EXPERIMENTAL AND NUMERICAL STUDY RETROFITTING BEAM WITH EXPANSION IN THE SUPPORT AREA

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Abstract
Retrofitting is one way to strengthen a building to withstand earthquakes and is often called an earthquake-resistant structure. Retrofitting beams will increase strength, stiffness, and ductility so that the structure is still stable when experiencing large earthquake forces. In addition to experimental methods, numerical methods are also used by researchers in developing a study of the behavior of building structures. Numerical methods using finite element software can examine the behavior of strength, stiffness, and ductility in beams. With this background, the author conducted a study of the retrofitting behavior of beams that were widened in the support area using numerical methods and theoretical analysis. The purpose of this study has been achieved so that a conclusion can be given that retrofitting with widening in the beam support area can increase the beam capacity quite significantly. Numerical, experimental, and theoretical analyses showed nominal moments of beam as 12.49 kNm, 14.07 kNm, and 10.20 kNm, respectively, and shear strengths as 17.84 kN, 20.10 kN, and 13.70 kN, respectively. Based on numerical research, with wide expansion reinforcement in the cross-sectional dimensions, the beam strength is increased by almost 45% and the beam stiffness is increased by 13-40% while ductility does not show a significant difference. These results are also expected to show the same behavior in experimental testing so that it will strengthen this reinforcement method. Experimental and numerical testing will be conducted in this study so that it will maintain the results and it is hoped that they can be accepted and practiced in the world of building construction.

Keywords: *beam, retrofitting, expansion, inovation, capacity*

INTRODUCTION

Indonesia cannot be separated from earthquake disasters (Da Conceição and Lisantono 2020). As a result of the earthquake, many buildings collapsed due to the power of the earthquake. Earthquakes produce repeated lateral forces from all directions. One force caused by earthquakes that must be considered when planning tall buildings is shear (Supaviriyakit, Pimanmas, and Warnitchai 2007). Shear force is a force that can cause a building structure to collapse suddenly without prior warning. Shear force due to earthquakes can occur throughout the structure of elements (Purba et al. 2023). Excessive deflection of beams often occurs in building structures (Purba, Supriyadi, and Suhendro

2023). Many studies have been conducted in high-rise buildings to increase the strength of the structure. Retrofitting is one way to strengthen the structure so that it remains stable when experiencing very large loads (Khan, Pimanmas, and Chindaprasirt 2023). Many researchers have retrofitted beams against shear forces to anticipate large forces due to earthquakes (Mahendra, Muslikh, and Fajar 2022).

Beam-column connections are something that needs to be considered when planning high-rise buildings (Pimanmas and Chaimahawan 2010). If the ability of the beam-column connection to experience a large enough shear force to collapse, then this is called structural failure. The shear resistance of the beam-column connection needs to be carefully calculated when planning the construction of high-rise buildings. Currently, many studies have been conducted in structural engineering to provide better knowledge about the behavior of reinforced concrete structures (Hernowo and Lisantono 2016). Two forces that need to be taken into account, namely shear force and bending force, will be the reference in reinforcement (George et al. 2023). Current computer applications are the most reliable technology in planning and analyzing reinforced concrete building structures. One of the apartments in the city of Yogyakarta, Indonesia was built with innovative reinforcement with an expansion of the area on the beam support as seen in Figure 1.

Before and after casting

Figure 1. Reinforcement of beams by expansion in the support area

This innovation is very unique and rare in high-rise buildings. This innovation is expected to increase the shear capacity of the beam and strength. Chaimahawan et al. (2010) studied beams with rectangular and triangular planar expansion retrofitting on the beam and it has been proven that expansion in the support area will significantly increase the shear capacity, strength, and strength of the beam (Pimanmas and Chaimahawan 2010). Chaimahawan et al. (2010) research can be associated with the construction of existing apartments because both show the same innovation, namely reinforcement with expansion in the support area (Pimanmas and Chaimahawan 2010).

The difference between Chaimahawan et al. (2010) research and this study is that the study expanded the height of the beam support cross-section, while this study refers to the existing construction of apartments, by expanding the width of the beam support cross-section. Hernowo and Lisantono (2016) conducted a study on Retrofitting of Reinforced Concrete Beam-Column Joints with Triangular Planar Expansion with Variations in Size (can be seen in Figure 2) (Hernowo and Lisantono 2016). They conducted research by making experimental beams with triangular planar expansion at the ends of the beam. Triangular planar expansion reinforcement significantly increases the ductility of the joint and planar expansion reinforcement is able to increase the strength of the joint. In this study, expansion was also given to the beam-column joint. The expansion carried out was in the form of triangular and rectangular planar expansion. From this study, triangular and rectangular planar expansion were able to provide retrofitting or add reinforcement to the beam-column joint.

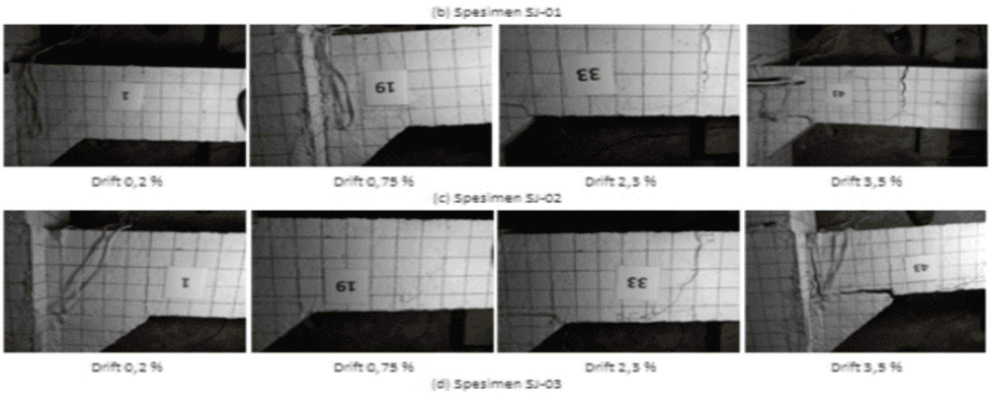

Figure 2. Planar expansion of a triangle at the support area (Hernowo and Lisantono 2016)

Figure 3. Reinforcement of beams with triangular and rectangular planar expansion in the support area (Pimanmas and Chaimahawan 2010).

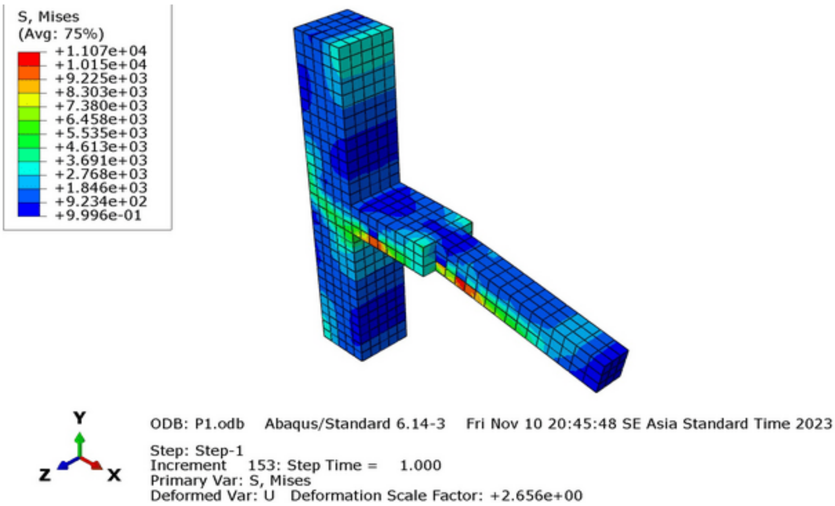

Figure 4. Numerical analysis of a beam with widening at the support (Purba, et al., 2023)

Purba, et al., 2023 conducted research on beam reinforcement with widening expansion in the support area numerically with ABAQUS software as shown in Figure 4 (Purba et al. 2023). In this study, it was proven that widening the support was able to increase the shear capacity, stiffness and nominal moment by up to 50%.

From previous research, there has been no experimental study of beam retrofitting by widening the dimensions at the supports. Experimental studies still refer to triangular and rectangular planar expansion where the dimensions are enlarged at the height of the cross-section. While in the existing beam, the support is enlarged at the width of the cross-section as in Figure 1. Purba, et al. (2023) conducted research related to Figure 1 but only numerical analysis method. An experimental study of this research will improve retrofitting beam by enlarging the dimensions at the width of the cross-section. Based on this background, it is necessary to conduct research on how much capacity increase is contributed by the innovation of expanding the width of the beam cross-section. This research was conducted using an experimental method in a structural laboratory.

Previous research has been widely published on beam reinforcement by enlarging the beam support area. Such as flexural reinforcement with shear using carbon fiber materials. Although this method significantly improves the behavior of the beam, the price of the material is very expensive. One method with partial enlargement of the cross-section dimensions has been carried out. Some of them are with triangular planar expansion which aims to strengthen the connection and stiffness.

Quadrilateral planar expansion has also been done and proven to be able to strengthen the beam. Recently, the construction of a 22-story apartment building in Yogyakarta has shown a new innovation in strengthening reinforced concrete beams. Purba, et al. (2008) conducted a numerical study on the reinforced concrete beam and showed an increase in capacity of up to 50%. The novelty in this study is that the widening of the dimensions in the cross-sectional width has not been done experimentally. This novelty will add an efficient and effective beam strengthening method for building construction practitioners.

RESEARCH METHOD

In this study, a sketch detail of the specimen section in the Laboratory is shown in Figure 5. This study also compares the results using FEA software and the modeling of beam can be seen in Figure 7. The sketch of setup beam is shown in Figure 6. The beam test setup in the Laboratory of the control beam (BG1) and the Beam with widening at the support (BG2) can be seen in Figure 8. The setup of the reinforced concrete beam test specimens were carried out using a load frame and a load actuator was used as a single-point load at the end of the beam. The maximum actuator loading capacity is 25,000 kg.

The reinforced concrete beam with clamped support is connected to the load frame using 4 bolts with a diameter of 19 mm. The shear strength of a D19 bolt is 372 MPa, and the number of bolts used is 4. The shear capacity of the bolts is calculated as: $R_n = 0{,}75 \times F_{nv} \times A_b = 0.75 \times 372 \times 4 \times 283.\ 39 = 316.26$ kN = 3.16 Tons. Based on this calculation, the bolts are safe, strong, and suitable for ensuring the rigidity of the connection. The beams to be setup are 2 beams and are named BG1 without widening and BG2 with widening. LVDT (Linear Variable Differential Transformers) are installed at 30 cm and 70 cm from the beam support and the LVDT is also installed at the end of the bolt connection in order to control the displacement of connection.

Load and deflection data collection is taken using a computer through a data logger. Test objects in the form of beams with normal concrete quality will be made into 2 types of beams. The planned beams are cantilever beams. Beam BG1 without widening at the support and Beam BG2 with widening at the support. In the shear zone of Beam BG1 and Beam BG2, no shear reinforcement is given. The length of Beam BG1 and BG2 is 800 mm and a height of 150 mm. And in beam BG2 the support width is 250 mm with a length of 300 mm and after the support area with a width of 120 mm with a length of 500 mm. Beam BG1 is given 3D10 tensile reinforcement and 2D10 compression reinforcement. Shear reinforcement is given P6 - 100 after the support area.

Detailed images of the reinforcement of beams BG1 and BG2 can be seen in the image below. Beam BG2 is given Tensile reinforcement at the 5D10 support and Tensile reinforcement after the 3D10 support area and 4D10 compression reinforcement at the support and 2D10 in the area after the field. Making concrete cylinders as specimen for collecting concrete compressive strength data. The concrete cylinders are 150 mm in diameter and 300 mm high, totaling 9 normal concrete cylinders. Three cylinders for compressive strength testing, three cylinders for split tensile strength testing, and three cylinders for concrete modulus of elasticity testing. Three reinforcing steel bars were tested in tension to obtain yield and ultimate tensile strength. The planned compressive strength is 25 MPa.

The specimen is also modelled in Lusas 2D software with dimensions and materials that have been determined according to the experimental study. The first is by modeling the Beam BG1 FEA test specimen without widening in the support area and the BG2 FEA beam test specimen with widening in the support. Modeling is without using shear reinforcement in the support area. After Lusas Software Modeling is complete, it is continued with Lusas software analysis. The results of the analysis will be a reference for the analysis of experimental test object test data so that it is expected that the two analysis results will not give too much difference. The beam to be tested is a cantilever beam with a single point load at the end of the beam. The cantilever beam support is a fixed support. The setup single point load at the end of the beam can be seen in Figure 8.

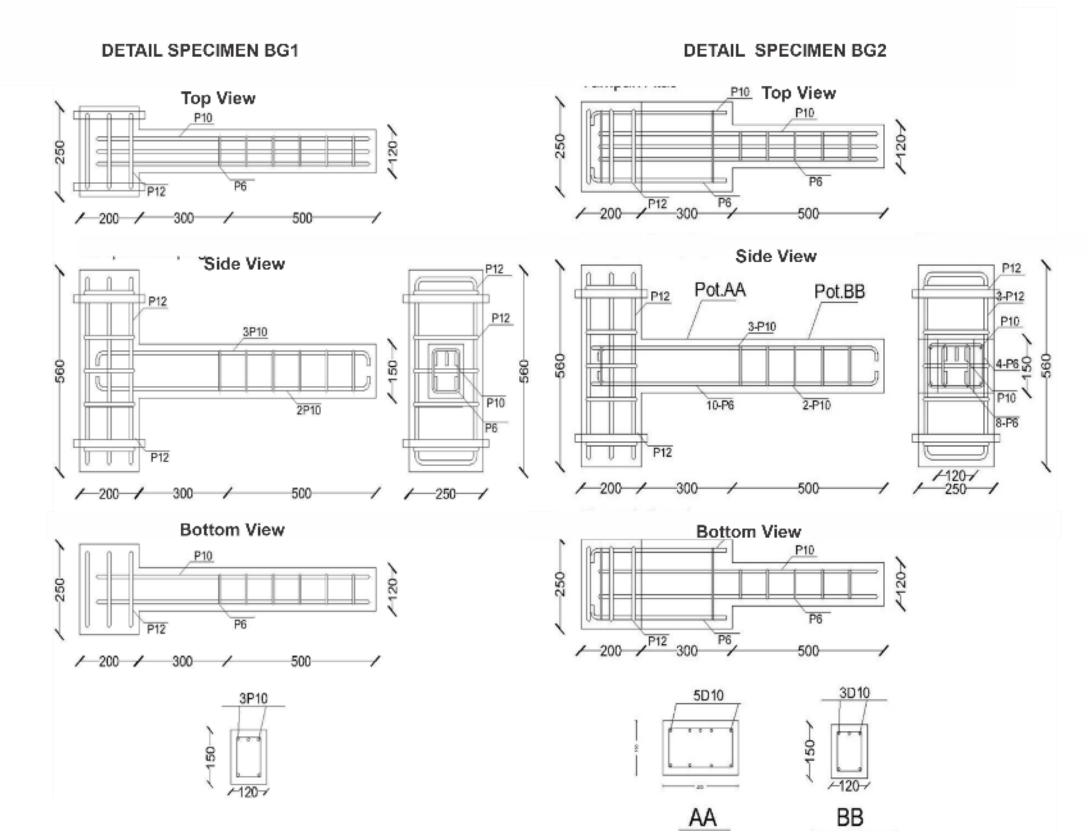

Figure 5. Detail specimens of BG1 and BG2 (units in mm)

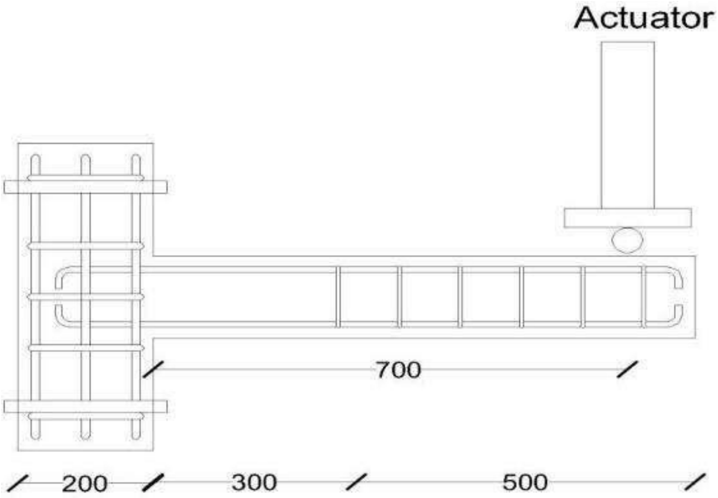

Figure 6. Setup loading sketch (units in mm)

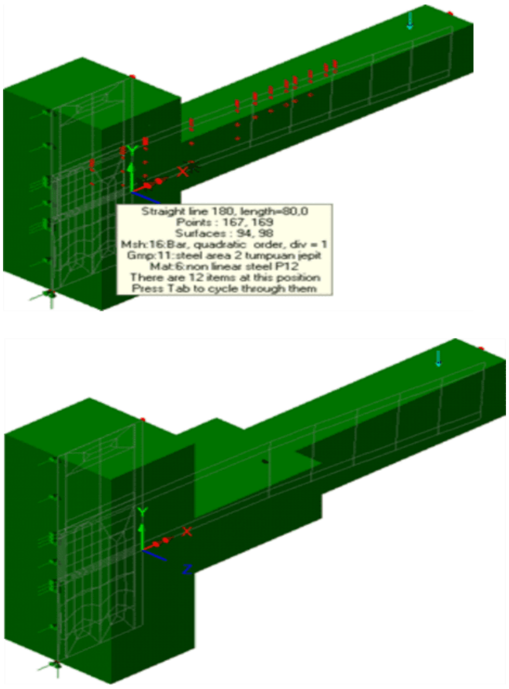

Figure 7. Beam Modeling Using FEA Software

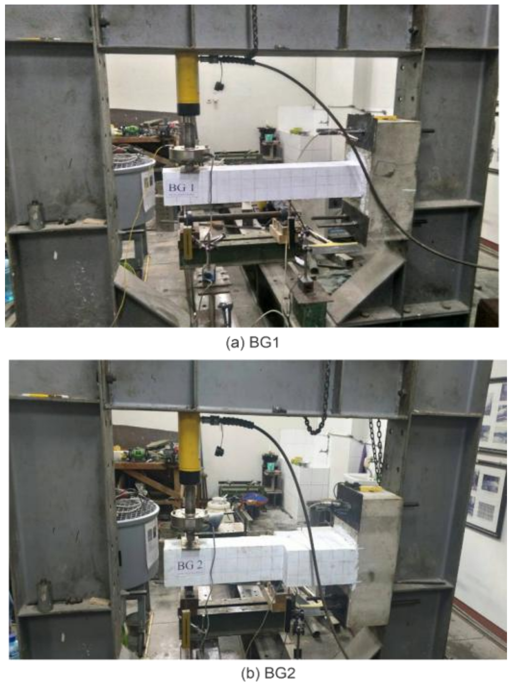

Figure 8. (a) Beam BG1 and (b) BG2 test setup in the Laboratory

RESULT AND DISCUSSION

Materials Test

Compressive strength testing on test specimen is carried out when the concrete age has reached 28 days. The results of the concrete compressive strength test can be seen in Table 1. The specimen test is a concrete cylinder with a diameter of 15 cm and a height of 30 cm. The test was carried out when the concrete age reached 28 days. The test was carried out with 3 test object samples. The results of the splitting tensile strength of concrete can be seen in table 2. The splitting tensile strength test of concrete can be seen in Figure 6. The average splitting tensile strength result is 2.55 MPa.

Testing of the modulus of elasticity of concrete when the concrete age has reached 28 days. The test results can be seen in table 3. The modulus of elasticity test can be seen in Figure 7. The average concrete modulus of elasticity test result is 19122.24 MPa. Reinforcement tensile strength testing was carried out using plain reinforcement with a size of ∅ 10 mm. The number of reinforcement test specimens to be tested was 3 samples each. The results of the reinforcement tensile strength test can be seen in table 5.4. The reinforcement tensile strength test can be seen in Figure 8. The results of the average reinforcement tensile strength with a diameter of 10 mm were fy = 355.21 MPa and Fu = 503.48 MPa.

Table 1. Concrete cylinder compressive strength results

Concrete Test					
No	Slump	Diameter	Section Area	Load	Compresive
	cm	mm	mm^2	kN	MPa
1	12	149,42	17526,17	530	30,24
2	10	149,38	17516,79	500	28,54
3	9	149,42	17526,17	290	16,54*
Compresive Strength Average					29,39

Note: *not considered

Table 2. Results of concrete splitting tensile strength testing

No	Diameter	Length	Load	Split Tensile Strength
	Mm	mm	kN	MPa
1	151,63	302,70	180	2,50
2	149,57	302,76	195	2,74
3	151,57	303,53	175	2,42
Split Tensile Strength Average				2,55

Table 3. Results of testing of concrete elasticity modulus in the Laboratory

No	Dimension	Load	Stress	R Strain (10^{-5})	Modulus E_c
	cm	kN	N/mm2		MPa
1	15 x 20	127,53	7,22	34,54	20898,88
2	15 x 20	93,20	5,28	30,44	17345,60
3	15 x 20	127,53	7,22	6,20	116375,23*
Modulus of Elasticity Average					19122,24

Note: *not considered

Table 4. Results of tensile strength testing of reinforcement in the Laboratory

Diameter	Section area	P_y	P_u	F_y	F_u
mm	mm^2	N	N	MPa	MPa
8,84	61,34	21974,40	31490,10	358,21	513,33
8,68	59,14	20601,00	29037,60	348,32	490,97
8,77	60,38	21680,10	30558,15	359,08	506,13
Average				355,21	503,48

Crack Pattern

The crack pattern results from the four-point load loading show significant differences between the two specimens. It can be seen in Figure 13 that the specimen without widening (BG1) failed to be supported by the beam. There are shear cracks in the beam indicating that the concrete is no longer able to withstand shear forces. However, flexural cracks are dominant in this beam.

Figure 14 shows the crack pattern of beam BG2. The crack pattern shows that the specimen with widening (BG2) gives a different crack pattern to beam BG1. Beam BG2 also has shear cracks so that the concrete of beam BG2 is no longer able to withstand shear. Flexural cracks are also dominant in the BG2 Beam test. The failure of beam BG2 occurs in the middle of the beam span. the calculation of nominal moment theoretically, experimentally and numerically can be seen in Table 5.

There are differences between these three methods. However, each method shows that the BG2 beam is able to increase the nominal moment and shear strength by 30 - 50 percent. From these results, the beam strengthening method by widening the beam support is quite significant in increasing strength.

Comparison between BG1 and BG2 specimens in terms of nominal moment and shear strength in theoretical, experimental, and numerical methods shows significant differences as showed in Table 5. For nominal moment, BG2 consistently shows higher values than BG1. Theoretical results show a 71% higher nominal moment for BG2 (17.49 kNm) compared to BG1 (10.20 kNm).

Experimentally, the nominal moment of BG2 (18.90 kNm) is 34% higher than BG1 (14.07 kNm), and numerically, BG2 achieves a 54% higher nominal moment (19.26 kNm) than BG1 (12.488 kNm). For shear strength, BG2 exhibited superior values across all methods. The theoretical analysis estimated the shear strength of BG2 (28.55 kN) to be 108% higher than that of BG1 (13.70 kN). Experimentally, BG2 achieved a 34% higher shear strength (27 kN) than BG1 (20.10 kN). Numerically, the shear strength of BG2 (27.52 kN) was 54% higher than that of BG1 (17.84 kN).

In summary, BG2 demonstrated significantly greater capacity in both nominal moment and shear strength across all methods, particularly in the theoretical prediction for shear strength.

Based on the results, the comparison between BG1 and BG2 specimens in terms of load, deflection, stiffness, and ductility in both experimental and finite element analysis (FEA) methods revealed differences as showed in Table 6. For load capacity, BG2 consistently showed higher values than BG1. Experimentally, the cracking load of BG2 (Pcrack) was only 1.35% higher than BG1, while its yield load (Py) was 31.6% higher, and its maximum load (Pmax) was 36.7% higher. In FEA, BG2 also showed superior performance, with Pcrack 83% higher than BG1, Py 50% higher, and Pmax 54% higher. In terms of deflection, BG2 generally had higher values than BG1 in both experimental and FEA methods.

Experimentally, the deflection of BG1 at crack (Ucrack) is 24.5% higher than BG2, but BG2 has 8% higher deflection at yield (Uy) and 7% higher deflection at maximum load (Umax) than BG1, indicating a stiffer response before failure. FEA results show that Ucrack of BG2 is 24.5% higher than BG1, and Uy is 8% higher, and Umax is 7% higher. For stiffness (K), BG1 shows slightly higher values experimentally, with a stiffness of 1.99 kN/mm compared to 2.25 kN/mm for BG2 (a difference of 13%). In FEA, the stiffness of BG1 is lower, with values of 1.48 kN/mm for BG1 and 2.18 kN/mm for BG2, indicating a difference of 47% in favor of BG2. Ductility (U) favors BG1, which experimentally has a 56% higher ductility (3.52 for BG1 versus 2.25 for BG2). In FEA, BG1 also shows higher ductility, by a factor of 2.29 compared to BG2's 2.26, only marking a difference of 1.3%. Overall, BG2 shows greater load and deflection capabilities, while BG1 maintains higher ductility, underlining the unique mechanical properties of each specimen suited to different structural demands.

The experimental and numerical values for BG1 are generally higher than the theoretical values, with the most significant difference observed in shear strength (+46.72% experimentally and +30.22% numerically). In contrast, for BG2, the nominal moment from experimental and numerical results shows only a slight increase compared to the theoretical value, while the shear strength is slightly lower (-5.43% and -3.61%). These variations may be attributed to material imperfections, testing methods, or assumptions made in theoretical calculations.

In Figure 13, Figure 14, and Figure 15, we can see the graph of the relationship between load and deflection experimentally and FEA. Experimentally, Beam BG1 EXP collapsed at a loading of 1784 kg while beam BG2 EXP collapsed at a loading of 2752 kg. From the graph, we can see that beam BG2 EXP is able to increase its strength in holding the load by 54.26% compared to beam BG EXP. The slope of the graph between beams BG1 EXP and BG2 EXP is still the same at a loading of 300 kg, then at a loading of 500 kg the slope of the graphs of the two beams begins to differ so that the graph of beam BG2 EXP looks stiffer than beam BG1 EXP. The maximum deflection when beam BG1 EXP collapses is 8.63 mm while the maximum deflection when beam BG2 EXP collapses is 22.57 mm.

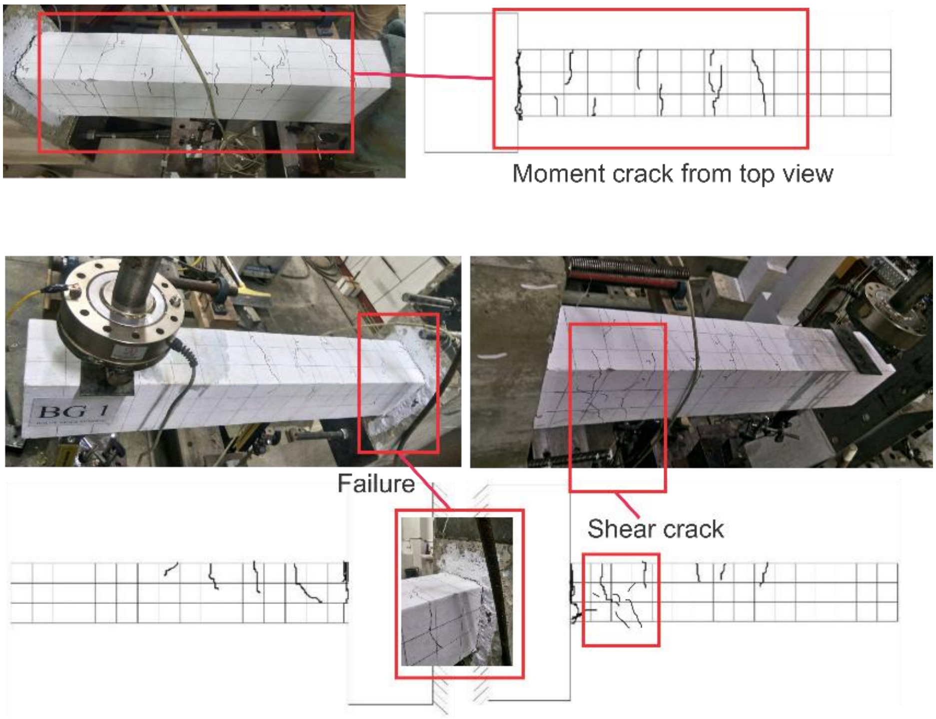

Figure 13. Results of the crack pattern specimen of BG 1

Table 5. The results of moment nominal and shear strength

Method	BG1		BG2	
	Moment Nominal kNm	Shear Strength kN	Moment Nominal kNm	Shear Strength kN
Theoretical	10.20	13.70	17.49	28.55
Experimental	14.07	20.10	18.90	27
Numerical	12.488	17.84	19.26	27.52

Table 6. The results of stiffness and ductility

Specimen	Load (kg)			Deflection (mm)			Stiffness kN/mm	Ductility
	P_{crack}	P_y	P_{max}	U_{crack}	U_y	U_{max}	K	U
BG1	889	1830.8	1974	4.46	14.5	45.21	1.99	3.12
BG2	901	2410	2700	4	15	33.75	2.25	2.25
BG 1 FEA	612	1631	1784	4.13	18.92	43.24	1.48	2.29
BG 2 FEA	1121	2446	2752	5.14	20.43	46.25	2.18	2.26

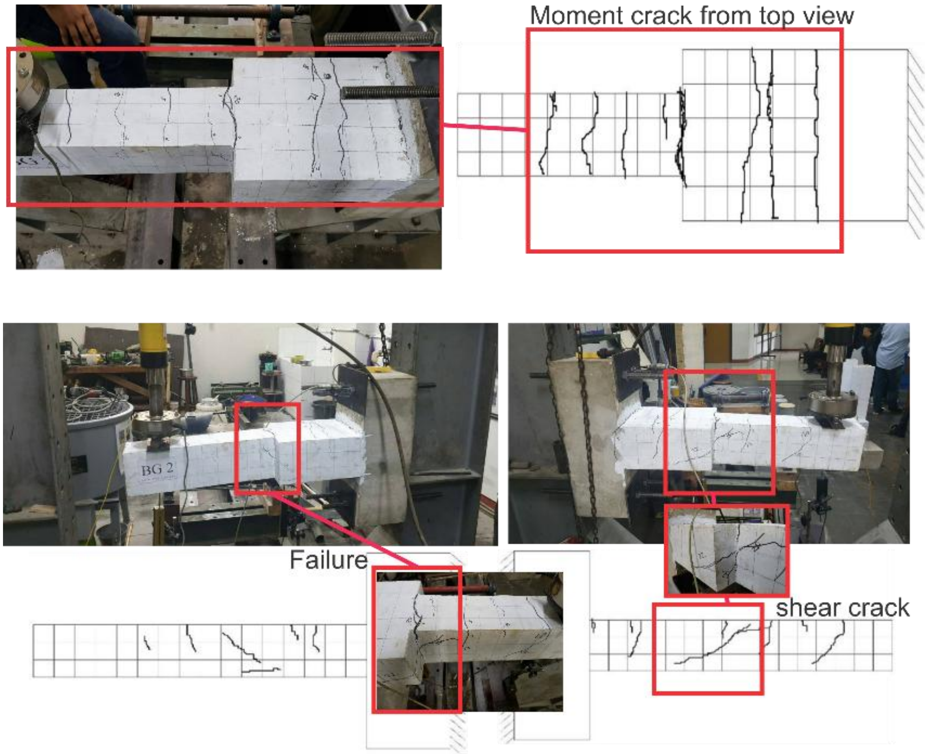

Figure 14. The crack pattern specimen of BG2

From the comparison of the experimental graph results with the Lusas software analysis, it can be seen that: The experimental BG1 EXP beam has a maximum load of 1974 kg while the BG1 FEA beam from the Lusas software analysis has a maximum load of 1784 kg. So the difference in the experimental maximum load results with the Lusas software analysis is 10.11%. The experimental BG1 EXP beam has a maximum deflection of 45.21 mm while the BG1 FEA beam from the Lusas software analysis has a maximum deflection of 22.50 mm. From these results, it can be concluded that there is a 67.08% difference in the maximum deflection results.

The experimental BG2 EXP beam has a maximum load of 2700 kg while the BG2 FEA beam from the Lusas software analysis has a maximum load of 2752 kg. So the difference in the experimental maximum load results with the Lusas software analysis is only 1.91% that the difference shows not significant. The experimental BG2 EXP beam has a maximum deflection of 33.5 mm while the BG2 FEA beam from the Lusas software analysis has a maximum deflection of 15.42 mm. From the experimental results and the results of the Lusas software analysis, both prove that the BG2 beam with widening at the support is stronger and stiffer than the BG1 beam.

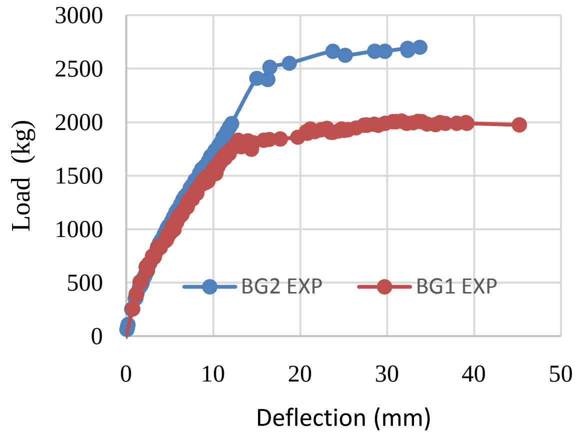

Figure 16. Experimental graph of load-to-deflection relationship between beams BG1 and BG2

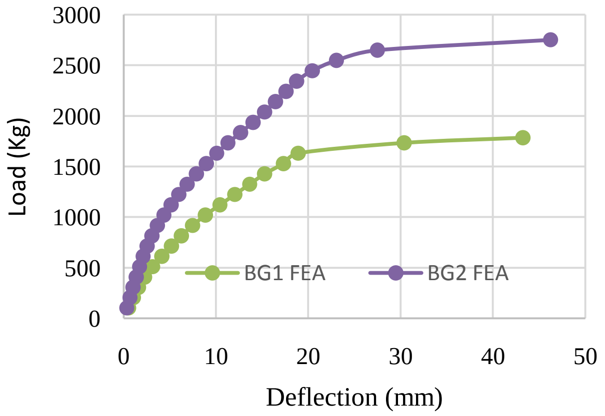

Figure 17. FEA graph of load-to-deflection relationship between beams BG1 and BG2

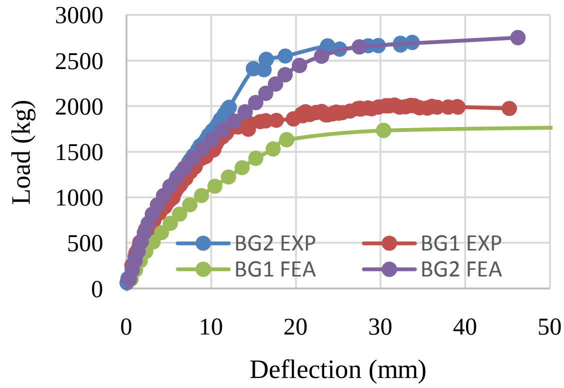

Figure 18. Experimental and FEA comparison graph of load against deflection of beams BG1 and BG2

CONCLUSION

Analysis of nominal moment and shear strength of the beam was carried out using theoretical, experimental, and numerical methods. The three methods prove that the reinforcement of BG1 beam with widening at the beam support is able to increase up to 30-50%. Comparison between experimental testing and FEA shows the behavior of the load relationship to the same deflection at the beginning, after which the stiffness of BG1 beam begins to decrease while BG2 beam remains constant. The reinforcement method with widening at the BG 2 beam support has been proven to be able to increase stiffness although it slightly reduces its ductility. In this study, experimental and FEA methods prove that reinforcement with widening at the beam support tends to increase the nominal moment and shear strength of the beam.

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REFERENCES

Da Conceição, Gilberto De Carvalho, and Ade Lisantono, 2020, “Sambungan Balok Beton Bertulang Pracetak Dengan Lapisan Cfrp Dan Plat Baja.” *Jurnal Teknik Sipil* 15(2): 124–32..

George, Greegar, P. K. Shreeram, A. S. Minalan, K. Lokesh, M. Mano, and Alwyn Prince, 2023, Numerical Investigation on the Flexural Behavior of Geopolymer Concrete Beam Reinforced with Different Types of Fiber-Reinforced Polymer Bars. *Materials Today: Proceedings* (xxxx).

Hernowo, Sigit, and Ade Lisantono, 2016, Retrofitting Sambungan Kolom-Balok Beton Bertulang Ekspansi Planar Segitiga Dengan Variasi Ukuran. *Forum Teknik* 37(1): 1–13.

Khan, Arslan Qayyum, Amorn Pimanmas, and Prinya Chindaprasirt, 2023, Flexural Strengthening of RC Beams Using Sisal Fibre Reinforced Polymer (SFRP) Composite with Anchorage Systems. *Results in Engineering* 18(April): 101116.

Mahendra, A., Muslikh, and A. S. Fajar, 2022, Numerical Simulation Reinforcement of RC T-Beam with Carbon Fiber Reinforced Polymer (CFRP). *Lecture Notes in Civil Engineering* 215(April): 119–35.

Pimanmas, Amorn, and Preeda Chaimahawan, 2010, Shear Strength of Beam-Column Joint with Enlarged Joint Area. *Engineering Structures* 32(9): 2529–45.

Purba, Luki Hariando, Salomo Simanjuntak, Bambang Supriyadi, 2023, Numerical Simulation Of Retrofitting With. *Wahana Teknik Sipil: Jurnal*

Pengembangan Teknik Sipil 28 No. 2(4): 290–99.

Purba, Luki Hariando, Bambang Supriyadi, and Bambang Suhendro, 2023, Long-Term Deflection of Prestressed Concrete Box Girder Bridges Due To Creep and Shrinkage. *International Journal of GEOMATE* 25(107): 17–24.

Supaviriyakit, Teeraphot, Amorn Pimanmas, and Pennung Warnitchai, 2007, Nonlinear Finite Element Analysis Of Non-Seismically Detailed Interior Rc Beam-Column. 24(4): 369–86.