NON-LINEAR ANALYSIS OF HOLLOW REINFORCED CONCRETE COLUMN QUARE CROSS-SECTION WITH VARIOUS LOAD ECCENTRICITY AND CONCRETE STRENGTH

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Abstract

Hollow due to plumbing system has an effect to the building's visual and the aesthetic quality in terms of architecture. To overcome this, the pipe is planted in a construction structure such as a column. However, this will affect on the strength degradation and modes of failure of structural elements such as a column. The objective of this research is to study the strength, stiffness, ductility, cracking patterns, and modes of failure of hollow RC columns with square cross-section with various load eccentricity and concrete strength. In this research, 13 reinforced concrete columns with square cross section were made. Two of them were massive columns (C1E1, C1E2) with cross-sectional dimension of $150 \times 150 \text{ mm}^2$ and 800 mm long, six of them were hollow with the same size (C2E1, C3E1, C4E1, C2E2, C3E2, C4E2). Concrete strength $f_c' = 34.52 \text{ MPa}$ with eccentricity = 60 mm and $f_c' = 35.72 \text{ MPa}$ with eccentricity 100 mm. Models were analyzed by nonlinear finite element method using ATENA v.2.1.10 software. The FE model is calibrated against recent experimental results from Zacob (2003). Once validated, the model is used to examine stiffness, ductility, cracking patterns, and modes of failure of hollow RC columns with a square cross-section with various load eccentricity. The numerical results show that the different ultimate load strength of C1E1, C2E1, C3E1, C4E1, C1E2, C2E2, C3E2, C4E2 are 0,32%, 2,22%, 1,61%, 7,74%, 1,25%, 0,65%, 2,63%, 1,94%, while the differents stiffnes are 18,30%, 21,30%, 23,79%, 31,57%, 15,22%, 22,67%, 21,39%, 14,41%, and the differents ductility are 48,71%, 33,64%, 3,39%, 41,04%, 52,30%, 22,99%, 18,11%, 7,76%. Crack pattern occurred in C1E1, C2E1, C3E1, C4E1, C1E2, C2E2, C3E2, C4E2 are flexural crack and shear cracks. Exhibit modes of failure of C1E1, C2E1, C3E1, C4E1 are compression failure and C1E2, C2E2, C3E2, C4E2 are tension failure.

Keywords: ATENA, columns, eccentricity, failure, hollow, nonlinear.

ANALISIS NON-LINEAR KOLOM BETON BERTULANG PENAMPANG SEGIEMPAT BERONGGA DENGAN VARIASI EKSENTRISITAS BEBAN DAN MUTU BETON

Abstrak

Lubang akibat pemasangan pipa pada konstruksi untuk keperluan instalasi (air hujan, sanitasi, listrik dan lain-lain) dapat berpengaruh pada visualitas bangunan dan akan mempengaruhi kualitas estetika dari segi arsitektur. Untuk mengatasi hal tersebut pipa ditanam didalam struktur konstruksi seperti kolom. Akan tetapi hal ini akan menyebabkan degradasi kekuatan beton dan pola keruntuhan struktur pada kolom. Selain secara eksperimental, penelitian ini dapat juga dilakukan secara numeris menggunakan metode elemen hingga nonlinier. Penelitian ini bertujuan untuk mengetahui kekuatan, kekakuan, daktilitas, pola retak dan model keruntuhan kolom beton bertulang penampang persegi berongga dengan variasi eksentrisitas beban dan variasi mutu beton. Dalam penelitian ini dimodelkan 8 jenis kolom beton bertulang penampang segiempat yang terdiri dari 2 kolom masif (C1E1 dan C1E2) dan 6 kolom berongga (C2E1, C3E1, C4E1, C2E2, C3E2, C4E2) dengan ukuran $150 \times 150 \text{ mm}^2$, panjang 800 mm. Mutu beton $f_c' = 34.52 \text{ MPa}$ dengan eksentrisitas = 60mm dan mutu beton $f_c' = 35.72 \text{ MPa}$ dengan eksentrisitas = 100mm. Kolom dianalisis menggunakan software elemen hingga nonlinier ATENA V.2.1.10 dan hasilnya dibandingkan dengan hasil eksperimen sebelumnya dari Zacoeb (2003). Setelah model divalidasi, dilakukan perhitungan kekakuan, daktilitas, pengamatan pola retak dan jenis keruntuhan yang terjadi pada kolom penampang segiempat berongga dengan variasi eksentrisitas beban. Hasil penelitian menunjukkan bahwa kolom beton bertulang berongga yang dimodelkan dengan ATENA yaitu untuk model kolom validasi C1E1, C2E1, C3E1, C4E1, C1E2, C2E2, C3E2, C4E2 mempunyai perbedaan beban maksimum dengan hasil eksperimen secara berturut-turut sebesar 0,32%, 2,22%, 1,61%, 7,74%, 1,25%, 0,65%, 2,63% dan 1,94%, dengan perbedaan kekakuan secara berturut-turut sebesar 18,30%, 21,30%, 23,79%, 31,57%, 15,22%, 22,67%, 21,39% dan 14,41%, dan perbedaan daktilitas secara berturut-turut sebesar 48,71%, 33,64%, 3,39%, 41,04%, 52,30%, 22,99%, 18,11% dan 7,76%. Pola retak yang terjadi adalah pola retak lentur dan retak geser. Pola keruntuhan pada C1E1, C2E1, C3E1, C4E1 merupakan keruntuhan tekan, sedangkan C1E2, C2E2, C3E2, C4E2 merupakan keruntuhan tarik.

Kata-Kata kunci: ATENA, berlubang, eksentrisitas, keruntuhan, kolom, nonlinear.

1. Introduction

Hollow concrete structure has been widely used in the construction field both of structural, architectural and ecological term. In this paper, authors emphasize the hollow structural elements such as columns, beams, floor slabs, walls and paving blocks. It aims to reduce the volume that used for the interior and exterior building and to reduce operational and maintenance costs. In addition, this is also serves as a support construction utility such as in installation of AC plumbing, electricity and water, lights, and etc. Thus the conditions of which are intended to conserve and to increase the space of the room.

Column has an important function in supporting the construction structures. In addition to supporting the construction structure, the columns are also designed with special ornaments to add aesthetic value that strengthens the character of the building in terms of an architectural side.

Furthermore, there are often cases of installation of pipes in the column for installation purposes (rainwater, sanitation, electricity and others) can affect the building's visual and the aesthetic quality in terms of architecture. To overcome this usually the pipe will be planted

in construction structures such as columns, walls, floors and so on. Holes due to the installation of pipes in construction will reduce the effective area of the cross-section and affect the capacity of the column.

According to SNI 03-2847-2007, Section 8.3.4, it is mentioned that channels and pipes, together with hooks, planted in columns shall not occupy more than 4 percent of the cross-sectional area required for strength or fire protection.

Given that columns are important structural elements, the failure of columns will directly affect other structural components associated with them. Therefore, in planning the column must provide a larger reserve of strength than other structural components. Experimental studies of bending capacity of short column of reinforced concrete of hollow rectangular section with hole variation have been done by Zacoeb (2003). The author conducted this study with numerical model analysis using experimental research results data earlier. Analysis of this column model using ATENA v.2.1.10 software is expected to get validation approaching an experimental result that has been done before. It is hoped that this research will also be able to complement and add value from previous research, which is used as a benchmark, because by utilizing the nonlinear element program, the variables that are not measured in the field when the experiment can be known in more detail and complete. The results of this study continued by applying the actual conditions in the field with a full-scale model. The modeled columns were analyzed using variables of load eccentricity and concrete quality variations.

2. Literature Review

According to Zacoeb (2003), the experimental research about the Flexural Capacity of Reinforced Concrete Short Column with Variations Hole which performed with the eccentric load of 60 mm and 100 mm. The ratios of holes were 0%, 3.63%, 7.95% and 12.50% and 20.28% with cross-sectional sections of 150 mm x 150 mm. The result from the experimental research shown that the hollow column with hole ratio up to 20,28% and 60 mm load eccentricity shown a decrease of maximum capacity and stiffness experienced to 11,90% and 53,88% relative to solid column. Whereas column with 100 mm load eccentricity, did not indicate a decrease in maximum load capacity and relative stiffness to solid columns. The maximum increase of ductility experienced by hollow column with hole ratio of 20.28% and 60 mm load eccentricity was 16.38% relative to solid column. The models of solid and hollow column collapse with 60 mm load eccentricity, shows the pattern of compression failures. While the hollow columns with hole ratios up to 20.28% and 100 mm load eccentricities, did not show any increase in ductility relative to solid column. Cracks in solid or hollow columns generally exhibit a fracture pattern that is in the same direction as the tensile reinforcement at the tension and spalling side of the tap. The model of solid and hollow column collapse with 100 mm load eccentricity shows the same pattern of tension failures.

Suprabowo (1996) suggests that the hollow beam section strength is the full beam strength plus the power contributed by the pipe (from steel or PVC) and reduced the strength of the concrete that once filled the cavities inside the pipe. The method of analysis was developed from the method of column analysis with a circular cross section, which was applied for force analysis on pipes and concrete in pipes.

Broadly speaking the step of analysis of forces in the pipe into 2 conditions is that the neutral line state falls on the pipe and the neutral line falls outside the pipe. From the results of the analysis has been done concluded that:

- The value of the column capacity using the pralon pipes in the compressive state determines, the balanced state and the tensile state determine smaller than the capacity compared to the standard columns (without holes).

- In the press state specify, for columns using the pralon pipes the smallest capacity is on the column whose pipe position shifts toward the tap. Medium for the column that uses steel pipe the smallest capacity is on the column that position the pipe shifted toward the press.
- In a balanced state and decisive state, for the column that uses the smallest capacity paralon pipe is on the column whose pipe position shifts toward the tap. Medium for the column that uses steel pipe the smallest capacity is on the column whose pipe position shifts toward the pull (Suprabowo, 1996).

Supriyadi (1997) has undertaken research on the effect of holes on strongly reinforced concrete column boundaries conducted experimentally and numerically. The ratio of holes made varies, ie 0 %, 3.8 %, 5.62% and 9.43% with a cross-section size of 120 mm x 120 mm. From this research concluded among others:

- And the experimental results show that up to a hole ratio of 9.43 %, at the same level of eccentricity the columns show relatively similar stiffness, then up to the limit of the column limit has not shown *buckling failure*. Columns to hole ratio 5.62% experimental capacity still shows greater than its numerical capacity.
- Numerically the effect of holes on column capacity shows the following results:
 - The greater the eccentricity the smaller the impact of the hole on the decrease in column capacity.
 - In the tensile collapse area the capacity decreases gradually, then decreases sharply in the boundary region between the *balanced* eccentricity of the hollow columns and the eccentricity of the *balanced* solid column.
 - The maximum descent is achieved at the minimum design eccentricity (0.1h).

Analysis Theory

According to Suprabowo (1996), cross section of a hollow square columns with distribution of strains-stresses and forces diagram that occurs on it can be seen in Figure 1.

Figure 1. Stresses and forces in column

Source: Suprabowo, 1996.

The Equation for balancing of forces can be seen as follow:

$$P_n = C_c - C_{cp} + C_s - T_s$$

With :

$$C_c = 0.85 f_c' b a$$

$$C_{cp} = 0.85 f_c' \cdot R^2 (\theta_4 - \sin \theta_4 \cdot \cos \theta_4)$$

$$C_s = A_s' \cdot f_s'$$

$$T_s = A_s \cdot f_s$$

(Concrete compressive force)

(The reduction due to the hole)

(steel compression force)

(steel stress force)

Moment balance equation can be seen as follows:

$$M_n = P_n \cdot e$$

$$M_n = MC_c - M_{cp} + MC_s + MT_s$$

With :

$$MC_c = 0,85 f_c' \cdot ba \left(y - \frac{a}{2} \right) \quad \text{(Moment of concrete)}$$

$$M_{cp} = 0.57 \cdot F_c' \cdot R^3 \sin^3 \theta_4 \quad \text{(reduction due to the hole)}$$

$$MC_s = A_{s'} \cdot F_{s'} (Y - d) \quad \text{(Moment of compression steel)}$$

$$MT_s = A_s \cdot F_s (d - y) \quad \text{(Moments tension steel)}$$

Isi kajian literature (bagian 2)

3. Methodology

This research was using numerical analysis 2.1.10 ATENA3D software reinforced concrete where the concrete was modeled by Material Prototype CC3DnonLinCementitious2 while reinforcement was modeled in CCReinforcement with Prototype Material CCReinforcement was used in this analysis. Nonlinear modeling was limited to material nonlinearity, while the geometry nonlinearity was not modeled. (Cervenka, 2007) Modeling of reinforced concrete material adjusted to the material that provided by the ATENA program called S-Beta Materials (Table 1). The modeling of material, which is available in ATENA, was assumed that a steel plate and PVC are Elasto isotropic.

Table 1. Material S-Beta

Parameter:	Formula:
Cylinder strength	$f_c' = -0,85f_{cu}'$
Tensile strength	$f_t' = 0.24 f_{cu}'^{2/3}$
Initial elastic modulus	$E_c = (6000 - 15.5f_{cu}') \sqrt{f_{cu}'}$
Poisson's ratio	$\nu = 0.2$
Softening compression	$w_d = -0.0005 \text{ mm}$
Type of tension softening	l-exponential, based on G_F
Compressive strength in cracked concrete	$c = 0.8$
Tension stiffening stress	$\sigma_{st} = 0.$
Shear retention factor	Variable (sect.2.1.7)
Tension-compression function type	Linear
Fracture energy G_f according to VOS 1983	$G_F = 0.000025f_t'^{ef} [\text{MN/m}]$
Orientation factor for strain localization	$\gamma_{max} = 1.5$ (sect.2.1.3)

Source: Cervenka, 2007.

Data collection for this research was collected from the experiment result that has been done before. This research were conducted modelling column with Non-Linear FEM ATENA3D software, validation model as: axial load and deflexion, ductilty, stiffness, crack on Pmax, and failure modes, comparring the experimental result and the numerical analysis result with ATENA3D software.

Rectangular cross-section reinforced concrete columns consisting of 8 experiments columns are 2 masif coulmnns (C1E1 and C1E2) and 6 hollow columns (C2E1, C3E1, C4E1, C2E2, C3E2,

C4E2) with size 150 x 150 mm², length 800 mm. Using quality of steel P12 : $f_y = 328,69$ MPa, $E_s = 234778,44$ MPa, $E_{steel} = 2.10^5$ MPa dan $E_{PVC} = 2760$ MPa. The average of Compressive strength of concrete used are $f_c' = 34.52$ MPa with $e = 60$ mm and $f_c' = 35.72$ MPa with $e = 100$ mm. As shown in Figure 2 and Tabel 2.

Figure 2. Details columns dimensions

Source: Zacoeb, 2003

Tabel 2. Details Column Data

Code Column	B (mm)	H (mm)	L (mm)	Size PVC Pipe	Diameter Actual (mm)	Ratio Hole (%)	Eccentricity (mm)
C1E1	150	150	800	0	0	0	60
C2E1	150	150	800	1 "	32.25	3.63	60
C3E1	150	150	800	1.5 "	47.75	7.95	60
C4E1	150	150	800	2 "	59.85	12.50	60
C1E2	150	150	800	0	0	0	100
C2E2	150	150	800	1 "	32.25	3.63	100
C3E2	150	150	800	1.5 "	47.75	7.95	100
C4E2	150	150	800	2 "	59.85	12.50	100

Source: Zacoeb, 2003

4. Result and Disucussion

The numerical modeling using finite element program ATENA v.2.1.10 and pre-processor programs to provide input ATENA 3D program using GID 7.4.4b. The type of failure that occurs in ATENA using the theory of Von- Misses and Menetrey-William or Drucker-Pruger failure and the iteration method used is Newton Raphson method. Discretization model of reinforced concrete columns using structured meshing as shown in Figure 3.

a. Defining column C1E1 and C1E2

b. Defining column C2E1, C3E1, C4E2, C2E2, C3E2 and C4E2

Figure 3. Defining column models (non skalatis)
Source: Analysis result from ATENA Program, 2010

Figure 3 shows defining the model column that was given a load on one of end of the column (b) and the other end is considered as the foundation that holds x direction (a1), y-direction (a2), and for monitoring point to the observed (c).

(a) Load Displacement

5.

Figure 4. Comparison of load deflection C4E2 column without PVC and with PVC ATENA results with experimental results

Source: Analysis result from ATENA Program, 2010

Figure 5. Modeling column C4E2 with PVC

Source: Analysis result from ATENA Program, 2010

Chart Comparison of load deflection C4E2 column without PVC and with PVC ATENA results with experimental results shown that the model results without PVC column closer to the experimental results as shown in Figure 4. Modeling column that using PVC can be seen in Figure 5. Therefore, for subsequent models modeled without PVC.

a. Column with ecentricity 60 mm

b. Column with ecentricity 100 mm

Figure 6. Comparison Chart Load-Displacement of C1E1, C2E1, C3E1, C4E2, C1E2, C2E2, C3E2 and C4E2 Columns Experimental Results with ATENA Results

Source: Analysis result from ATENA Program, 2010

In Figure 6 can be seen that the maximum deflection resulted from ATENA finite element program in massive column greater than the result from the experimentation while hollow column closer the experimental results. Value of load-deflection columns of ATENA, shown that graph after yield to the ultimate no load decreased anymore. This is due to the typical graph for reinforcement material ATENA modeling is CCRReinforcement2 which has a straight trendline any tension increase yielding. In the finite element model ATENA maximum load that occurs in C1E1, C2E1, C3E1 C4E1, C1E2, C2E2, C3E2, and C4E2 columns had the differences with the experimental results, respectively for 0.32%, 2.22%, 1, 61%, 7.74%, 1.25%, 0.65%, 2.63% and 1.94%. With the difference in deflection values respectively by 62.14%, 29.62%, 16.72%, 35.32%, 67.24%, 0.13%, 3.26% and 19.71%.

(b) Stiffness and ductility of columns C1E1, C2E1, C3E1, C4E2, C1E2, C2E2, C3E2 and C4E2

Stiffness and ductility values above are based on the load and deflection at nodal points in the middle of the span or column which is 700 mm from the foothold. The differences stiffness and ductility values of Numerical columns and experiment columns can be seen in **Table 3** and **Table 4**. The value of the stiffness results of non-linear finite element ATENA average larger than the experimental results respectively by 18.30%, 21.30%, 23.79%, 31.57%, 15.22%, 22.67 %, 21.39% and 14.41%. This is due to the restrictions of the use of modeling of the tensile and compressive reinforcement as smeared reinforced and perfect bond model. And the value of the ductility results of non-linear finite element ATENA respectively by 48.71%, 33.64%, 3.39%, 41.04%, 52.30%, 22.99%, 18.11% and 7.76%.

7.

Table 3. Comparison of the stiffness of the column

Models	Eccentricity (mm)	ATENA		Experiment		Stiffness (EI) (kNm ²)		Difference (%)
		M _y (kNm)	Curvature Yield, Φ_y (m ⁻¹)	M _y (kNm)	Curvature Yield, Φ_y (m ⁻¹)	ATENA A	Experiment	
C1E1	60	17,37	0,0256	17,46	0,021	679,26	831,43	18,30
C2E1	60	17,35	0,0245	17,20	0,031	709,38	554,84	21,78
C3E1	60	16,70	0,0230	17,18	0,031	727,23	554,19	23,79
C4E1	60	17,37	0,0256	15,34	0,033	679,26	464,85	31,57
C1E2	100	15,34	0,0281	14,34	0,031	545,62	462,58	15,22
C2E2	100	14,78	0,0238	13,92	0,029	620,70	480,00	22,67
C3E2	100	14,25	0,0227	14,28	0,029	626,40	492,41	21,39
C4E2	100	14,78	0,0243	14,55	0,028	607,10	519,64	14,41

Source: Analysis result from ATENA Program and Experiment, 2010

Table 4. Comparison of column ductility

Models	Eccentricity (mm)	ATENA		Experiment		Ductility		Difference (%)
		Curvature Yield, Φ_y (m ⁻¹)	Curvature Ultimit, Φ_y (m ⁻¹)	Curvature Yield, Φ_y (m ⁻¹)	Curvature Ultimit, Φ_y (m ⁻¹)	ATENA	Experiment	
C1E1	60	0,0256	0,0736	0,021	0,031	2,88	1,48	48,71
C2E1	60	0,0245	0,0582	0,031	0,049	2,38	1,58	33,64
C3E1	60	0,0230	0,0391	0,031	0,051	1,70	1,65	3,39
C4E1	60	0,0256	0,0736	0,033	0,056	2,88	1,70	41,04
C1E2	100	0,0281	0,1407	0,031	0,074	5,00	2,39	52,30
C2E2	100	0,0238	0,0481	0,029	0,072	2,02	2,48	22,99
C3E2	100	0,0227	0,0472	0,029	0,071	2,07	2,45	18,11
C4E2	100	0,0243	0,0573	0,028	0,071	2,35	2,54	7,76

Source: Analysis result from ATENA Program and Experiment, 2010

(c) Crack and Failure modes

Figure 7. Cracking pattern and Failure Modes C4E2 coulumn ATENA 3D Post Result
Source: Analysis result from ATENA Program, 2010

From non-linear finite element ATENA software shows that the crack pattern that occurred in C1E1, C2E1, C3E1, C4E1, C1E2, C2E2, C3E2, C4E2 are crack flexural and shear cracks. Exhibite modes of failure of C1E1, C2E1, C3E1, C4E1 are compression failure and C1E2, C2E2, C3E2, C4E2 are tension failure. The sample column that shown cracking pattern and failure modes can be seen in **Figure 7**.

5. Conclusion

The numerical results show that the different ultimate load strength of C1E1, C2E1, C3E1, C4E1, C1E2, C2E2, C3E2, C4E2 are 0,32%, 2,22%, 1,61%, 7,74%, 1,25%, 0,65%, 2,63%, 1,94%, while the differents stiffnes are 18,30%, 21,30%, 23,79%, 31,57%, 15,22%, 22,67%, 21,39%, 14,41%, and the differents ductility are 48,71%, 33,64%, 3,39%, 41,04%, 52,30%, 22,99%, 18,11%, 7,76%. Crack pattern occurred in C1E1, C2E1, C3E1, C4E1, C1E2, C2E2, C3E2, C4E2 are flexural crack and shear cracks. Exhibite modes of failure of C1E1, C2E1, C3E1, C4E1 are compression failure and C1E2, C2E2, C3E2, C4E2 are tension failure. From the anlysis show that the numerical results was approaching the experimental results that has been done before. This research also be able to be complement and add value for previous experiment that used as a benchmark. By using nonlinear finite element program, the variables that not measured in the field when the experiment occurred can be seen with more detail and complete. In addition using nonlinear finite element program will reduce time, energy and cost compare to experimental research. For further research using ATENA is recommended to use the latest version of ATENA 3, because this version has 8000 elements, more than version 2.1 10 that has only 3000 elements. The new version also provides a special modeling for retrofitting. It is recommended to use the hardware with higher specifications for use ATENA requires a very large amount of memory, which is proportional to the number of elements used. For the experimental test, must to ensure the quality of the recorded data and documentation of completeness, in order to ensure the sustainability of these studies either experimental or with the nonlinear finite element.

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