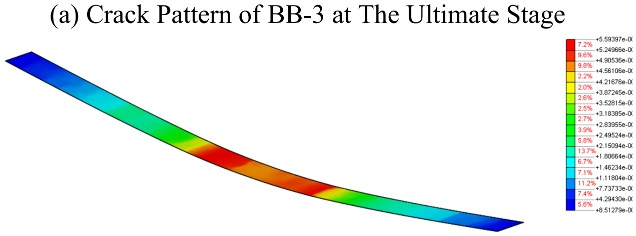
FIGURE 9. Result Analysis of BB-2 Using Finite Element Method



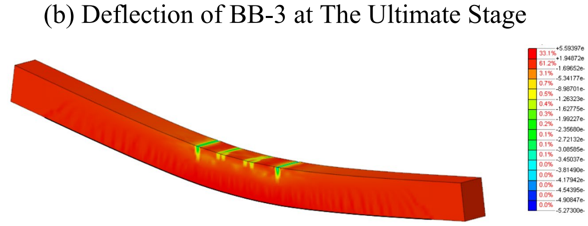
(a) Crack Pattern of BB-3 at The Ultimate Stage



(b) Deflection of BB-3 at The Ultimate Stage



(c) Strain of GFRP at The Ultimate Stage



(d) Strain of Concrete at The Ultimate Stage

FIGURE 10. Result Analysis of BB-3 Using Finite Element Method

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Load vs displacement graph as presented in Fig. 11, shows increasement of flexural capacity everytime a GFRP layer is added.

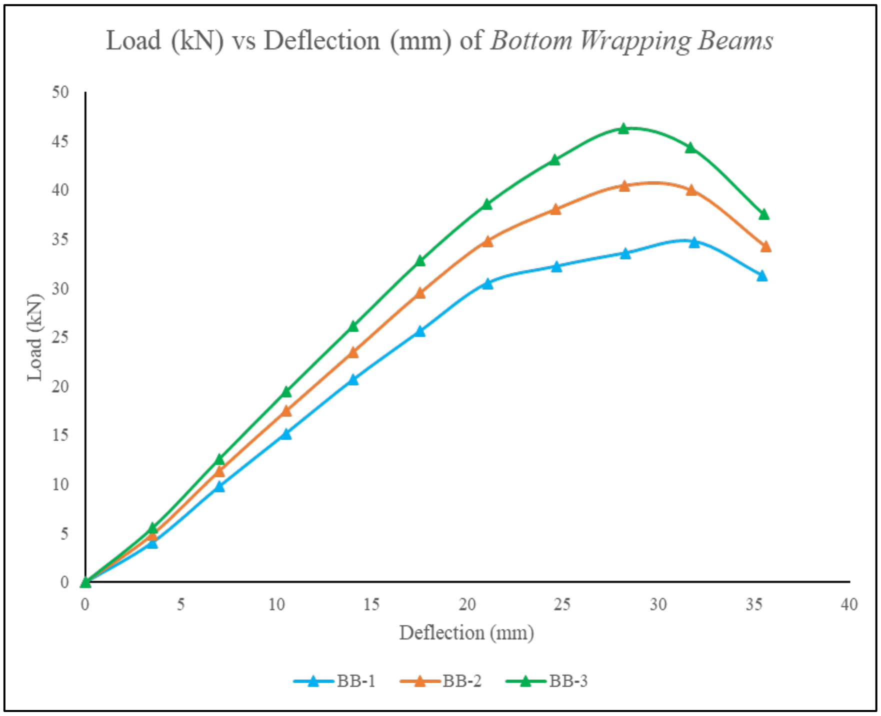

FIGURE 11. Load vs Displacement Graph of All Bottom Wrapping Models

When compared to theoretical calculations, FEM analysis shows a similar result with the biggest difference of 3,064% as shown in Table 4 and Table 5. However, compared to experimental results (BF-1, BF-2, and BF-3) in the laboratory, FEM analysis gives a lower flexural capacity result at the ultimate stage

TABLE 4. Flexural Capacity of Bottom Wrapping Beams

Code	FEM		Theoretical		Experiment	
	P_{max} (kN)	M_{max} (kNm)	P_{max} (kN)	M_{max} (kNm)	P_{max} (kN)	M_{max} (kNm)
BB-1	34,717	20,830	35,398	21,239	43,107	25,864
BB-2	40,442	24,265	40,772	24,463	-	-
BB-3	46,280	27,768	44,864	26,919	-	-

TABLE 5. Result Comparison of Bottom Wrapping Beams Analysis

Code	FEM vs Theoretical (%)	FEM vs Experiment (%)	Experiment vs Theoretical (%)
BB-1	1,927	19,464	17,882
BB-2	0,811	-	-
BB-3	3,064	-	-

The biggest flexural capacity increment percentage is obtained from BB-3 model with 70,521% as shown in Table 6. Load vs displacement graph comparison of BB-1 model can also be seen in Fig. 12

TABLE 6. Percentage of Load Carrying Capacity Increasement from FEM Analysis

Code	Load Capacity (kN)	Bending Moment Capacity (kNm)	Midspan Deflection (mm)	Flexural Capacity Increasement (%)
BK	27,140	16,284	34,511	-
BB-1	34,717	20,830	31,884	27,915
BB-2	40,442	24,265	28,204	49,010
BB-3	46,280	27,768	28,142	70,521

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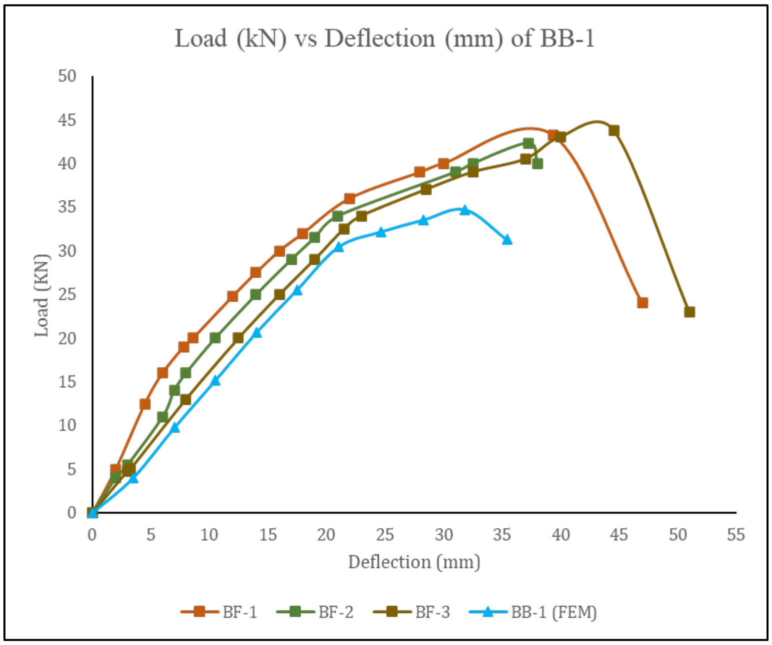

FIGURE 12. Load vs Deflection Graph Comparison of BB-1 Model

CONCLUSION

1. The result of this study shows that the use of GFRP sheets is capable of increasing the flexural capacity such as load carrying capacity and maximum moment capacity of beams.
2. The highest flexural capacity increment is obtained from a reinforced concrete beam wrapped with 3 layers of GFRP (BB-3) which is 70,521% compared to the control beam.
3. All models tested show concrete crushing mode of failure instead of debonding. This means the relationship between GFRP and concrete beam is well maintained until models reach its failure.
4. Finite element modeling of a model with 1 layer GFRP bottom wrapping gives a conservative approach in predicting laboratory test result.

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