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Research Article

Flexural Behavior Analysis of Geopolymer Reinforced Concrete Beams Using Finite Element Method

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Abstract : This study aims to analyze and validate the flexural behavior of reinforced geopolymer concrete beams compared to conventional concrete using a numerical approach through the Finite Element Method (FEM) with ANSYS software. The simulations were based on geometric and material parameters from previous experimental studies, including those by Abraham et al. (2013), Dattatreya et al. (2011), and Ojha et al. (2022). The simulation results indicate that the load–deflection behavior, crack distribution patterns, and flexural capacity of geopolymer concrete beams are comparable to those of conventional concrete beams. Validation against experimental data shows small deviations in both ultimate load and maximum deflection, confirming the accuracy of the numerical model. Crack propagation in the flexural zone also demonstrates similar characteristics, suggesting that geopolymer concrete is a viable alternative structural material. This research contributes to the development of numerical modeling to support the implementation of geopolymer concrete in sustainable construction.

Keywords: ANSYS; experimental validation; finite element method; flexural behavior; geopolymer concrete; numerical simulation; reinforced concrete beam.

1. Introduction

As construction technology advances, efforts to create environmentally friendly and sustainable materials have become an urgent need, along with growing concerns about the environmental impact of Portland cement production, which contributes significantly to CO_2 emissions. According to Andrew[1]Global Portland cement production in 2017 reached 4.1 billion tons per year and is projected that by 2050 cement consumption will reach 4.83 billion tons per year, which will result in CO_2 emissions of around 4.83 billion tons into the atmosphere, meaning CO_2 emissions will increase by almost the same amount. One promising solution is the use of geopolymer concrete, which utilizes fly ash as an alternative binder to replace conventional cement. Geopolymer concrete is considered to have great potential to support sustainable structural construction because it reduces CO_2 emissions.

Concrete technology has advanced rapidly with the discovery of reinforced concrete, a combination of concrete and steel reinforcement, comprising elements such as beams, columns, slabs, and foundations in buildings. Reinforced concrete beam structures play a crucial role in supporting loads, both gravitational and other loads, which can cause bending, deformation, or instability of the structural elements as a whole.[2]Flexure in beams occurs due to deformation from the loads applied to the elements, affecting the performance of the structural system as a whole. To avoid sudden or brittle compression failure, in flexural design, tensile reinforcement must meet ductility requirements to ensure ductile failure.

Therefore, this study aims to analyze the flexural behavior of geopolymer reinforced concrete beam structural elements with conventional reinforced concrete beams by applying the finite element method using ANSYS software. This analysis was carried out to obtain a more detailed modeling related to the distribution of stress, deformation, and flexural response of the beam and analytical calculations were carried out regarding the maximum load based on SNI 2847:2019 to ensure the validity of the results obtained from the numerical model so as to provide a deeper understanding and develop the potential for its application in sustainable construction.

The problem formulation that this article aims to answer is: (1) How is the modeling of reinforced concrete beams based on experimental data from literature studies using a numerical analysis approach? (2) How is the comparison between experimental data and analysis results using the finite element method with ANSYS software for both types of reinforced concrete beams? and (3) How do you verify the results of the numerical analysis?

2. Literature Review

The flexural behavior of reinforced concrete beams is a fundamental topic in structural analysis, given that beam elements are directly affected by gravity loads, lateral loads such as wind, and deformation due to shrinkage and temperature changes. The strains generated by external loading cause flexural deformations that develop as the load intensity increases, ultimately leading to the formation of flexural cracks until the element's capacity limit is reached. According to Nawy,[3]This condition is called the flexural failure limit state, which marks the end of the structure's ability to withstand additional loads.

The stress distribution in the compression area of the beam, especially when approaching the ultimate condition, follows a non-linear curved shape of the concrete stress-strain curve. In the context of design calculations, the Whitney approach using a rectangular equivalent stress block with an effective height a and an average compressive stress of 0.85f'c is a more practical method than the parabolic approach, without sacrificing analytical accuracy. The nominal flexural strength value of the section, after being multiplied by a reduction factor according to SNI 2847:2019, is used to assess the design capacity against the ultimate moment that may occur in the field.

In recent decades, the emergence of geopolymer concrete as an alternative to conventional concrete has attracted widespread attention, particularly for its contribution to environmental sustainability. Geopolymer concrete is the result of the polymerization of aluminosilicate materials such as fly ash or clay, activated by an alkaline solution. Davidovits, who first proposed this terminology, pointed out that geopolymer concrete can be an environmentally friendly alternative because it does not use Portland cement, a major source of CO_2 emissions in construction. However, the complexity of mixing the materials and controlling the chemical reaction process makes its production more complicated than conventional concrete.

Structurally, reinforced concrete beams experience increasing deflection and flexural strain as the load increases. This process begins with an elastic phase, followed by a post-cracking phase when the tensile strain reaches the concrete's limit, and ends with failure characterized by the crushing of the concrete in the compression zone or the yielding of the tensile reinforcement. Based on the ratio between the concrete and steel strains, beam failure is classified into three conditions: balanced, over-reinforced, and under-reinforced. In a balanced condition, the concrete and steel reach their ultimate strain simultaneously. In an over-reinforced condition, the concrete fails before the steel reinforcement yields, while in an under-reinforced condition, the steel reinforcement yields first, providing a more ductile and safer structural behavior because it provides signs before failure.

The relationship between load and beam deflection is generally represented by a trilinear curve consisting of three phases: pre-crack (elastic), post-crack initial, and post-serviceability (collapse). In the initial phase, the structure exhibits linear elastic behavior, where the deflection increases proportionally with the load. After flexural cracks appear, stiffness changes due to stress redistribution, and when the concrete compression zone reaches its capacity, failure occurs. The type of failure in a beam is strongly influenced by the span-to-depth ratio (a/d ratio). There are three main types of failure according to Nawy (1998): flexural failure (at a/d > 5.5), diagonal tension failure (at a/d = 2.5–5.5), and shear compression failure (at a/d = 1–2.5).

Deflection is also an important parameter in structural design, especially to meet serviceability criteria. The magnitude of deflection is highly dependent on the bending moment and cross-section stiffness (EI), with a mathematical relationship expressed in a differential equation.

$$\frac{d^2v}{dx^2} = \frac{M}{EI}$$

The maximum deflection value in a simple beam with a concentrated load in the middle of the span is formulated as

$$\delta = v_{max} = \frac{PL^3}{48\ x\ EI}$$

whereas for uniform loading it can be calculated using the expression

$$\delta = \frac{5}{384} q \frac{L^4}{EI} + \frac{Pa}{48EI}\ (3L^2 - 4a^2)$$

Given the complexity of reinforced concrete structural behavior, a numerical approach using the Finite Element Method (FEM) becomes crucial. The FEM allows for discrete modeling of continuous structures through a discretization process that divides the geometry into small elements and connects them through nodes. By forming a system of algebraic equations based on the properties of the elements and then solving them simultaneously, the FEM can predict deformation, stress, and failure of a structure. Software such as ANSYS is widely used for this numerical analysis due to its ability to handle various boundary conditions and complex geometries.

Several previous studies have strengthened the validity of this approach. Tjitradi used ANSYS to model the failure of reinforced concrete beams and found that under-reinforced conditions provided higher ductility.[4]Celik showed that geopolymer blocks exhibited similar flexural and shear behavior to conventional blocks although with faster crack initiation.[5]Research by Wibowo using the 3D-NLFEA approach shows high accuracy of moment-curvature prediction compared to experimental results.[6]Meanwhile, Irmawaty showed that the use of geopolymer mortar with PVA fiber can increase the load capacity and reduce the width of beam cracks.[7]A study by Purnamasari and Adawiyah showed that the presence of holes in the cross-section significantly affects structural performance, as well as the importance of local strengthening strategies.[8]

Thus, based on the available literature review, it can be concluded that the study of the flexural behavior of reinforced concrete beams, whether made from cement or geopolymer, requires an integrative approach between material mechanics theory, structural behavior characteristics, and numerical modeling based on the finite element method to obtain accurate and representative results for actual conditions in the field.

3. Method

This study uses a numerical simulation approach based on experimental data obtained from literature studies to analyze the flexural behavior of geopolymer-based reinforced concrete beams compared to conventional reinforced concrete. The data used in the modeling were obtained through tracing and collecting the results of relevant previous studies, especially those that have conducted experimental tests on geopolymer-based reinforced concrete beams with various material compositions and implementation methods. The purpose of this approach is to replicate the test conditions numerically with a finite element analysis model and evaluate the structural parameters that affect the flexural performance of both types of beams.

The research stages begin with a comprehensive literature review of previous studies, such as Abraham's research.[9], Dattatreya[10], and Ojha[11]. These three sources provide detailed descriptions of the beam dimensions, reinforcement configurations, types of concrete constituents, curing methods, as well as test data on compressive strength, flexural strength, splitting tensile strength, and modulus of elasticity. These data are used as the basis for developing numerical modeling. Geometric modeling is carried out according to the test specimen specifications, where SOLID65 solid elements are used to represent concrete due to its ability to model non-linear behavior, including cracking and plastic failure. Steel reinforcement is modeled with LINK180 elements as uniaxial elements with the capacity to withstand tensile and compressive stresses. Bearings and loading plates are modeled using SOLID185 elements that are capable of simulating large deformations and non-linear material behavior.

The meshing process was carried out carefully with cubic mesh shape settings to maintain the accuracy and stability of convergence in the simulation. Nodes between concrete components, loading plates, and support were aligned and linked using the merge item command to ensure structural and numerical interconnection between the elements. The loading scheme in the simulation followed the experimental test scheme from each literature, both two-point and four-point loading. Next, material data was input according to the characteristic values reported in each study, such as compressive strength, elastic modulus, and reinforcement geometric parameters.

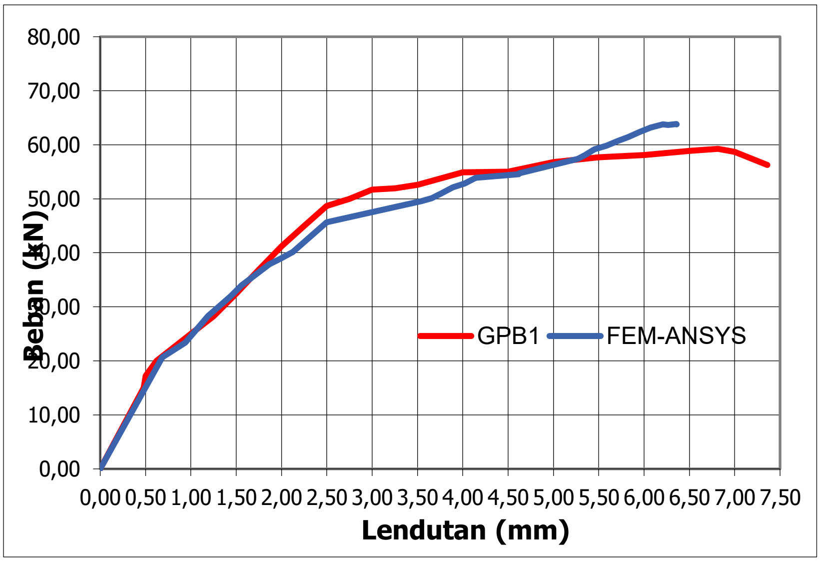
The final stage of this method is the verification process, which compares the results of the numerical simulation with experimental data to assess the validity and accuracy of the modeling. Verification is carried out by reviewing the conformity of the deflection values, crack patterns, and maximum load values obtained from the simulation with the results of laboratory testing. This process aims to ensure that the numerical model is able to represent the actual behavior of reinforced concrete beams under flexural loading conditions. The results of this simulation are then used as a basis for assessing the effectiveness and superiority of geopolymer materials compared to conventional concrete in terms of flexural strength and structural efficiency.

4. Results and Discussion

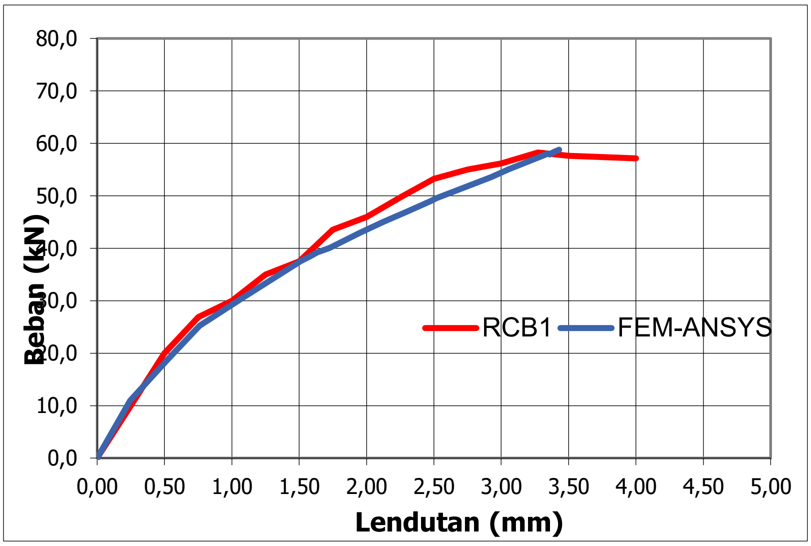
The results of the flexural behavior analysis of geopolymer reinforced concrete beams and conventional reinforced concrete are presented in this section based on numerical modeling using the finite element method (FEM). Simulations were performed using ANSYS software, with reference to geometric parameters, materials, and loading schemes from several previous experimental studies.

This method, which is based on a diverse literature study, aims to broaden the scope of the evaluation and ensure that the FEM model used can accurately represent a variety of experimental conditions. This analysis is based on previous literature studies, which began with Abraham[9], Dattatreya[10], and finished with Ojha[11].

Numerical simulations based on the study by Abraham et al. (2013) were conducted using experimental geometric and material parameters to model the flexural behavior of geopolymer and conventional concrete beams using the finite element method (FEM). The results, as shown in Figure 19, show that the load–deflection relationship curves from the simulations are very close to the experimental results, for both geopolymer and conventional beams. This indicates that the numerical approach used is capable of representing the structural response of both types of beams with high accuracy, especially in the elastic phase up to near maximum load.



(a)



(b)

Figure 1. Load and Deflection Relationship: (a) geopolymer concrete;(b) conventional concrete[9]

Figure 1 shows a comparison of the load and deflection relationship between experimental results and finite element method (FEM) simulation results on geopolymer reinforced concrete beams and conventional concrete. To ensure that the simulation results can be directly validated with the actual behavior of the beam, modeling was performed using the experimental loading configuration and scheme found in previous studies.

In the geopolymer reinforced concrete beam model (Figure 1), the FEM simulation results show a curve pattern very similar to the experimental results. This is especially true for the elastic phase. The simulation results show that the numerical model generally exhibits flexural behavior quite well; the simulated maximum load is slightly larger. Because the elastic modulus values used in the simulation have been calibrated from experimental results, the remaining differences in deflection may be due to errors in model assumptions such as the use of isotropic and homogeneous materials. In addition, factors such as microcracking, shrinkage and creep, and temperature-induced volume changes were not taken into account.

Meanwhile, the conventional reinforced concrete beam model shows excellent agreement between the experimental and simulation curves, especially in the elastic range up to near peak loads. Figure 1 shows that both graphs have nearly identical patterns, indicating that this numerical modeling can accurately represent the flexural response of conventional reinforced concrete beams.

The flexural behavior of geopolymer reinforced concrete beams and conventional reinforced concrete beams obtained from test results and numerical modeling results using the finite element method (FEM) is shown in Table 1. The table presents the maximum load and maximum deflection values of both types of beams, both based on experimental results and FEM simulation results.

Table 1. Comparison of Beam Flexural Capacity (Abraham et.al., 2013)[9]

Test Object Specimen	Collapse Load (kN)		Deflection (mm)	
	Experiment	FEM-ANSYS	Experiment	FEM-ANSYS
GPB1	59.25	63.84	6,814	6,360
RCB1	58.25	58.76	3,273	3,429

As expected, the experimental results showed that the initial cracking in the flexural beams began at mid-span. As the load increased, the crack propagated and expanded along the span. Overall, the crack patterns between geopolymer concrete and conventional concrete were similar.

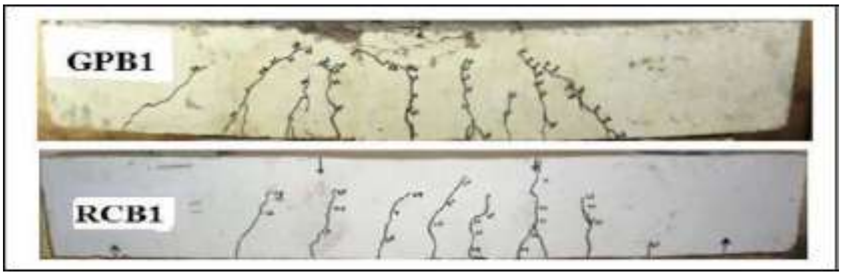


Figure 2. Crack patterns of geopolymer and conventional reinforced concrete (Abraham et. al. 2013)

The distribution and propagation patterns of cracks in geopolymer reinforced concrete beams based on the results of finite element method simulations using ANSYS are shown in Figure 21. Cracks are distributed evenly along the beam span, but are generally concentrated in the mid-span area which is the maximum moment zone.

Figure 3. Crack propagation simulation of RGB1 beam (FEM)–ANSYS) based on experimentsAbraham, et. al. 2013

Figure 3 presents the results of a simulation of the crack propagation pattern of a conventional reinforced concrete beam. The initial crack was identified as appearing in the center of the beam span, and as the load increased, the crack propagated upward, creating additional cracks. In the later stages, the tensile reinforcement yielded.

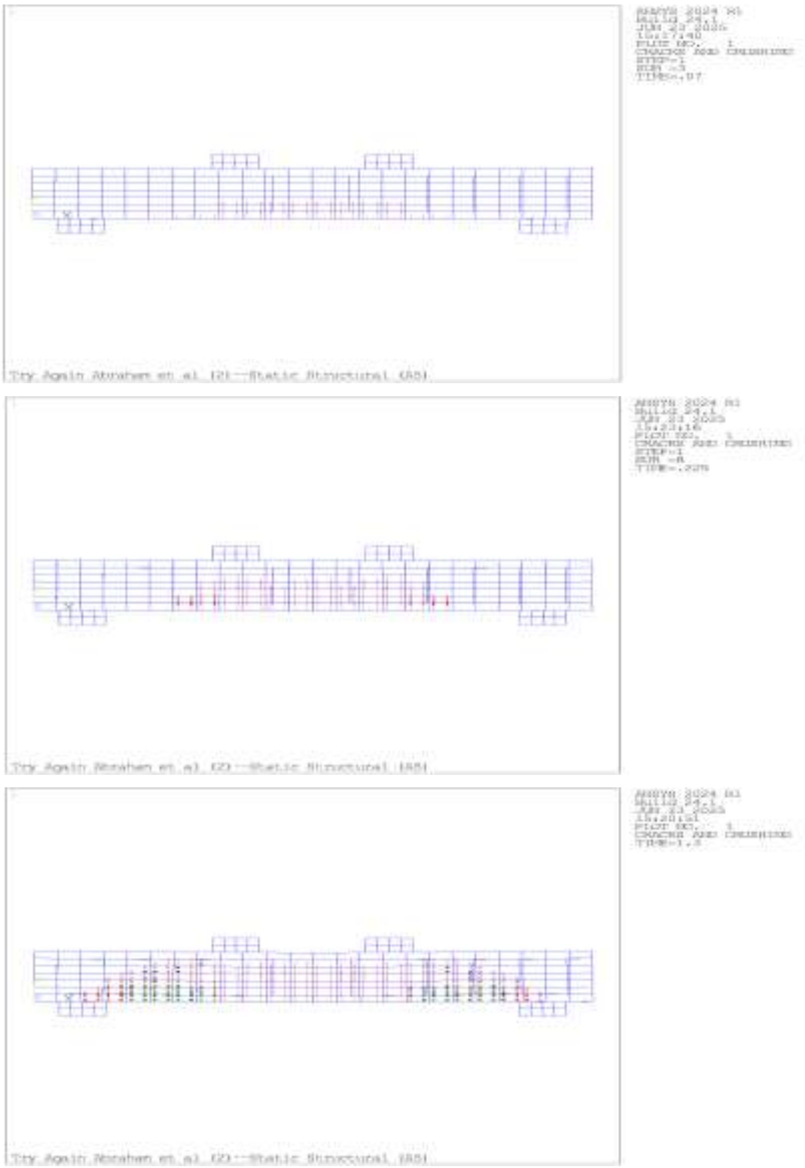
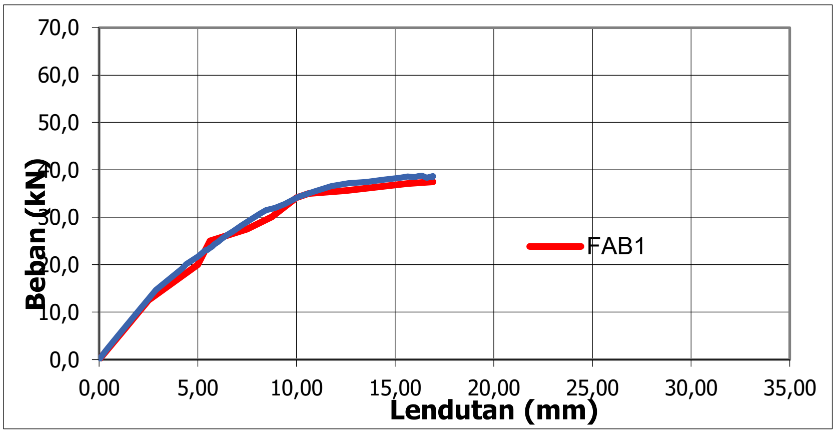
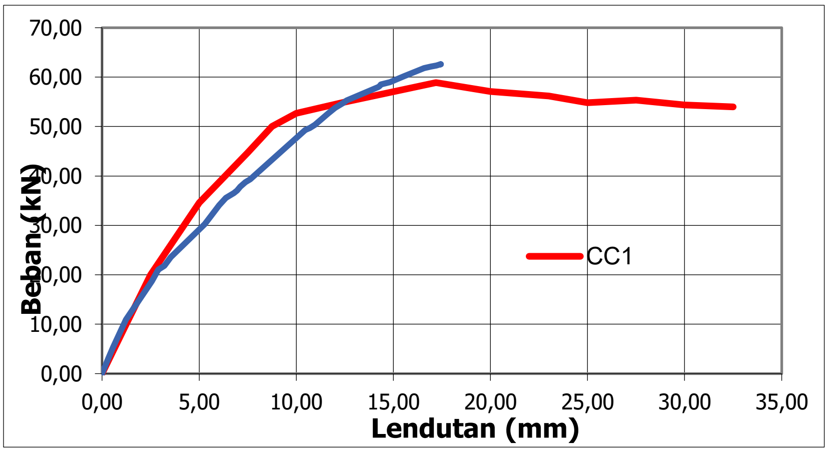


Figure 4. Crack propagation simulation of RCB1 beam (FEM)–ANSYS) based on experimentsAbraham[9]

The numerical simulations performed in this section refer to experimental data from Dattatreya.[10], using the same geometric and material parameters as used in the original tests to ensure consistency in the finite element method (FEM) modeling. Figure 23 presents a comparison between the load-deflection relationship curves from the experimental results and the FEM simulation results for both geopolymer reinforced concrete and conventional concrete beams. Numerical modeling was carried out carefully following the geometric configuration and experimental loading scheme, so that the validity of the simulation results against the actual response of the beams could be directly tested. The results show that the numerical approach is able to represent the flexural behavior of both types of beams with a good degree of accuracy, especially in the elastic range up to near the peak load.



(a)



(b)

Figure 5. Load and Deflection Relationship: (a) geopolymer concrete;(b) conventional concrete (Dattatreya et. al., 2011)

In the geopolymer reinforced concrete beam model (Figure 5), the numerical simulation results show excellent agreement with the experimental data, where both load–deflection relationship curves almost coincide, especially in the elastic range up to near the maximum load, thus indicating that the finite element method (FEM) approach is able to accurately represent the flexural behavior of geopolymer beams. In contrast, in the conventional reinforced concrete beam model (Figure 5), the differences between the simulation and experimental results are more apparent, especially after the peak load is reached, although the general pattern of the curves remains similar; the simulation results show a tendency for a slightly higher maximum load compared to the experimental results, which is likely due to limitations in the numerical model assumptions. Table 2 complements this analysis by presenting the flexural capacity values in the form of failure load and maximum deflection for both types of beams, both based on experimental test data and numerical modeling results, which strengthens the evaluation of the accuracy of the simulation approach used.

Table 2. Comparison of Flexural Capacity of Beams (Dattatreya et.al., 2011)

Test Object Specimen	Collapse Load (kN)		Deflection (mm)	
	Experiment	FEM-ANSYS	Experiment	FEM-ANSYS
FAB1	**37.50**	**38.76**	**16.92**	**15.88**
CC1	**58.90**	**62.61**	**17.19**	**17.44**

Finite element method (FEM) simulation results show that geopolymer and conventional reinforced concrete beams exhibit similar flexural behavior, both in terms of load–deflection relationship curves and crack distribution patterns. Both types of beams exhibit a linear elastic response in the initial loading stage, then experience a significant increase in deflection until they reach the crack point, yielding the reinforcement, and concrete failure. FEM simulations performed using ANSYS software successfully represent this process well, especially in the phase before the maximum load is reached. The observed crack patterns, both from simulations and experimental data, indicate crack initiation that appears in the tension zone at mid-span and develops vertically toward the compression zone, which then expands following the maximum moment distribution. This strengthens the validity of the FEM model in accurately capturing the flexural failure process.

Numerical simulations using the finite element method (FEM) on geopolymer and conventional reinforced concrete beams show that crack propagation in both types of beams occurs similarly. The results of the study by Dattatreya[10]and Ojha[11], both in experimental observations and simulation results, show that the initial crack always appears in the flexural zone at the mid-span, just below the loading point, which is the region with the maximum bending moment. As the load increases, the crack develops vertically from the tension side towards the compression zone and propagates outward along the beam span. The FEM simulation visualizations generated by ANSYS consistently show realistic and validated crack distribution patterns and propagation directions, where the crack pattern in geopolymer concrete beams is almost indistinguishable from conventional concrete beams.

In terms of the load and deflection relationship, the simulation refers to the experimental data of Ojha[11]shows that the graphs for geopolymer concrete beams show good agreement with the experimental results, especially in the initial elastic phase until near the maximum load. Deviations begin to appear after the peak load point is reached, where the simulated deflection is slightly lower than the test data. In contrast, for conventional concrete beams, the simulation produces load values that tend to be higher along the curve, especially in the plastic phase. This is thought to be caused by the use of ideal material input parameters in numerical modeling, especially the concrete's elastic modulus, which often does not reflect actual conditions such as variations in temperature, humidity, and material defects that affect experimental results.

Based on the test and simulation results on flexural capacity, the values of collapse load and maximum deflection were obtained which were relatively close between the experimental results and the FEM results. The M40 RGC BEAM 1 beam (geopolymer concrete) showed a collapse load of 178.70 kN in the experiment and 174.70 kN in the simulation, as well as deflections of 24.76 mm and 24.21 mm respectively. Meanwhile, the M40 RCC BEAM 1 beam (conventional concrete) recorded a collapse load of 162.50 kN in the experiment and 170.85 kN in the simulation, as well as deflections of 28.62 mm and 27.81 mm respectively. These results strengthen the finding that the finite element method numerical model is able to represent the flexural behavior and failure patterns of reinforced concrete beams, both geopolymer and conventional, with a high level of accuracy and valid technical reliability against experimental data.

4.1 Comparison of Geopolymer and Conventional Concrete Performance

Finite element method (FEM) simulation results show that geopolymer and conventional reinforced concrete beams exhibit similar flexural behavior, both in terms of load–deflection relationship curves and crack distribution patterns. Both types of beams exhibit a linear elastic response in the initial loading stage, then experience a significant increase in deflection until they reach the crack point, yielding the reinforcement, and concrete failure. FEM simulations performed using ANSYS software successfully represent this process well, especially in the phase before the maximum load is reached. The observed crack patterns, both from simulations and experimental data, indicate crack initiation that appears in the tension zone at mid-span and develops vertically toward the compression zone, which then expands following the maximum moment distribution. This strengthens the validity of the FEM model in accurately capturing the flexural failure process.

Validation was carried out by comparing the simulation results against experimental data from three main studies, namely Abraham[9]Dattatreya[10]and Ojha[11]by reviewing the parameters of collapse load and maximum deflection. The validation results from Abraham's study showed an average deviation of 5.72% for deflection and 4.31% for maximum load, with simulation values close to the experimental results and theoretical calculations based on SNI 2847:2019. In Dattatreya's study, the comparison between simulation and experiment also produced a small deviation, namely an average of 3.78% for deflection and 4.83% for maximum load. These results again show that the numerical approach through FEM is quite reliable in modeling the structural performance of both types of beams.

Meanwhile, validation based on data from Ojha[11]provided the smallest deviation compared to the two previous studies, namely 2.13% for maximum deflection and 3.69% for collapse load. Calculations based on SNI 2847:2019 also showed good consistency with the experimental results. Thus, it can be concluded that the numerical model of the finite element method used in this study is able to model the flexural behavior of reinforced concrete beams, both geopolymer and conventional, with a high level of accuracy and in accordance with national technical planning standards.

5. Comparison

Research conducted by Tjitradi[4]entitled "3D ANSYS Numerical Modeling of Reinforced Concrete Beam Behavior Under Different Collapsed Mechanisms" focuses on the analysis of reinforced concrete beam behavior with various failure mechanisms, especially tensile failure. The results show that beams with smaller steel reinforcement ratios tend to exhibit more ductile behavior compared to beams experiencing compression failure. Simulations using ANSYS software produce outputs that are consistent with manual calculations based on SNI 03-2847, especially in terms of flexural capacity and stress distribution. The similarity with this study lies in the use of the finite element method (FEM) to study flexural behavior, but the main focus of Tjitradi's study is on the effect of variations in the reinforcement ratio, not on the material comparison between conventional concrete and geopolymer.

Next, Celik[5]In his research entitled "Numerical Analysis of Flexural and Shear Behaviors of Geopolymer Concrete Beams" discussed the comparison between geopolymer concrete (GPC) and Portland cement-based concrete (OPC) beams in terms of response to flexural and shear loads. The results showed that both types of concrete have comparable mechanical properties and fracture patterns, although GPC showed slightly faster crack initiation. This study used a numerical approach based on FEM, but did not specifically model reinforced beams and did not validate against standards such as SNI. The difference with this study lies in the absence of structural discussion of reinforcing elements and a design approach based on national technical regulations.

Research by Wibowo[6]entitled "Numerical Investigation of Geopolymer Reinforced Concrete Beams Under Flexural Loading Using Finite Element Analysis" focuses its study on the numerical simulation of reinforced geopolymer concrete beams under flexural loads using 3D-NLFEA software. This study successfully modeled the moment-curvature relationship and predicted crack patterns accurately, with deviations from the predictions to experimental data ranging from 1.3% to 2.4%. The advantage of this approach is the use of a multi-surface plasticity model to represent the nonlinear behavior of concrete. However, significant differences with this study lie in the software used and the absence of model validation against national design standards such as SNI 2847:2019. This study also does not discuss the equivalence between geopolymer concrete and conventional concrete in the context of broader structural design applications.

Thus, while previous studies provide important conceptual and methodological foundations, there are still research gaps in the validation of numerical models against national standards and in the direct assessment of the structural performance equivalence between conventional and geopolymer concrete in the context of reinforced beams. This research aims to fill these gaps.

6. Conclusion

Based on the results of numerical evaluation conducted using the finite element method, it was obtained that geopolymer-based reinforced concrete beams showed flexural performance comparable to conventional reinforced concrete, both in terms of collapse load, deflection, and crack patterns. Simulations conducted using ANSYS software with SOLID65, LINK180, and SOLID185 elements were able to represent flexural behavior accurately, with an average deviation below 10% compared to experimental data. Validation of theoretical results based on SNI 2847:2019 showed consistency and strengthened the reliability of the simulation model used.

The relationship between load and deflection produced in both types of concrete shows typical and consistent stages of structural behavior, including the initial elastic phase, initial cracking, and failure. This indicates that geopolymer concrete has an acceptable structural response and follows the basic design pattern of flexible elements. Therefore, the design standards currently used for conventional concrete can generally be applied to geopolymer concrete with some adjustments to the material parameters.

To support these findings and improve generalizability, further research is recommended, including experimental testing with more varied load types, such as cyclic loads or a combination of bending and shear. Furthermore, nonlinear numerical modeling that considers long-term effects such as creep and shrinkage is needed. Comparisons with deflection calculations based on SNI also show significant discrepancies, requiring further review to improve the model's accuracy and relevance in future structural designs.

Author Contribution: This research is part of a student's final assignment, where Reynaldo Jeremy Sela (Author 1*) acts as the main author responsible for study design, literature data collection, numerical modeling with the finite element method, analysis of results, and manuscript preparation. Dody MJ Sumajouw (Author 2) and Mieke RIAJ Mondoringin (Author 3) act as supervisors who provide conceptual guidance, methodological supervision, academic validation of modeling and analysis results, and corrections to the substance and structure of scientific writing.

All authorshas read and approved the final version of the manuscript submitted for publication.

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Reference

[1] RM Andrew, "Global CO 2 emissions from cement production,"*Earth Syst. Sci. Data*, vol. 10, no. 1, p. 195–217, 2018.
[2] MD Sumajouw, P. Christian, and SO Dapas,*Geopolymer Reinforced Concrete Structural Elements*. Andi, 2013.
[3] EG Nawy, T. Surjaman, and B. Suryoatmono,*Reinforced Concrete: a basic approach*. PT. Eresco, Bandung, 1990.
[4] D. Tjitradi, E. Eliatun, and S. Taufik, "3D ANSYS numerical modeling of reinforced concrete beam behavior under different mechanisms collapsed,"*Int. J. Mech. Appl.*, pp. 14–23, 2017.
[5] A.İ. Çelik, A. Özbayrak, A. Şener, and MC Acar, "Numerical analysis of flexural and shear behaviors of geopolymer concrete beams,"*J. Sustain. Constr. Mater. Technol.*, vol. 7, no. 2, Art. no. 2, Jun 2022, doi: 10.47481/jscmt.1116561.
[6] YN Wibowo, B. Piscesa, and Y. Tajunnisa, "Numerical Investigation of Geopolymer Reinforced Concrete Beams Under Flexural Loading Using 3Dnlfea,"*J. Civ. Eng.*, vol. 37, no. 1, p. 27–32, 2022.
[7] MN Hakrah, "STUDY OF REINFORCED CONCRETE BEAMS REINFORCING BEHAVIOR WITH GEOPOLYMER MORTAR AND GROUTING MATERIAL," other, Hasanuddin University, 2023. Accessed: July 6, 2025. [Online]. Available at: https://repository.unhas.ac.id/id/eprint/27194/
[8] "The Effect of Holes on Reinforcement in Reinforced Concrete Beams... - Google Scholar." Accessed: July 6, 2025. [Online]. Available at: https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=The Effect of Holes on Reinforcement in Reinforced Concrete Beams Based on SNI 2847%3A2013&btnG=
[9] R. Abraham, S. Raj, and V. Abraham, "Strength and behavior of geopolymer concrete beams,"*Int. J. Innov. Res. Sci. Eng. Technol.*, vol. 2, no. 1, p. 159–166, 2013.
[10] "Flexural behavior of reinforced geopolymer concrete beams." Accessed: July 6, 2025. [Online]. Available at: https://ieeexplore.ieee.org/abstract/document/7755347
[11] PN Ojha, B. Singh, A. Trivedi, P. Singh, A. Singh, and C. Pede, "Short-term mechanical performance and flexural behavior of reinforced slag-fly ash-based geopolymer concrete beams in comparison to OPC-based concrete beams,"*J. Res. Eng. Struct. Mater.*, vol. 9, no. 1, p. 31–51, 2023.