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COMPARATIVE STUDY OF FLEXURAL PERFORMANCE OF GEOPOLYMER AND PORTLAND CEMENT CONCRETE BEAM USING FINITE ELEMENT ANALYSIS

*Muhammad Sigit Darmawan[1], Yuyun Tajunnisa [2], Priyo Suprobo[3], Wahyuniarsih Sutrisno[4], and Muhammad Wildan Aziz[5]

[1,2] Faculty of Vocations, Institut Teknologi Sepuluh Nopember Surabaya, Indonesia;
[3-5] Faculty of Civil, Planning, and Geo Engineering, Institut Teknologi Sepuluh Nopember Surabaya, Indonesia

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ABSTRACT: Geopolymer concrete is an innovative construction material that has been developed to substitute OPC concrete. Compared to OPC concrete, geopolymer concrete has better strength and bond performance. As geopolymer concrete uses waste material such as fly ash, it produces less CO2, and it is more environment-friendly than OPC concrete. In order to ensure the safety of the structure, structural response analysis is needed to be carried out, and flexural performance is one of the important analyses. Previous studies related to geopolymer concrete performance are mainly performed experimentally, which is time-consuming and uneconomical. This research conducted a comparative study of flexural performance and cracked pattern of Geopolymer and OPC concrete using finite element analysis. The OPC and Geopolymer beam was analyzed using ATENA 3D FEA. The finite element simulation using ATENA 3D showed a similar load-displacement pattern to the experimental results. However, the finite element result showed lower ultimate displacement than the experimental results. Based on the finite element modeling result, it was found that the Geopolymer concrete beam has better flexural performance than OPC. It was shown by the post-yield deflection of GPC, which has a 44% higher value of deflection and 12% higher ductility value than OPC with higher compressive strength.

Keywords: Finite Element Analysis, Geopolymer Concrete Structure, Portland Concrete Structure, Flexural Performance

1. INTRODUCTION

Geopolymer concrete is a promising substitution or even a replacement material for Portland cement concrete. In the geopolymer or polymerization process, the alkali activators react with high Alumina and Silica materials [1]. Geopolymer concrete has high compressive strength, and it also has high fire-resistant properties [2]. Moreover, it has dimensional stability and acid-resistant materials for engineering applications [3]. Raw materials of Geopolymer, created from common waste materials (ex: fly ash), contain high alumina, silica, and alkali activator. Therefore, Geopolymer has less pollution in its production as it uses waste materials than conventional Portland cement concrete. This is due to the fact that the cement production industry is estimated to produce 5% of the total carbon dioxide gas emissions [4]. One of the raw materials of Geopolymer is fly ash. It is a waste material from the power plants industry. As a waste material, the utilization of fly ash is still limited, and it is less than half of the production. For example, out of 54 million metric tons of fly ash produced in 2013, only 23 million metric tons (42.6%) were used, and the rest were dumped as waste materials [5].

An analysis of structural response requires to be conducted to ensure the geopolymer structure's safety. As an integral aspect of the flexural elements, load-deflection capacity needs to be analyzed to ensure the performance of the geopolymer structure. Experimental research performed by Ranjbar et al. compared the performance of Geopolymer with OPC reinforced concrete specimens. This study found that geopolymer concrete beam had a slightly higher load-carrying capacity than the Portland cement concrete beam, even though the Portland concrete had higher compressive strength than geopolymer concrete [6]. Another study performed by Abraham et al. focused on flexural behavior and ductility of reinforced concrete beams. It compared Geopolymer with Portland cement specimens with the same compressive strength. The results showed that the curvature ductility of the geopolymer beam was greater than the Portland cement beam [7].

Geopolymer concrete had several eminences such as fire resistance, durability, and bond performance compared to OPC concrete. Concerning bond behavior, geopolymer concrete had better bonding with steel reinforcement compared to OPC concrete with similar pull-out testing parameters [8].

Previous studies related to the flexural performance of geopolymer concrete showed that geopolymer concrete has a higher load-deflection value than that OPC concrete. However, to better understand the geopolymer structural element behavior, a lot of experimental tests should be performed, and it is time-consuming and uneconomical. Finite element simulation is one of the solutions that can help understand the full behavior of geopolymer concrete. Therefore, in this research, a finite element simulation using ATENA 3D FEM was performed to analyze the flexural performance of geopolymer concrete. A simulation of the OPC concrete beam was performed in this research to compare its flexural behavior with geopolymer concrete. All the simulation results were compared with the experimental results to see the robustness of the numerical simulation.

2. RESEARCH SIGNIFICANCE

As geopolymer concrete is new material in the construction industry, its structural behavior is still not fully known. Therefore, research to study the behavior of geopolymer concrete is needed. Flexural behavior can be defined through ultimate moment capacity, the value of ductility and the crack pattern of the beam to identify the failure. Even though the experimental test is the best way to observe the real behavior of the structural element, it was proved to be time-consuming and expensive. Therefore, in this research, numerical analysis using ATENA 3D FEA was used to simulate and predict the flexural behavior of the Geopolymer beam.

3. COMPARISON OF HARDENED CONCRETE MECHANICAL PROPERTIES

3.1 Compressive Strength

Geopolymer concrete compressive strength was affected linearly by the average particle size distribution and fly ash source [9]. The higher concentration or molarity of sodium hydroxide solution and the ratio of sodium silicate to sodium hydroxide increased the compressive strength of the geopolymer concrete [10]. The higher sodium hydroxide (NaOH) concentration, which acts as an alkaline activator on geopolymer concrete, could help raise geopolymer concrete compressive strength. The research indicated that the amount of strength of 3 different sodium hydroxide concentrations: 8 M, 12 M, and 16 M, showed different compressive strengths of geopolymer paste results [11]. Comparative studies on dry method Geopolymer and Portland cement concrete discovered that lower water-cement ratio produced higher compressive strength of geopolymer concrete [12]. Patankar et al. found that higher temperature in the heat curing treatment produced high compressive strength of geopolymer mortar. In addition, Patankar et al. discovered that a higher concentration of sodium hydroxide in an alkaline activator solution generated higher compressive strength of geopolymer mortar [13]. Other research conducted by Patankar et al. found that the finesses of fly ash as a raw material of geopolymer concrete affect the compressive strength of geopolymer concrete. The results showed that when the quantity of fly ash increased, the compressive strength of geopolymer concrete increased [14].

3.2 Tensile Strength

The tensile strength of geopolymer cement was better than Portland cement. Low Young Modulus, which produced shrinkage strain, was lower than the material's tensile strength. It provides higher resistance to the generation of microcracks [15]. The tensile strength of the Geopolymer concrete and Portland Cement concrete did not have much difference. It still needed reinforcement when it was applied to the main building structure.

Nonetheless, geopolymer concrete had a better adhesive strength [16]. Sarker obtained that the bond strength of geopolymer concrete was higher for the same compressive strength than that of Portland cement concrete. This was due to the tensile strength effect of geopolymer concrete, which was higher than that of PC concrete [17]. The tensile strength of geopolymer concrete depended on the initiation of cracks in the concrete material [18]. Al Majidi found that in dog bone-shaped geopolymer mortar specimens, the flexural strength and tensile strength increased with the increasing levels of GGBFS [19]. Mohammad et al. discovered that the optimal percentage of sodium metasilicate solids mixed in an alkaline activator was 12% of the required geopolymer cement, yet there was a 22% decrease in the tensile strength geopolymer concrete compared to the optimal mixture [20].

The value of the tensile strength of geopolymer concrete can be calculated using equation 1 [21]. The approach Portland cement concrete was taken using eq. 2 [22].

$$f_{ct\_GPC} = 0.7\sqrt{f'_{co}} \quad (1)$$

$$f_{ct\_OPC} = 0.36\sqrt{f'_{co}} \quad (2)$$

3.3 Elastic Modulus of Concrete

The modulus of elasticity of geopolymer concrete was smaller than Portland concrete (OPC). The modulus of elasticity of geopolymer concrete was calculated using Eq. (3) [23].

$$E_{GPC} = -11400 + 4712\sqrt{f'_c} \quad (3)$$

Meanwhile, the modulus of elasticity of Portland cement concrete was calculated according to the equation listed in ACI 318-19 using Eq. (5).

$$\boldsymbol{E_{GPC} = 2707\sqrt{f'_{co}} + 5300}$$
(4)

$$\boldsymbol{E_{OPC} = 4700\sqrt{f'_c}} \quad (5)$$

3.4 Poisson's Ratio of Concrete

Poisson's ratio is the ratio between the strain that occurs in the horizontal or transverse direction to the strain that occurs in the vertical or axial direction. The Poisson's ratio of geopolymer concrete ranged between 0.2 – 0.24 [24]. Previous research showed that the Poisson's ratio value for geopolymer concrete was 0.15 [21], whereas Portland cement material was 0.2 [22]. It can be seen that geopolymer concrete has a slightly lower Poisson's ratio compared to portland cement concrete.

3.5 Bonding Adhesive Between Reinforcement and Concrete

This study indicated that geopolymer concrete had a better bonding strength with reinforcement than Portland cement concrete, with the same compressive strength value. Several values affected the bond strength of concrete materials with the reinforcement, and one of them was the strength of the materials. The tensile strength of the Geopolymer concrete was relatively higher compared with Portland cement concrete with the same compressive strength properties. This condition directly affected the bonding of geopolymer concrete with the reinforcement, so the Geopolymer concrete had higher bonding strength than Portland cement concrete with similar compressive strength [17], [25]. Previous studies state that the bonding strength of the concrete material increased when the concrete cover and compressive strength increased [17].

4. STRUCTURAL PROPERTIES OF CONCRETE

4.1 Flexural Properties of Reinforced Concrete

An experimental study was carried out to compare flexural behavior between Geopolymer cement (GPC) reinforced concrete and Ordinary Portland cement (OPC) reinforced concrete. Load deflection behavior of OPC and GPC had a similar shape of curvature curve. The first crack and service load of the GPC beam was slightly higher when it was compared to the OPC beam [26]. The ultimate load capacity of the GPC beam was 16.27% higher than the OPC beam [26].

Another test was also performed to study the flexural behavior of the GPC beam. Specimen geometry used in the experimental test is shown in Fig 1. Shear and longitudinal reinforcing steel used in the test was 10 mm in diameter with a tensile strength of 548 MPa and ultimate strength of 675 MPa. Meanwhile, a beam with 200 mm height, 150 mm width, and 1700 mm span was used for the cross-sectional specimen. The test applied a 4-point bending test [27]. Test results also showed a significantly large serviceability displacement of GPC. It was 400% higher than Portland cement reinforced concrete (OPC) [27].

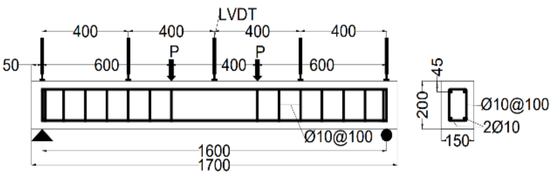

Fig. 1 Geometry and Cross Section of Beam Specimen [27]

Table 1 Variation of Experimental Research Specimens [27]

Beam	A_s (mm^2)	f_c' (MPa)	E_c (MPa)	f_{ct} (MPa)
OPC	157	33	27.0	3.4
GPC	157	44	19.9	3.7

Table 2 Experimental Load, Center Deflection of Beam on Various Conditions [27]

Beam	$P_{maximium}$ (kN)	$\delta_{service}$ (mm)	δ_{yield} (mm)	$\delta_{ultimate}$ (mm)
OPC	26.3	3.8	9.3	38
GPC	28.6	6.4	12.1	42

4.2 Reinforced Concrete Beam Crack Pattern

The crack pattern identification, which is associated with the flexural behavior of concrete, can be observed experimentally or using numerical simulation. Ranjbar et al. evaluate the cracks in reinforced concrete with multiple layers of precast geopolymer material experimentally. A compelling result showed that the value of the load capacity of the specimen with full GPC material (B5) with crack pattern in Fig.2 was similar to that of the OPC material specimen (B1) with the crack pattern shown in Fig 3. The compressive strength of geopolymer concrete was lower than the compressive strength of portland cement concrete. However, the flexural ability of geopolymer concrete was higher compared to the flexural ability of OPC at a similar load-bearing capacity. Previous experimental studies with B2, B3, and B4 specimens showed that the increasing mixture between geopolymer concrete and Portland cement concrete increased load-bearing capacity. When it was compared to the full specimens with a mixture of GPC (B5) and OPC (B1), specimens B2, B3, and B4 indicated higher load-carrying capacities [6].

Another study discussed experimental and numerical reinforced concrete beam crack patterns. The half-span modeling crack pattern results using the 3D ATENA program were similar to the experimental four bending point test [28]. Therefore, the analysis of the flexural cracking pattern of the reinforced concrete beam in this study was performed by using a finite element method with the help of ATENA 3D program. The results were compared to previous studies' experimental crack pattern collapse results [29].

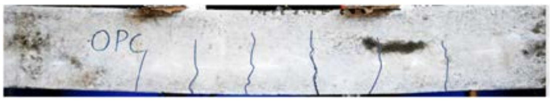

Fig. 2 Crack Pattern on Reinforced Portland Concrete Beam [27]

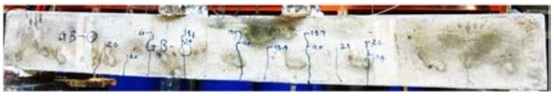

Fig. 3 Crack Pattern on Reinforced Geopolymer Concrete Beam [27]

5. MODELING CONSIDERATION

5.1 Concrete Stress-Strain Constitutive Model

GPC specimen modified stress-strain model for fly-ash based geopolymer concrete based on Prachasaree's concrete model gives the compressive stress (fc') for a given strain in terms of the maximum compressive stress (fc'). According to final strain, concrete model is modified using strain at peak stress, as in the Eq. (11) [30]. The fracture energy of GPC is 10 times higher than OPC based on experimental research.

$$\boldsymbol{f_c = f'_c\left[n\left(\frac{\varepsilon}{\varepsilon_o}\right) \Big/ (n-1) + \left(\frac{\varepsilon}{\varepsilon_o}\right)^{nk} \right]} \quad (6)$$

$$\boldsymbol{E_i / E_o = \frac{n}{n} - 1} \quad (7)$$

$$\boldsymbol{n = 0.5 + \left(\frac{f'_c}{14.3}\right) - \left(3 \times \frac{{f'_c}^2}{10^4}\right)} \quad (8)$$

$$\boldsymbol{\varepsilon_o = 0.0051 - \left(4 \times \frac{f'_c}{10^5}\right)} \quad (9)$$

According to the ATENA Manual, the tensile stress-strain model is defined in 3 parts [30]. Uncracked, Process Zone, and Cracked Zone.

$$\boldsymbol{\sigma_c^{ef} = E_c \times \varepsilon^{eq}, 0 \leq \sigma_c \leq f_t'^{ef}} \quad (10)$$

$$\boldsymbol{W_c = \frac{2 \times G_f}{f'_t}} \quad (11)$$

$$\boldsymbol{w = \varepsilon_{cr} \times L'_t} \quad (12)$$

$$\boldsymbol{G_f = 0.000025 \times F_T} \quad (13)$$

The constitutive concrete model as CEB-FIP model code 1990 was used in this research. The concrete's compressive and tension stress-strain is shown in Fig.4 and Fig.5, using Eq. (6) and Eq. (7) for the OPC specimen.

$$\boldsymbol{\sigma_c{}^{ef} = f_c{}'^{ef}\ \frac{kx - x^2}{1 + (k-2)x}} \quad (14)$$

$$\boldsymbol{x = \frac{\varepsilon}{\varepsilon_c}\ , k = \frac{E_o}{E_c}} \quad (15)$$

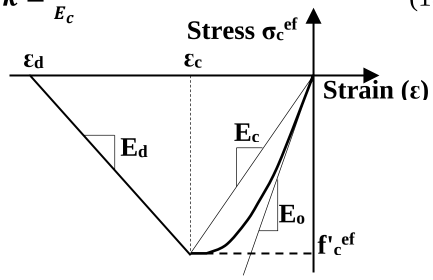

Fig. 4 Compressive Stress-Strain of Concrete Constitutive Model [31]

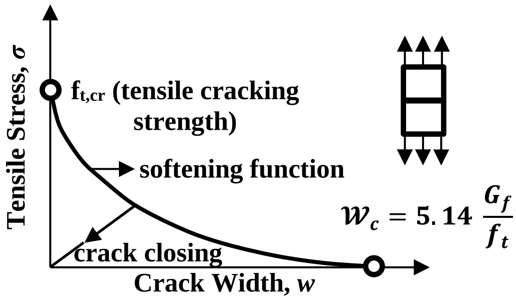

Fig. 5 Tension Stress-Strain of Concrete Constitutive Model [31],[32]

5.2 Steel Reinforcement Stress-Strain Constitutive Model

The stress-strain material model of reinforcing steel bars and confinements was modeled as an idealized isotropic hardening material with a bilinear curve, as shown in Fig. 6 [27].

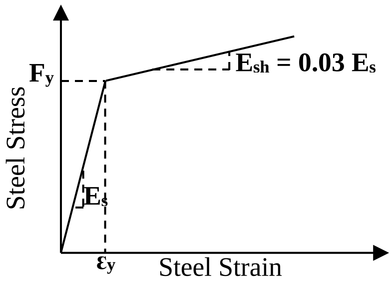

Fig. 6 Stress-Strain for Steel Reinforcement [27]

6. RESULT AND DISCUSSION

6.1. Flexural Performance of Geopolymer and Portland Cement Concrete Beam Structure

Finite element analysis was performed by using ATENA 3D FEM to simulate the flexural response of the Geopolymer and Portland cement beam. A comparative study of load-deflection and crack patterns of beam was performed in this research.

The nonlinear analysis of concrete beam structure was performed using the Newton-Raphson method, and the displacement control loading using ATENA 3D FEM software based on experimental research by Tran [27].

Table 3 OPC and GPC Material Properties [27]

Beam	f_{ct} (MPa)	f_c' (MPa)	E_c (Gpa)
OPC	3.4	33	27
GPC	3.7	44	19.9

Table 4 OPC and GPC Material Properties

Beam	υ	Gf (MN/m)	Wd (m)
OPC	0.2 [22]	8.5E-05	-5E-04
GPC	0.15 [21]	2.8E-04	-5E-04

Table 5 Reinforcement Properties (Ø10 mm) [27]

E_s (Gpa)	E_{sh} (Gpa)	f_y (MPa)	f_u (MPa)
200	6	548	675

The bond between steel reinforcement and concrete depended primarily on the contact area, the surface texture of reinforcing bars, bar diameter, and concrete cover [33]. Therefore the load-carrying capacity was affected by the un-bonded length of tensile reinforcement [33]. Specific fracture energy (Gf) and critical compressive displacement were counted using the default equation as used in the ATENA 3D [34].

The difference between those two models on ATENA 3D was in the concrete material properties, the experimental research, and the bond for reinforcement (bond-slip relation), which were based on CEB-FIP model code 1990 [31]. As a previous study discovered that the Geopolymer concrete had better bond strength than the Portland concrete [17], the bond for reinforcement of the geopolymer concrete assumed was modeled as "good condition"; otherwise, the Portland concrete was modeled as "all other cases" confined concrete. Fig. 7 and Table 6 define parameters based on CEB-FIP model code 1990 for the nonlinear analysis by ATENA 3D:

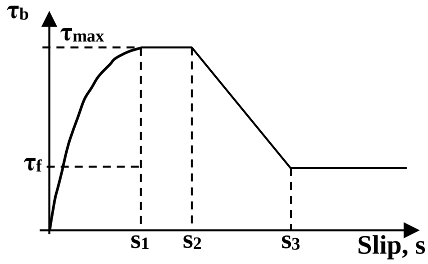

Fig. 7 Bond-Slip Law Based on CEB-FIP Model Code 1990 [31]

$$\tau_b = \tau_{max} \times \left(\frac{S}{S_1}\right)^{\alpha}, 0 \leq S \leq S_1 \quad (16)$$

$$\tau_b = \tau_{max}\ , S_1 < S \leq S_2 \quad (17)$$

$$\tau_b = \tau_{max} - \left(\tau_{max} - \tau_f\right) \times \left(\frac{S - S_2}{S_3 - S_2}\right)$$
$$, S_2 < S \leq S_3 \quad (18)$$

$$\tau_b = \tau_f\ , S_3 < S \quad (19)$$

Table 6 Bond-Slip Model for Reinforcement Parameter [31]

Category	OPC	GPC
Confinement	Confined	Confined
Bond Condition	All other cases	Good
S_1	1 mm	1 mm
S_2	3 mm	3 mm
S_3	90 mm	90 mm
α	0.4	0.4
τ_{max}	$1.25 \times \sqrt{fc'}$	$2.5 \times \sqrt{fc'}$
τ_f	0.4 τ_{max}	0.4 τ_{max}

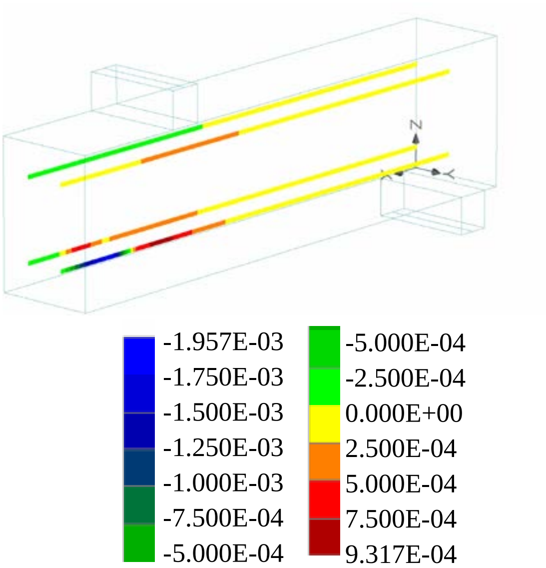

Fig. 8 Reinforcement Bond-Strength OPC Beam

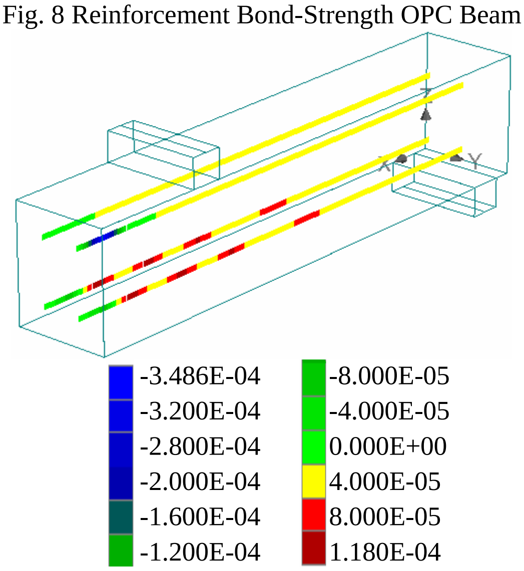

Fig. 9 Reinforcement Bond-Strength GPC Beam

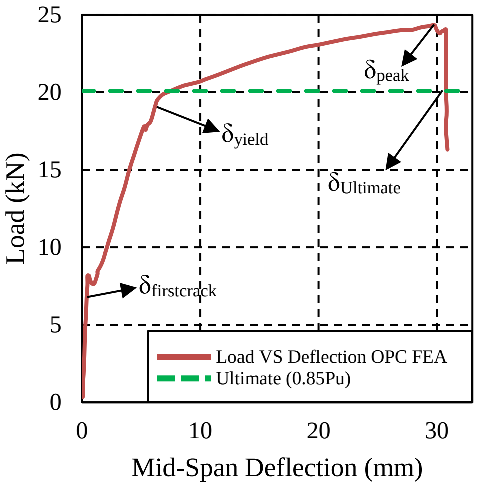

Fig. 10 Load-Deflection Curve of OPC Beam Structure using Finite Element Analysis

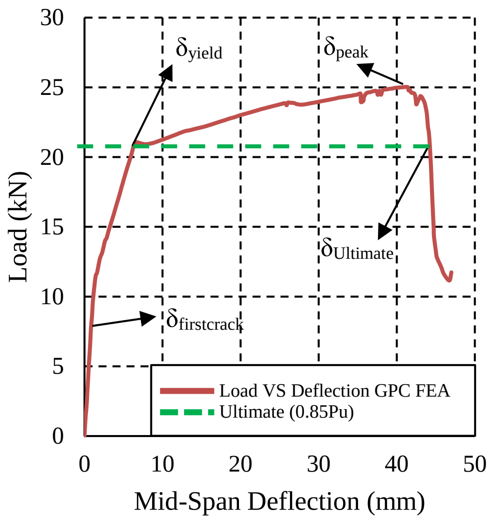

Fig. 11 Load-Deflection Curve of GPC Beam Structure using Finite Element Analysis

Table 7 Value of Yield and Ultimate Deflection Comparison on Experimental Research & Finite Element Analysis

Beam	fc' (MPa)	Experiment [27]		Finite Element	
		δ_{yield}	$\delta_{ultimate}$	δ_{yield}	$\delta_{ultimate}$
OPC	33	9.3	38	6.4	30.8
GPC	44	12.1	42	8.22	44.24

Table 8 First Crack Deflection and Maximum Load Comparison on Experimental Research & Finite Element Analysis

Beam	fc' (MPa)	Experiment [27]		Finite Element	
		$\delta_{firstcrack}$ (mm)	$P_{maximum}$ (kN)	$\delta_{firstcrack}$ (mm)	$P_{maximum}$ (kN)
OPC	33	0.41	26.3	0.46	24.3
GPC	44	0.63	28.6	0.82	25.03

Table 9 Comparison of Ductility Experiment and FEA

Beam	fc' (MPa)	Experimental Ductility [27]	Finite Element Ductility
OPC	33	4.1	4.8
GPC	44	3.5	5.38

The curve showing the mid-span deflection and load resulting from the finite element analysis of OPC and GPC are represented in Fig. 10 and Fig. 11. It leads the uncracked stage to the cracking point, and on the post-cracked stage to the serviceability stage, OPC and GPC had a similar shape.

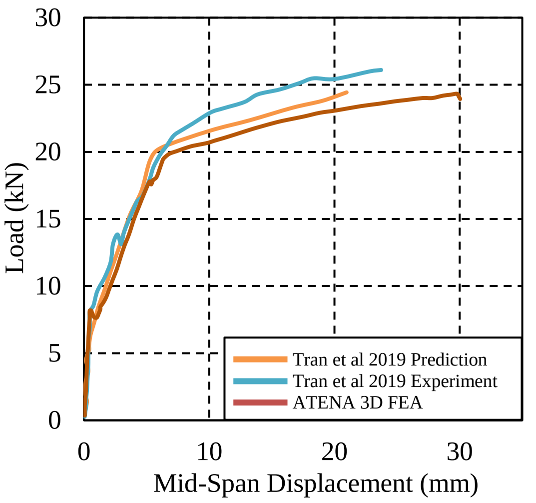

Fig. 12 Load – Deflection Curve Comparison OPC Beam Structure

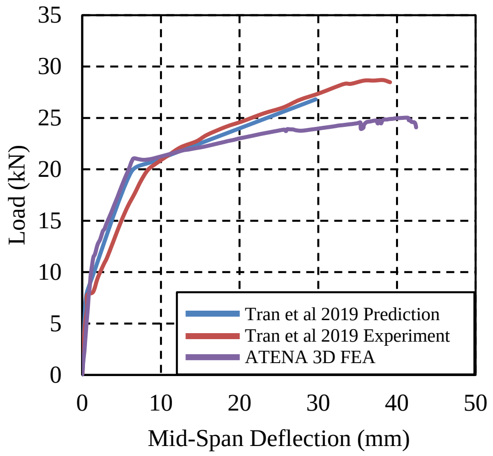

Fig. 13 Load – Deflection Curve Comparison GPC Beam Structure

The differences showed that in the post-yielded stage, the load-carrying capacity of GPC was higher than OPC. Yet, compared to the deflection on post-yielded stage GPC, it had a 44% higher deflection value than OPC until it reached the ultimate condition because GPC Beam had better bond strength than that OPC modeled on the Finite Element Analysis.

The ductility of the GPC beam was higher than that of OPC because GPC was able to stand longer on load on the post-yielded stage. Geopolymer concrete had a higher value of tensile strength and better bond strength with the reinforcement, as shown in Fig.9, which had lower total slip than OPC, as shown in Fig. 8. It indicated a better reinforcement bond of GPC that caused load-carrying capacity to last long after the first crack condition and transformed it into a deformation of the reinforced concrete beam structure (ultimate deflection).

6.2. Flexural Crack Pattern of Geopolymer and Portland Cement Concrete Beam Structure

The experimental research crack pattern of the OPC beam structure shown in Fig. 3 has fewer visually crack patterns than GPC. The GPC with more cracks is shown in Fig. 4 with more crack holes. The finite element analysis crack pattern resulting from the OPC beam structure on ultimate condition is shown in Fig. 14 with a higher hole crack width (3.71 x 10^{-3} m). Meanwhile, Fig. 15 shows that GPC has fewer crack patterns than OPC with smaller hole crack widths (2.68 x 10^{-3} m).

It may have happened due to the higher value of fracture energy of GPC than the value of fracture energy of OPC. Fracture energy affected the energy required to open the unit area of the crack surface so that the GPC had fewer cracks and smaller hole crack width.

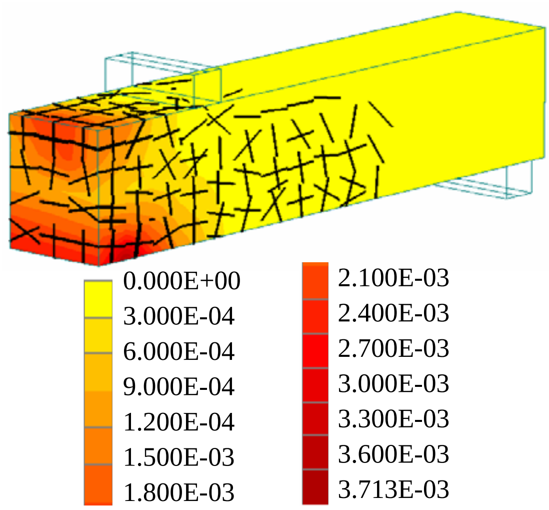

Fig. 14 Crack Pattern and Principal Strain OPC Beam Structure

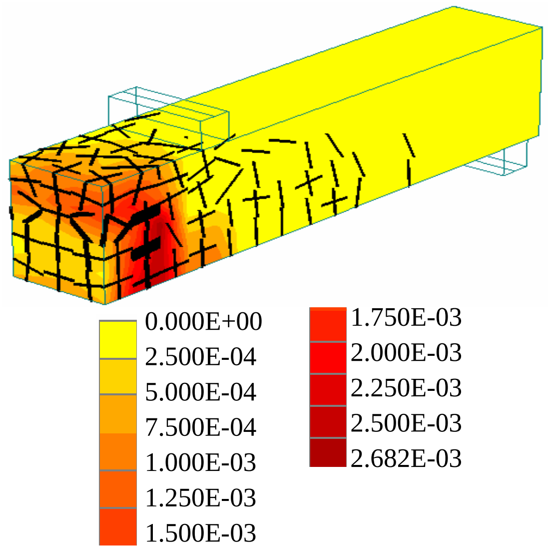

Fig. 15 Crack Pattern and Principal Strain GPC Beam Structure

7. CONCLUSION

Finite element analysis using ATENA 3D to be identified flexural performance and crack pattern of OPC and GPC beam structure are investigated and compared with experimental research. The conclusions are as follows:

1. Geopolymer Concrete (GPC) beam structure shows on post-yielded stage GPC has 44% higher value of deflection than OPC before it reaches the ultimate condition because GPC Beam has better bond-strength than OPC which is modelled on this Finite Element Analysis.
2. GPC beam value of ductility is 12% higher than OPC beam.
3. Based on FEA, the ultimate load capacity ratio finite element analysis of GPC is 3% higher than OPC, as the compressive strength of GPC (44 MPa) is higher than OPC (33 MPa).
4. The first crack deflection of finite element analysis is similar to experimental research.
5. GPC modeled with better bond-strength as "Good Condition" of bond-slip based on CEB-FIP Model 1990 as the other research shows that GPC has a higher value of bond-strength than OPC.

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