Displacement and curvature ductility in mid-rise reinforced concrete buildings

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Abstract. When an earthquake occurs, ductility will maintain strength and stiffness in the structure so that the building structure still works even though it is on the verge of collapse. To get a description of the structural behavior starting from the structure in linear elastic, the first yielding of the structural elements until the structure collapse due to earthquake load, it can be done with non-linear static analysis namely pushover analysis. In this study, the geometry of mid-rise reinforced concrete structure consists of four storey buildings. The dimensions of the column structure 400x400 mm and beam structure 250x500 mm, where the dimensions of the beams and columns are the same from the 1st floor to the 4th floor. To find out the behavior that affects the ductility value in mid-rise reinforced concrete structures, a variation material used in this study are the spacing of stirrup, ratio of longitudinal reinforcement, ratio of compressive and tensile longitudinal reinforcement, and compressive strength of concrete. Structural geometry modeling, structural loads, and modeling of material variations used the program SAP 2000. From the output of this program, an analysis of the value of curvature ductility and displacement ductility was performed. The result of this study are the higher the value of compressive strength of concrete and the ratio of longitudinal reinforcement in beam structure will increase the value of ductility. The smaller the value of the spacing of stirrup and the ratio of longitudinal reinforcement in column structure will increase the value of ductility.

Keywords: Curvature Ductility, Displacement Ductility, Pushover

1. Introduction

The lack of a monitoring mechanism in the structure of reinforced concrete buildings, especially low and medium-rise reinforced concrete structures makes these structural systems often do not have enough ductility, strength and stiffness to withstand earthquakes [1]. One of the most dominant reasons that causes earthquake-damaged structures is ductility in cross-section systems and carrying capacity that is difficult to ascertain [4], [7].

Research on the influence and relationship of intermediate-level reinforced concrete with a sway-column collapse mechanism has been carried out with the result that decreases in the spacing of the stirrup, increased the compressive strength of concrete, increased the ratio of longitudinal compressive and tensile reinforcement, decreased the ratio of flexural reinforcement can increase curvature and displacement ductility [1]. In the relation of curvature ductility and displacement, the strongest
correlation occurs in column elements where columns play an important role mainly in the effect of displacement ductility on the structure [12].

In estimating and determining local (curvature) and global ductility (displacement) and structural behavior of lateral loads, research is carried out based on variations in parameters used and restrictions on the Indonesian National Standard code for for special moment frame systems, knowing ductility behavior in cases of fourth-level reinforced concrete buildings, curvature ductility in beam and column structural elements, and displacement ductility in frame structures determined by variations in parameters of compressive strength of concrete, spacing of stirrup, ratio of longitudinal compressive and tension reinforcement on beam, and ratio of flexural reinforcement on column structure. Then a correlation and regression analysis was performed to determine the relationship between the displacement ductility and curvature ductility with the location of the structure in Jakarta.

Ductility values that are difficult are certainly needed to be estimated to determine the capacity of the structure, especially the structure of four-level reinforced concrete buildings, as well as local behavior which curvature ductility to global behavior that is displacement ductility. In this study, to analyze the curvature ductility and displacement used SAP2000 with Indonesian National Standard code limitations on the weak-beam strong-column mechanism by modeling 3D structures.

2. Study Literature

2.1 Curvature Ductility

Moments obtained from modeling beam and column elements based on the parameters used were analyzed by the SAP2000 program designer section, determined the yield and ultimate points in the curvature, to obtain the curvature ductility value [1].

\[ \mu_\phi = \frac{\phi_u}{\phi_y} \] (1)

Where, curvature ductility (\( \mu_\phi \)), curvature at ultimate (\( \phi_u \)), curvature at yield (\( \phi_y \)).

In beam curvature ductility, the highest curvature ductility occurs in a combination of BT24, where the ratio of compressive and tensile reinforcement does not reach the highest ratio and after that, ductility does not increase, even decreases [3]. In column curvature ductility, ductility is highest when the lowest column bending ratio, where the parameter is very significant in the influence of column curvature ductility.

2.2 Displacement Ductility

Determining the location of plastic joints that are used based on the special moment frame structure or the strong-column weak-beam on Indonesian National Standard code [9] [10] and ASCE 41-13 for the limits of the plastic joints used [2]. The load is fully applied, with a reduced live load so that a living load of 30% is used. The plot method used is the FEMA 440 DM method [5].

The pushover curve obtained from the structure modeling based on the parameters used and analyzed with the SAP2000 program, determined the yield and ultimate points on the displacement, to obtain the displacement ductility value [1].

\[ \mu_\delta = \frac{\delta_u}{\delta_y} \] (2)

Where, displacement ductility (\( \mu_\delta \)), displacement at ultimate (\( \delta_u \)), displacement at yield (\( \delta_y \)).

3. Methodology

The study was conducted by determining the range of parameters used in beam elements and column elements with parameters in the form of compressive strength of concrete, the spacing of stirrup, ratio of compressive and tension reinforcement of beam, and ratio of column flexural reinforcement. The range of parameters used is based on Indonesian National Standard code limits for special moment frame structure systems in order to maintain the behavior of the strong-column weak-beam structure and other constraints in the form of minimum beam and column dimensions, minimum number of
column flexural reinforcement, minimum number of beam tensile reinforcement, minimum spacing of stirrup, minimum distance between flexural reinforcement in column and beam, minimum compressive strength of concrete, and minimum load used [6].

In curvature ductility analysis, it is done by determining the moment of curvature on beam elements and columns using the SAP2000 program designer section. After obtaining the curvature on the beam and column elements, we determine the yield curvature value where yield is caused by the yield reinforcement in the cross section, and the ultimate curvature in which the concrete crush when it reaches that point based on the curvature moment graph. After obtaining these two parameters, curvature ductility is calculated by dividing between curvature values when ultimate to curvature at yield [1].

In the analysis of displacement ductility, the determination of the fixed column combination of the beam changes and the fixed beam of the changing column is determined to achieve the behavior of the structure while maintaining the framework of the special moment frame structure behavior. One factor in maintaining a fixed structure in the special moment frame behavior is to determine the column capacity to beams > 1.2 based on SNI 2847-2013 Article 21.6.2.2 [6] which is calculated by the ETABS program. The loads used are dead loads, and live loads are enclosed into one called gravity load as the basis of applying pushover loads for pushover analysis. Variety of mass is also calculated to reach 90% in accordance with SNI 1726-2012 Article 7.9.1 [9]. The limits of plastic joints used in columns and beams are based on ASCE 41-13 [2] with plot results on pushover analysis using FEMA 440-DM [5]. The results obtained are in the form of a plot of the graph of peak displacement with respect to the base shear force in the structure, where the yield and ultimate points are determined so that the displacement ductility can be calculated as in curvature ductility, with the distribution of displacement values at ultimate to yield.

Validation is done by doing correlation and linear regression on column curvature ductility on column displacement ductility, where in both relationships strong correlations occur [12]. Subsequent validation was carried out by calculating the modification factor of response to the structure with the 3D model and based on the methods and curves in the previous study to match the effect of displacement ductility on the modification of structural response factors obtained [8], [11].

| Table 1. Parameters Research |
|-----------------------------|
|                            |
| Shear Reinforcement Spacing (mm) | Flexural Reinforcement Ratio | Compression to Tension Reinforcement Ratio | Concrete Compressive Strength (MPa) |
| Column 400x400 mm 250 | 0.01 | 0 | 20.75 |
| 200 | 0.02 | - | 24.9 |
| 150 | 0.03 | - | 33.2 |
| Beam 250x500 mm 250 | 0.4 | 20.75 |
| 200 | 0.6 | 24.9 |
| 150 | 0.8 | 33.2 |

4. Results and Discussion

4.1 Curvature Ductility

Determination of curvature ductility based on the research parameters, there are 27 models for columns and beams with predetermined limits based on Indonesian National Standard code for special moment frames. Loading is performed until the concrete element has collapsed.
Figure 1. Beam and Column Parameters

Table 2. Beams Curvature Ductility

| No. | Name | Spacing of stirrup, $S_c$ (mm) | Ratio Compression and Tension Longitudinal Reinforcement $\rho'/\rho$ | Compressive Strength of concrete, $f_c$ (MPa) | Ultimate Curvature, $\varphi_u$ (rad/m) | Reinforcement Yield Curvature, $\varphi_y$ (rad/m) | Curvature Ductility, $\mu_\varphi$ |
|-----|------|-------------------------------|---------------------------------------|---------------------------------|-------------------------------|-----------------------------------|----------------------------------|
| 1   | BT1  | 250                           | 0.4                                   | 20.75                           | 0.117                          | 0.00692                          | 16.825                           |
| 2   | BT2  | 250                           | 0.4                                   | 24.90                           | 0.120                          | 0.00671                          | 17.849                           |
| 3   | BT3  | 250                           | 0.4                                   | 33.20                           | 0.142                          | 0.00656                          | 21.663                           |
| 4   | BT4  | 200                           | 0.4                                   | 20.75                           | 0.123                          | 0.00692                          | 17.801                           |
| 5   | BT5  | 150                           | 0.4                                   | 20.75                           | 0.145                          | 0.00698                          | 20.734                           |
| 6   | BT6  | 250                           | 0.6                                   | 20.75                           | 0.145                          | 0.00683                          | 21.253                           |
| 7   | BT7  | 250                           | 0.8                                   | 20.75                           | 0.202                          | 0.00665                          | 30.310                           |
| 8   | BT8  | 250                           | 0.6                                   | 24.90                           | 0.158                          | 0.00679                          | 23.193                           |
| 9   | BT9  | 250                           | 0.6                                   | 33.20                           | 0.184                          | 0.00642                          | 28.658                           |
| 10  | BT10 | 250                           | 0.8                                   | 24.90                           | 0.215                          | 0.00652                          | 33.019                           |
| 11  | BT11 | 250                           | 0.8                                   | 33.20                           | 0.254                          | 0.00646                          | 39.352                           |
| 12  | BT12 | 200                           | 0.4                                   | 24.90                           | 0.140                          | 0.00675                          | 20.705                           |
| 13  | BT13 | 200                           | 0.4                                   | 33.20                           | 0.159                          | 0.00666                          | 23.875                           |
| 14  | BT14 | 200                           | 0.6                                   | 20.75                           | 0.167                          | 0.00695                          | 24.066                           |
| 15  | BT15 | 200                           | 0.6                                   | 24.90                           | 0.175                          | 0.00669                          | 26.076                           |
| 16  | BT16 | 200                           | 0.6                                   | 33.20                           | 0.208                          | 0.00643                          | 32.312                           |
| 17  | BT17 | 200                           | 0.8                                   | 20.75                           | 0.228                          | 0.00667                          | 34.180                           |
| 18  | BT18 | 200                           | 0.8                                   | 24.90                           | 0.252                          | 0.00661                          | 38.056                           |
| 19  | BT19 | 200                           | 0.8                                   | 33.20                           | 0.259                          | 0.00650                          | 39.759                           |
| 20  | BT20 | 150                           | 0.4                                   | 24.90                           | 0.158                          | 0.00692                          | 22.835                           |
| 21  | BT21 | 150                           | 0.4                                   | 33.20                           | 0.186                          | 0.00662                          | 28.103                           |
| 22  | BT22 | 150                           | 0.6                                   | 20.75                           | 0.195                          | 0.00683                          | 28.609                           |
| 23  | BT23 | 150                           | 0.6                                   | 24.90                           | 0.206                          | 0.00664                          | 30.984                           |
| 24  | BT24 | 150                           | 0.6                                   | 33.20                           | 0.252                          | 0.00619                          | 40.684                           |
| 25  | BT25 | 150                           | 0.8                                   | 20.75                           | 0.261                          | 0.00680                          | 38.392                           |
| 26  | BT26 | 150                           | 0.8                                   | 24.90                           | 0.260                          | 0.00668                          | 38.877                           |
| 27  | BT27 | 150                           | 0.8                                   | 33.20                           | 0.259                          | 0.00659                          | 39.250                           |
In determining the curvature value at yield and ultimate point is very important to the results of curvature ductility. Accuracy even using curve bilinearization techniques is needed to achieve accurate results. In the result of beam curvature ductility, the highest increase in curvature ductility occurs by increasing the ratio of compressive and tensile longitudinal reinforcement, compressive strength of concrete, and the spacing of stirrup. The higher of compressive strength of concrete with high ratio and high spacing of stirrup, curvature ductility crosses the optimal limit and there is no increase in curvature ductility, even decreasing and getting brittle as the three parameters increase.

Table 3. Columns Curvature Ductility

| No. | Name | Spacing of stirrup, Sc (mm) | Flexural Reinforcement Ratio, $\rho_f$ | Compressive Strength Concrete, $f'_c$ (MPa) | Ultimate Curvature, $\varphi_u$ (rad/m) | Reinforcement Yield Curvature, $\varphi_y$ (rad/m) | Curvature Ductility, $\mu_\phi$ |
|-----|------|-----------------------------|----------------------------------------|------------------------------------------|--------------------------------|--------------------------------|-----------------------------|
| 1.  | CT1  | 250                         | 0.01                                   | 20.75                                    | 0.223                          | 0.00810                      | 27.514                      |
| 2.  | CT2  | 250                         | 0.01                                   | 24.90                                    | 0.232                          | 0.00795                      | 29.233                      |
| 3.  | CT3  | 250                         | 0.01                                   | 33.20                                    | 0.267                          | 0.00779                      | 34.273                      |
| 4.  | CT4  | 200                         | 0.01                                   | 20.75                                    | 0.242                          | 0.00808                      | 29.941                      |
| 5.  | CT5  | 150                         | 0.01                                   | 20.75                                    | 0.269                          | 0.00809                      | 33.272                      |
| 6.  | CT6  | 250                         | 0.02                                   | 20.75                                    | 0.129                          | 0.00908                      | 14.156                      |
| 7.  | CT7  | 250                         | 0.03                                   | 20.75                                    | 0.107                          | 0.00978                      | 10.941                      |
| 8.  | CT8  | 250                         | 0.02                                   | 24.90                                    | 0.130                          | 0.00891                      | 14.572                      |
| 9.  | CT9  | 250                         | 0.02                                   | 33.20                                    | 0.140                          | 0.00860                      | 16.325                      |
| 10. | CT10 | 250                         | 0.03                                   | 24.90                                    | 0.108                          | 0.00950                      | 11.400                      |
| 11. | CT11 | 250                         | 0.03                                   | 33.20                                    | 0.118                          | 0.00915                      | 12.918                      |
| 12. | CT12 | 200                         | 0.01                                   | 24.90                                    | 0.260                          | 0.00795                      | 32.729                      |
| 13. | CT13 | 200                         | 0.01                                   | 33.20                                    | 0.296                          | 0.00783                      | 37.762                      |
| 14. | CT14 | 200                         | 0.02                                   | 20.75                                    | 0.141                          | 0.00911                      | 15.503                      |
| 15. | CT15 | 200                         | 0.02                                   | 24.90                                    | 0.143                          | 0.00888                      | 16.067                      |
| 16. | CT16 | 200                         | 0.02                                   | 33.20                                    | 0.157                          | 0.00857                      | 18.385                      |
| 17. | CT17 | 200                         | 0.03                                   | 20.75                                    | 0.117                          | 0.00971                      | 12.044                      |
| 18. | CT18 | 200                         | 0.03                                   | 24.90                                    | 0.118                          | 0.00947                      | 12.504                      |
| 19. | CT19 | 200                         | 0.03                                   | 33.20                                    | 0.130                          | 0.00919                      | 14.143                      |
| 20. | CT20 | 150                         | 0.01                                   | 24.90                                    | 0.291                          | 0.00799                      | 36.396                      |
| 21. | CT21 | 150                         | 0.01                                   | 33.20                                    | 0.320                          | 0.00788                      | 40.604                      |
| 22. | CT22 | 150                         | 0.02                                   | 20.75                                    | 0.160                          | 0.00904                      | 17.745                      |
| 23. | CT23 | 150                         | 0.02                                   | 24.90                                    | 0.162                          | 0.00883                      | 18.301                      |
| 24. | CT24 | 150                         | 0.02                                   | 33.20                                    | 0.179                          | 0.00860                      | 20.833                      |
| 25. | CT25 | 150                         | 0.03                                   | 20.75                                    | 0.132                          | 0.00974                      | 13.507                      |
| 26. | CT26 | 150                         | 0.03                                   | 24.90                                    | 0.133                          | 0.00952                      | 13.949                      |
| 27. | CT27 | 150                         | 0.03                                   | 33.20                                    | 0.147                          | 0.00920                      | 15.936                      |
4.2 Displacement Ductility

In the column ductility and beam ductility, there are 27 modeling in fixed column structures and fixed beams with the direction of each in the x and y directions. Determining the location of plastic joints that are used based on the special moment frame structure or the strong-column weak-beam on Indonesian National Standard code and ASCE 41-13 [2] for the limits of the plastic joints used. The load is fully applied, with a reduced live load so that a living load of 30% is used. The plot method used is the FEMA 440 DM method [5].

![Figure 3. Pushover Analysis](image1)

![Figure 4. Pushover Curve](image2)

| No. | Name | Beam | Column | $\delta_y$ (mm) | $\delta_u$ (mm) | $\mu_\delta$ |
|-----|------|------|--------|----------------|----------------|-------------|
| 1.  | FTB1 | CT21 | BT1    | 20.066        | 138.070        | 6.881       |
| 2.  | FTB2 | CT21 | BT2    | 20.025        | 138.257        | 6.904       |
| 3.  | FTB3 | CT21 | BT3    | 19.978        | 138.514        | 6.933       |
| 4.  | FTB4 | CT21 | BT4    | 20.065        | 140.413        | 6.998       |
| 5.  | FTB5 | CT21 | BT5    | 20.064        | 140.425        | 6.999       |
| 6.  | FTB6 | CT21 | BT6    | 17.292        | 137.941        | 7.977       |
| 7.  | FTB7 | CT21 | BT7    | 18.471        | 137.279        | 7.432       |
| 8.  | FTB8 | CT21 | BT8    | 17.303        | 137.533        | 7.949       |
| 9.  | FTB9 | CT21 | BT9    | 17.350        | 137.951        | 7.951       |
| 10. | FTB10| CT21| BT10   | 18.294        | 135.986        | 7.433       |
| 11. | FTB11| CT21| BT11   | 18.332        | 136.357        | 7.438       |
| 12. | FTB12| CT21| BT12   | 20.025        | 140.601        | 7.021       |
| 13. | FTB13| CT21| BT13   | 19.978        | 140.873        | 7.052       |
| 14. | FTB14| CT21| BT14   | 17.292        | 137.951        | 7.978       |
| 15. | FTB15| CT21| BT15   | 17.303        | 139.877        | 8.084       |
16. FTB16 CT21 BT16 17.402 140.329 8.064
17. FTB17 CT21 BT17 18.471 139.646 7.560
18. FTB18 CT21 BT18 18.294 139.750 7.639
19. FTB19 CT21 BT19 18.744 139.426 7.438
20. FTB20 CT21 BT20 20.025 140.616 7.022
21. FTB21 CT21 BT21 19.978 140.229 7.019
22. FTB22 CT21 BT22 17.292 140.282 8.113
23. FTB23 CT21 BT23 17.303 139.879 8.084
24. FTB24 CT21 BT24 17.402 140.353 8.065
25. FTB25 CT21 BT25 18.471 140.026 7.581
26. FTB26 CT21 BT26 18.294 139.764 7.640
27. FTB27 CT21 BT27 18.744 139.443 7.439

In the results of column variation displacement ductility, the highest displacement ductility occurs in the FT21 structure with CT21 column variation, this is due to the high compressive strength of concrete and spacing of stirrup, increasing displacement ductility, and the small flexural reinforcement ratio increases displacement ductility with the highest decrease in displacement ductility flexural reinforcement and this is based on the increase in the rotation moment that occurs.

Table 5. Displacement Ductility of Fixed Beam in X Direction

| No. | Name | Beam | Column | Yield Displacement, \( \delta_y \) (mm) | Ultimate Displacement, \( \delta_u \) (mm) | Displacement Ductility, \( \mu_\delta \) |
|-----|------|------|--------|--------------------------------------|--------------------------------------|--------------------------------------|
| 1.  | FT1  | BT1  | CT1    | 18.159                               | 90.960                               | 5.009                                |
| 2.  | FT2  | BT1  | CT2    | 19.403                               | 98.253                               | 5.064                                |
| 3.  | FT3  | BT1  | CT3    | 20.029                               | 109.883                              | 5.486                                |
| 4.  | FT4  | BT1  | CT4    | 18.176                               | 100.980                              | 5.556                                |
| 5.  | FT5  | BT1  | CT5    | 18.186                               | 114.712                              | 6.308                                |
| 6.  | FT6  | BT1  | CT6    | 28.529                               | 100.188                              | 3.512                                |
| 7.  | FT7  | BT1  | CT7    | 40.882                               | 108.708                              | 2.659                                |
| 8.  | FT8  | BT1  | CT8    | 29.118                               | 108.783                              | 3.736                                |
| 9.  | FT9  | BT1  | CT9    | 31.765                               | 119.309                              | 3.756                                |
| 10. | FT10 | BT1  | CT10   | 40.290                               | 118.503                              | 2.941                                |
| 11. | FT11 | BT1  | CT11   | 44.485                               | 131.167                              | 2.949                                |
| 12. | FT12 | BT1  | CT12   | 19.416                               | 109.717                              | 5.651                                |
| 13. | FT13 | BT1  | CT13   | 20.101                               | 123.264                              | 6.132                                |
| 14. | FT14 | BT1  | CT14   | 27.941                               | 110.316                              | 3.948                                |
| 15. | FT15 | BT1  | CT15   | 29.419                               | 119.945                              | 4.077                                |
| 16. | FT16 | BT1  | CT16   | 33.456                               | 131.581                              | 3.933                                |
4.3 Correlation and Regression of Column Displacement and Curvature Ductility

On the results of the correlation between the fixed beam displacement ductility in x direction relate to curvature ductility of column, the Pearson correlation value is 0.977 where the value is more than 0.7 and close to 1 and the significant value is smaller than 0.01. It shows that the ductility relationship of column variation and column curvature ductility is strong and significant, where column curvature ductility affects the displacement ductility of fixed beam.

In the linear regression results with SPSS for displacement ductility of fixed beams on curvature ductility of columns where the independent variables are curvature ductility and the dependent variable is displacement ductility, linear regression is calculated to predict the displacement ductility of fixed beams in the x direction based on column curvature ductility.

![Figure 5. Regression of Columns Displacement and Curvature Ductility](image)

5. Conclusion

Based on the results of research conducted several conclusions that can be drawn:

- The smaller the spacing of stirrup and the highest the value of the reinforcement ratio of compression-tension will increase the value of curvature ductility on beam structure.
- The highest the value of the compressive strength of concrete and the reinforcement ratio of compressive-tension will increase the value of curvature ductility on beam structure.
- The highest the spacing of stirrup and the highest the value of longitudinal reinforcement ratio, it will reduce the value of curvature ductility on column structure.
• The smaller the spacing of stirrup and the highest the value of compressive strength of concrete, it will increase the value of curvature ductility on column structure.
• The highest the spacing of stirrup and the highest the value of the longitudinal reinforcement ratio, the value of displacement ductility will decreases on column structure.
• The smaller the spacing of stirrup and the greater the value of compressive strength of concrete, the displacement ductility will increase on column structure.
• The optimum value of displacement ductility occurs when the reinforcement ratio of compression-tension is equal to 0.6 on beam structure.
• Comparison of the value of compressive strength of concrete and the distance of stirrup produces tend horizontal graph on displacement ductility on beam structure.

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