International Journal of GEOMATE, Oct., 2022, Vol.23, Issue 98, pp.75-83
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2022.98.3451
Geotechnique, Construction Materials and Environment

EFFECTS OF HIGH-STRENGTH STEEL BARS ON SHORT CONCRETE COLUMNS UNDER AXIAL LOAD

Agustiar[1,2], Tavio[1]*, I Gusti Putu Raka[1], and Retno Anggraini[1,3]

[1]Department of Civil Engineering, Institut Teknologi Sepuluh Nopember (ITS), Surabaya, Indonesia
[2]Department of Civil Engineering, Muhammadiyah University Aceh, Indonesia
[3]Department of Civil Engineering, Brawijaya University, Indonesia

*Corresponding Author, Received: 04 May 2022, Revised: 24 Aug. 2022, Accepted: 09 Oct. 2022

ABSTRACT: The study involved the effect of high-strength longitudinal steel bars in normal-strength concrete columns. It aims to investigate the axial behavior of reinforced concrete columns due to the use of high-strength steel bars as longitudinal reinforcement. The experimental tests included five-column specimens under axial compressive loading. The longitudinal steel bars used were 13 mm in diameter with average yield strengths of 442.30 and 553.01 MPa. The stirrups used were 10 mm in diameter with average yield strengths of 436.06 and 522 MPa. The tests were carried out under axial compressive loading. The results showed that the capacity of the column specimen with high-strength longitudinal reinforcement (f_y 550 MPa) was increased compared to the column with normal-strength longitudinal steel bars (f_y 420 MPa). Column specimens with higher-strength longitudinal and transverse reinforcements indicated an increase in compressive strength. It can be concluded that the use of high-strength longitudinal steel bars does not significantly increase the capacity of reinforced concrete columns. Based on the deformations of the specimens under the conditions of peak stress and 0.85 peak stress (post-peak condition), the strain of the column specimen with normal-strength longitudinal and transverse reinforcements is greater than the other column specimens. The number of longitudinal reinforcements used could increase the deformability (ductility) of the concrete column. The stress-strain relationships of all test column specimens show ductile failure modes. It was found that the post-peak stress-strain relationships did not decrease considerably in all column specimens.

Keywords: Axial behavior, Compressive strength, Concrete column, Disaster risk reduction, Steel reinforcement.

1. INTRODUCTION

Steel reinforcements in concrete are well known [1-5]. Columns are structural members which are very important in carrying loads. The collapse of the building can be caused by the failure of the column to withstand the loads. The development of high-rise buildings is increasing with economic development and population growth. The increase in building story and height requires greater column dimensions and amount of reinforcement. In addition, the members of buildings located on sites with high seismicity require more reinforcement and better detailing such as the need for confinement to ensure the deformability (ductility) of structural members [6]. To improve the deformability (ductility) of the columns, more reinforcement either longitudinal or transverse reinforcement (stirrups) is required [7-8]. Previous research regarding the use of reinforcement for confinement in reinforced concrete columns shows that the confinement could increase the strength and ductility of concrete [9-16].

The increases in the loading capacity of the columns cause the need for more reinforcement and create challenges during concreting and compaction. This might cause honeycombing in concrete. To reduce the need for reinforcement in columns, one solution is to introduce high-strength steel bars [17-19]. The use of high-strength steel bars as reinforcement in concrete provides several advantages. For example, improved placing and compaction, reduction in the need for reinforcement, reduction in transportation, and labor costs, and reduced time of construction. [17-19]. The effects of axial load levels ($0.1P_0$, $0.3P_0$, and $0.5P_0$) on the relationship between various ductility factors have been investigated [20]. The results showed that with increasing axial load, the P-Δ effect became more pronounced and the attainable displacement ductilities and drift capacities reduced considerably. For high axial load levels, the drastic decrease in curvature ductility resulted in a considerable decrease in displacement ductility and drift capacity. The factors affecting the deformation capacity of the reinforced concrete column are the compressive strength of concrete, the ratio of longitudinal reinforcement, the volumetric ratio of confinement, the shear ratio a/d, and the axial load ratio. Furthermore, the axial load level affects the relationships between various ductility parameters (curvature ductility, displacement ductility, and drift capacity). As the axial load increases, the loss in lateral load-carrying capacity becomes higher due to the P-Δ effect.

New types of steel bars have been introduced by reinforcement manufacturers to serve certain desired special characteristics. In the United States, reinforcing bars with Grade 100 (100 ksi or 690 MPa) have already been implemented for several structures conforming to ASTM A1035 [21]; and in Japan, SD685A and SD685B [22]. All these reinforcements had yield strengths greater than 420 MPa. The objective of this research [23] was to study the potential of using high-strength steel bars as flexural reinforcement in reinforced concrete beam members. Two types of high-strength steel bars were evaluated, i.e. Grade 100 steel bars (ASTM A1035) from the United States, and SD685 steel from Japan. Both had the specified yield strength of 690 MPa (100 ksi). Tensile test results indicated that the fracture strain of 5.5 percent obtained was less than the minimum requirement of 7.0 percent per ASTM A1035 [21]. For the SD685 steel, the tensile test of the steel samples failed to achieve the minimum ultimate yield ratio and minimum strain requirements at the onset of strain hardening.

Indonesia is a country with high seismicity in most regions, which means major earthquakes could happen anytime and bring serious disaster. According to SNI 2052:2017 [24], It is allowed to use high-strength steel reinforcement up to 700 MPa, but only as confining steel. This clause is also available in ACI 318-19 [25]. The research used high- and normal-strength reinforcements to compare the tensile strength (TS) and yield strength (YS) [26]. Tensile tests of steel samples were carried out in displacement control mode to capture the complete stress-strain curve and especially the post-yield response of the steel bars. It concluded that Grades 420 and 550 performed higher TS/YS ratios and they were able to reach up to more than 1.25. However, higher strength steel (HSS) bars (Grades 600 and 700) resulted in lower TS/YS ratios compared with those of Grades 420 and 550. The behaviors of high-strength steel bars, particularly in terms of stress-strain relationships of reinforcing bars with the yield strengths of 550, 650, and 690 MPa were investigated [27]. Tensile test results showed that the higher the yield stress of the steel bar, the smaller the resulting strain. The yield stresses above 500 MPa have shown a shorter or no clearly defined yield plateau in the stress-strain diagram. A study was conducted to determine the effects of the yield strength of steel bars on their elongations [28-31]. The results showed that the elongations of the steel bars with a yield strength of 420 MPa were longer than those of the steel bars with a yield strength of 550 MPa. It was also remarked that the elongations of steel bars with yield strengths of 420 and 550 MPa still satisfied the requirements of ASTM A706/706M-16 [32].

2. RESEARCH SIGNIFICANCE

The load-carrying capacity of a column depends upon the compressive strength of concrete, the percentage of steel reinforcement, and column size. Increasing column capacity can be performed by increasing the grade of concrete, column size, and additional longitudinal reinforcement. One way to reduce the reinforcement ratios of concrete structures is to use high-strength steel bars. Higher-strength steel bars can solve the problem of steel bar congestion during concreting and compaction, thus improving the construction quality. The results of previous studies showed that high-strength steel bars had different characteristics from normal-strength steel bars. Although in the United States and Japan, the high-strength steel bars could have similar yield strengths, they have different characteristics [26]. Based on these facts, it is necessary to study the influences of using high-strength reinforcing bars on the behavior of reinforced concrete columns due to axial compressive loads. In addition, the requirements of SNI 2847:2019 [33] still limit the application of longitudinal reinforcement in reinforced concrete members to only 420 MPa for special moment frames while transverse reinforcement for confinement it is allowed up to 700 MPa. These requirements are the same as those in the ACI 318M-14 [34]. According to ACI 318-19 [25], for special moment frames (structural members that resist axial, bending, and shear forces), the allowable grade steel bars could be up to 550 MPa from the previous one which was limited only up to 420 MPa. For all other members resisting shear and/or torsion, the maximum yield strength of steel bars that can be used is also limited to 420 MPa.

3. METHODOLOGY

A total of five column specimens were tested in the experimental program presented in this paper. All column specimens were designed to have a cross-sectional dimension of 180 × 180 mm and a height of 720 mm. The detailed dimensions of the column test specimens are shown in Figure 1.

An experimental program was carried out to investigate the performance of column test specimens. All the column test specimens used longitudinal reinforcing steel bars with a diameter of 13 mm and from two variations of the design yield strengths of 420 and 550 MPa. The transverse reinforcement in all specimens were stirrups with a diameter of 10 mm and spaced at 50 mm (s) and 30 mm in test and non-test regions, respectively, and also from two variations of the design yield strengths of 420 and 550 MPa. All column test specimens were designed with concrete compressive strength of 30 MPa (f_c') and found to have an actual average strength of 28.5 MPa. To test the mechanical properties of concrete, three standard test cylinder specimens (150 × 300 mm) were also prepared during the concreting of the column specimens to represent the actual strength of the corresponding specimens. Table 1 shows the design of reinforced concrete column test specimens.

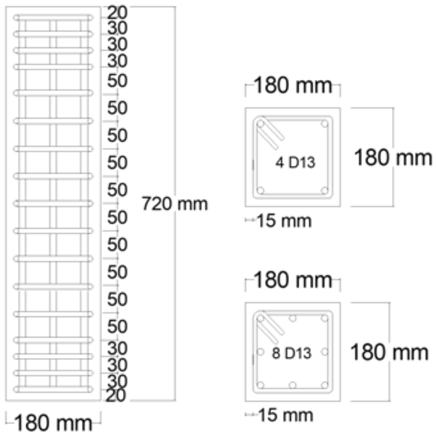

Fig.1 Details of the column test specimen

Table 1 Design of reinforced concrete column test specimens

Specimen ID	Longitudinal steel bar		Transverse steel bar	
	f_y (MPa)	diameter (mm)	f_y (MPa)	diameter (mm)
K1	420	4-D13	420	10
K2	550	4-D13	420	10
K3	420	4-D13	550	10
K4	550	4-D13	550	10
K5	550	8-D13	550	10

All columns were tested using the Universal Testing Machine (UTM) with a compressive capacity of 5000 kN. The loading method was carried out by axial compression which was applied gradually until the post-peak column capacity reached a minimum of 40 percent of the maximum load. Data reading used the Linear Variable Differential Transducers (LVDTs) which were installed on all four sides of the concrete column specimens to obtain the shortening data of the column specimens. The LVDTs were also installed on the UTM device to control any unexpected movement. At both ends of column specimens, special confined steel belts were mounted to prevent rupture of non-test regions at both ends of the column specimens such that more representative data could be obtained.

The test setup of a column specimen is presented in Figure 2.

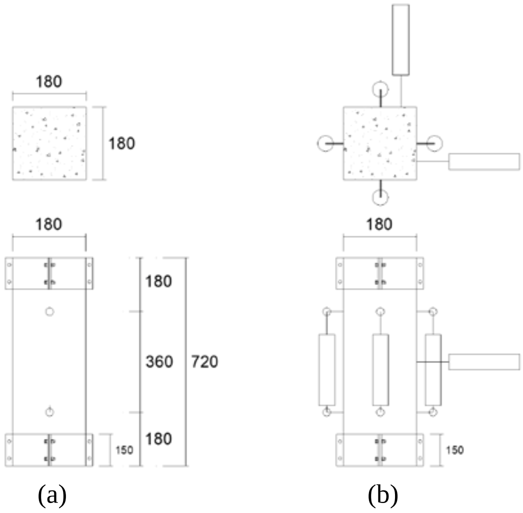

Fig.2. Test setup of column specimen (a) elevation, (b) LVDTs positions

Four strain gauges were attached to the longitudinal and transverse steel bars to measure the strain that occurred in the steel bars during loading. Two for stirrups and two for longitudinal reinforcement. Before testing, all the measuring devices and instruments as well as the concentricity of the column test specimens were checked and then zeroed.

4. RESULTS AND DISCUSSIONS

Five column specimens were experimentally tested under axial compressive loading to investigate the influences of using high-strength reinforcing steel bars as longitudinal and transverse reinforcements. The normal-strength concrete used in the study had an average compressive strength of 28.5 MPa. The average mechanical properties of the longitudinal and transverse reinforcements used for column test specimens obtained from the tensile test results are listed in Table 2.

The results obtained from the experimental tests of column specimens were loading data, column shortening data, and reinforcement strain data. Table 3 shows the capacities of the column specimens at maximum load (P_{max}) and 85 percent of maximum load ($0.85P_{max}$, post-peak condition). The ratio in Table 3 is the result of a comparison between K1 as the standard specimen with the other specimen at maximum load conditions.

Column K1 was a control column test specimen with normal-strength steel bars for both longitudinal and transverse reinforcements.

Table 2 Mechanical properties of reinforcing steel bars used for column specimens

Steel bar diameter and f_y	f_y (MPa)	ε_y	TS (MPa)
D10-420	436.06	0.00218	625.15
D10-550	522.00	0.00261	696.83
D13-420	442.30	0.00221	635.91
D13-550	553.01	0.00277	725.49

Table 3 The capacity of specimens based on the test results

No.	Specimen ID	Load (kN)		P_{max}
		P_{max}	$0.85P_{max}$	Ratio
1	K1	990.48	841.91	1.000
2	K2	998.81	848.99	1.008
3	K3	987.04	838.99	0.997
4	K4	1045.88	889.00	1.056
5	K5	1276.83	1085.31	1.289

The first crack and spalling of column K1 occurred at loads of 764.92 kN and 961.06 kN, respectively, before reaching the maximum peak load.The maximum peak load for column K1 was 990.48 kN. Column K2 used high- and normal-strength steel bars for longitudinal and transverse reinforcements, respectively. The maximum peak load of column K2 was 998.81 kN. The ratio of maximum peak loads of columns K2 and K1 was 1.008. The increase in strength due to the use of high-strength longitudinal reinforcement was insignificant. Whereas for column K3, high-strength steel bars were used for transverse reinforcement only. The maximum peak load of column K3 was 987.04 kN. The ratio of maximum peak loads of columns K3 and K1 was 0.997. The slight decrease in the strength of column K3 indicates that the use of high-strength steel bars for transverse reinforcement does not always provide an increase in strength compared to that of normal-strength steel bars, particularly when their stresses are similar and the concrete core crushes before the transverse steel yielding.

Column K4 was reinforced with high-strength steel bars for both longitudinal and transverse reinforcements. The maximum peak load of column K4 was 1045.88 kN. The ratio of maximum peak loads of columns K4 and K1 was 1.056. It shows that there was an increase in strength when using high-strength steel bars for both longitudinal and transverse reinforcements. There was a delay in concrete crushed due to the better confinement cage contributed by a combination of high-strength longitudinal and transverse reinforcements. For column K5, both longitudinal and transverse reinforcements were made of high-strength steel bars. Four additional longitudinal steel bars were placed on all four sides making a total of 8 bars. The ratio of maximum peak loads of columns K5 and K1 was 1.289. The significant increase in strength of column K5 was due to the addition of the amount of longitudinal reinforcement.

The results of the analysis of the capacity of the column specimens based on the experimental tests and theoretical approach are presented in Table 4. The theoretical analysis of the capacity of the column specimen is calculated using the formula 1.

$$\boldsymbol{P_0 = 0.85\, f'_c\, A_g + A_{st}\,(f_y - 0.85 f'_c)} \quad (1)$$

where $\boldsymbol{f'_c}$ is the concrete compressive strength, $\boldsymbol{A_g}$ is the cross-sectional area, and $\boldsymbol{f_y}$ is the yield strength of longitudinal reinforcement. The term $\boldsymbol{0.85\, f'_c\, A_g}$ is the contribution of concrete and $\boldsymbol{f_y - 0.85 f'_c}$ is the net contribution of longitudinal reinforcement. The higher the yield strength of longitudinal reinforcement used, the higher the expected capacity of the column. Based on the analysis, it can be concluded that the application of high-strength steel bars as transverse reinforcement in the concrete column gives an insignificant impact on strength. The strength increases if the column uses high-strength steel bars for longitudinal reinforcement.

Table 4 Comparisons of the experimental and theoretical capacities of column specimens

No.	Specimen ID	P_{max} (kN)		$\frac{P_{max,exp.}}{P_{max,theo.}}$	$\frac{P_{max,exp.}}{P_{max,exp.K1}}$	$\frac{P_{max,theo.}}{P_{max,theo.K1}}$
		Exp.	Theo.			
1	K1	990.48	1006.75	0.98	1.00	1.00
2	K2	998.81	1065.5	0.94	1.01	1.06
3	K3	987.04	1006.75	0.98	1.00	1.00
4	K4	1045.88	1065.5	0.98	1.06	1.06
5	K5	1276.83	1346.1	0.95	1.29	1.34
Average				0.97	1.07	1.09

The comparisons of the corresponding column specimen capacities based on the experimental data against the data obtained from the theoretical approach show almost the same values with a mean value of 0.97. These results indicate that the experimental data are very close to the theoretical data. The comparison of the maximum peak stresses obtained from the experimental and theoretical data of all column test specimens against the corresponding data of control column specimen K1 shows nearly the same values with an average of 1.07 and 1.09, respectively. This indicates that there are similarities in the increase of column capacities both theoretically and experimentally.

In addition to the column capacity, another important parameter is the deformation of the column specimens. Columns subjected to loads and compressive forces cause stresses and strains in both concrete and reinforcement. The deformation behavior of reinforced concrete columns is normally described using the stress-strain relationship. The results of the stress-strain analysis of the column test specimens are presented in Table 5.

Table 5 Stress and strain data of column specimens

No.	Specimen ID	$f_c'_{,exp}$ MPa	$\varepsilon_{c\max}$	$0.85f_c'$ * MPa	ε_c at $0.85f_c'$ *	$f_c'_{,exp}/f_c'$
1	K1	30.57	0.0278	25.98	0.0473	1.073
2	K2	30.83	0.0191	26.20	0.0283	1.082
3	K3	30.46	0.0219	25.89	0.0371	1.069
4	K4	32.28	0.0181	27.44	0.0298	1.133
5	K5	39.41	0.0227	33.49	0.0381	1.383

*at the post-peak conditions

Column K1 as a control specimen reached the maximum peak stress of 30.57 MPa with a corresponding strain of 0.0278. At the post-peak condition at 0.85 of maximum peak stress (post-peak condition), the corresponding stress was 25.98 MPa with a strain of 0.0473. After the peak load, the column specimen was still able to carry the load and deform well without any abrupt failure. This condition can be seen in Figure 3.

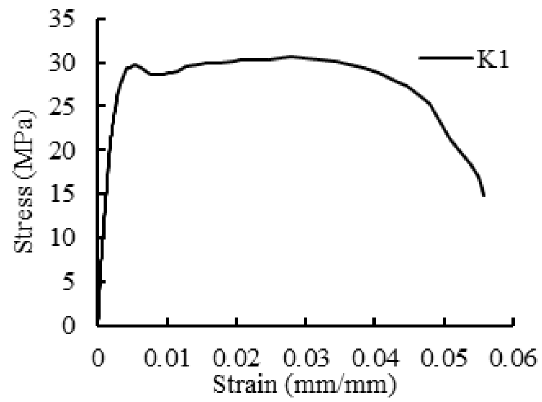

Fig.3. Stress-strain curve of column K1

At the end of the test, the longitudinal reinforcement in column specimen K1 was bent out and the transverse reinforcement was still attached. The collapse of column K1 was preceded by cracks that occurred evenly on each side of the column which was followed by the spalling of the concrete cover.

The measurement results showed that the longitudinal reinforcement strain had yielded before the peak stress. In this condition, the stress occurred at 29.04 and 26.83 MPa from the first and second strain gauges, respectively. While the transverse reinforcement did not yield before or after the peak stress. At the peak stress condition at 30.57 MPa, the longitudinal reinforcement strain was at 0.03913 and 0.02186 from the first and second strain gauges, respectively. Based on the obtained stress-strain curve, column K1 showed that the use of longitudinal and transverse reinforcements with the yield strength of 442.30 and 436.06 MPa, respectively, spaced evenly at 50 mm provided reasonably good ductility.

The comparison of columns K1 and K2 are intended to investigate the effect of using high-strength steel bars for longitudinal reinforcement in column K2 with a yield strength of 553.01 MPa. The transverse reinforcement used the same yield strength as column K1. The test results showed that the maximum peak stress occurred at 30.57 and 30.83 MPa for columns K1 and K2, respectively. The peak strength ratio of columns K1 and K2 is 0.84 percent.

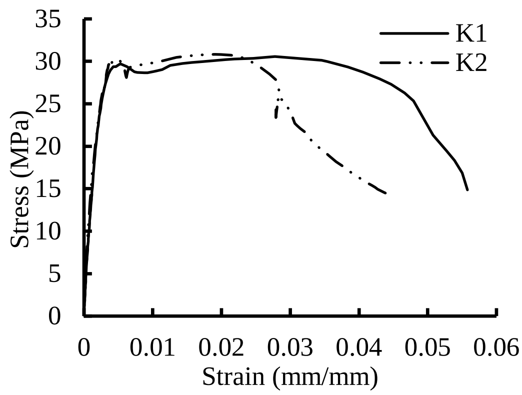

Fig.4 Stress-strain curves of columns K1 and K2

At maximum peak load, the strains of columns K1 and K2 were 0.0278 and 0.0191, respectively. Meanwhile, under the conditions of 0.85 maximum peak loads (post-peak condition), the strains that occurred were 0.0473 and 0.0283 in columns K1 and K2, respectively. This indicates that the deformation of column K1 is greater than that of column K2. The strains of the column test specimens K1 and K2 are presented in Figure 4.

Comparisons of columns K3 and K4 were carried out to investigate the effect of using high-strength steel bars as longitudinal reinforcement. The similarity of columns K3 and K4 was in the use of transverse reinforcement. Both columns used high-strength steel bars for transverse reinforcement with a yield strength of 522 MPa. The test results showed that the maximum peak stresses of columns K3 and K4 were 30.46 and

32.28 MPa, respectively. The stress ratio of columns K3 and K4 is 5.59 percent. The maximum peak stress of column K4 was greater than that of column K3.

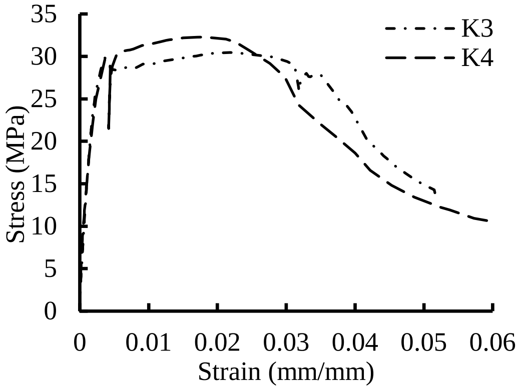

Fig.5 Stress-strain curves of columns K3 and K4.

The results from the stress-strain analysis of the columns showed that the strains at maximum peak stress of columns K3 and K4 are 0.0219 and 0.0181, respectively. At 85 percent of the maximum peak stress conditions, the strains of columns K3 and K4 were 0.0371 and 0.0298, respectively. These results indicate that the strain of column K3 is greater than that of column K4 in both conditions. The stress-strain comparison of the columns is given in Figure 5. Columns K4 and K5 were used to examine the influence of the number of longitudinal reinforcements used in columns. Both columns used high-strength steel bars for both longitudinal and transverse reinforcements. The longitudinal and transverse reinforcements had yield strengths of 553.01 and 522 MPa, respectively. At maximum peak load conditions, the stresses of columns K4 and K5 were 32.28 and 39.41 MPa, respectively. The strength ratio due to the difference in the amount of longitudinal reinforcement is 22.09 percent.

As depicted in Figure 6, based on the stress-strain analysis of the columns at maximum peak load conditions, the strains of columns K4 and K5 are 0.0181 and 0.0227, respectively. At 85 percent of the maximum peak stress conditions, the strains of columns K4 and K5 were 0.0298 and 0.0381, respectively. This indicates that the strain of column K5 is greater than that of column K4.

Based on the observed strains of the two-column test specimens, it can be seen that the addition of the number of longitudinal reinforcements increased the strains of the column. The increase in concrete strain was caused by the closer spacing of the longitudinal reinforcement, thereby increasing the confinement effectiveness of the reinforcement cage. The stress-strain curves of columns K4 and K5 are presented in Figure 6.

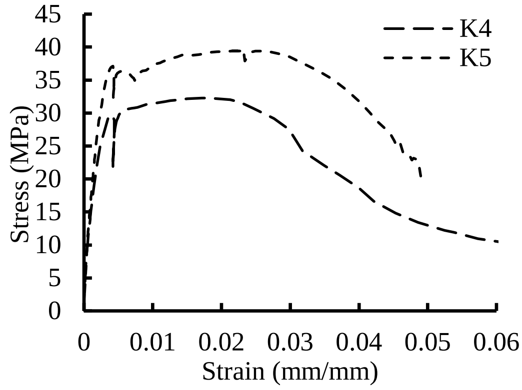

Fig.6 Stress-strain curves of columns K4 and K5

Comparisons were also made between columns K1, K4, and K5 to evaluate the use of high-strength steel bars in terms of load capacity and deformation of the columns. Column K1 used normal-strength steel bars for both longitudinal and transverse reinforcements. Columns K4 and K5 used high-strength steel bars for both longitudinal and transverse reinforcements. As depicted in Figure 7, the maximum peak stresses in columns K1, K4, and K5 were 30.57, 32.28, and 39.41 MPa, respectively. The stress increases for columns K4 and K5 from control column K1 were 5.59 and 28.92 percent, respectively. Figure 7 illustrates the stress-strain curves of columns K1, K4, and K5.

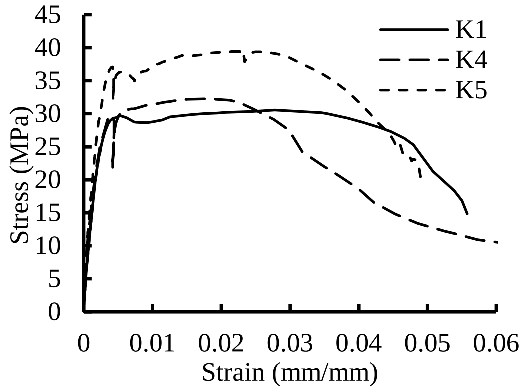

Fig.7 Stress-strain curves of columns K1, K4, and K5

As shown in Figure 7, based on the columns' capacities at maximum peak stresses, the strains in columns K1, K4, and K5 were 0.0278, 0.0181, and 0.0227, respectively. In addition, at 85 percent of the maximum stress conditions, the corresponding strains in columns K1, K4, and K5 were 0.0473, 0.0298, and 0.0381, respectively. This indicates that the deformation capacity of column K1 reinforced with normal-strength steel bars was greater than that of columns K4 and K5 which used high-strength steel bars. The stress-strain curves for all column test specimens can be seen in Figure 7.

Column K1 which used normal-strength

reinforcement could deform better than those columns K4 and K5. However, the application of high-strength reinforcement also provides quite stable stress and deformation with an adequate amount of longitudinal reinforcement as can be seen in column K5.

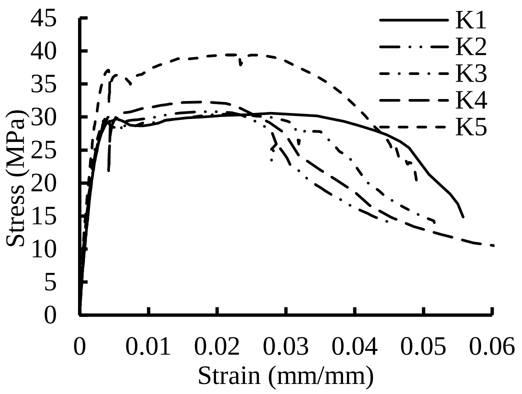

Fig.8 Comparison of stress-strain curves of all column test specimens

5. CONCLUSIONS

The research aims to determine the behavior of reinforced concrete columns due to the use of high-strength steel bars for longitudinal and/or transverse reinforcement. The average concrete compressive strength, f_c', used for all columns was 28.5 MPa. The average yield strengths of the longitudinal reinforcements were 442.30 and 553.01 MPa for normal- and high-strength steel bars, respectively. The transverse reinforcement had yield strengths were 436.06 and 522 MPa for normal- and high-strength steel bars, respectively. The results showed that the effect of using high-strength steel bars for longitudinal reinforcement only was unnotable. These results were obtained from the comparison of columns with normal- and high-strength steel bars as longitudinal reinforcement. The increasing ratio in column strength was just 0.84 percent. The use of high-strength steel bars for both longitudinal and transverse reinforcements increased the capacity of the column only up to 5.59 percent. The capacity of the column specimen with high-strength reinforcement did not increase the strength significantly. The comparison of the capacities of the column specimens based on the experiments and theoretical analysis shows a ratio that is almost the same with an average of 0.97. Based on the deformation of the column specimen under the maximum peak stress conditions and 85 percent of the maximum peak stress, the strain in the column with normal-strength steel reinforcements is greater than that of the other column specimens. The use of more longitudinal steel bars can increase the compressive strength of the column. These phenomena can be found in columns K4 and K5. Based on the stress-strain curves, all column test specimens showed ductile manner failure. Beyond the peak stress, the stress-strain curves of all column test specimens are still stable. There are no sharp decreases in the descending branches of the curves for all column test specimens. Future research on higher-strength steel bars with various steel bar diameters and proposed stress-strain relationships for high-strength steel bars need to be explored further.

6. ACKNOWLEDGMENTS

The authors would like to extend their sincere gratitude for all the support received, particularly from PT. Tunggal Jaya Steel, PT. Bhirawa Steel, and PT. Varia Usaha Beton. The authors gratefully acknowledge financial support from the Institut Teknologi Sepuluh Nopember for this work, under the project scheme of the Publication Writing and IPR Incentive Program (PPHKI) 2022.

7. REFERENCES

[1] Tavio and Kusuma B., Ductility of Confined Reinforced Concrete Columns with Welded Reinforcement Grids, Excellence in Concrete Construction through Innovation–Proceedings of the International Conference on Concrete Construction, CRC Press, Taylor and Francis Group, London, UK, 2009, pp. 339–344.

[2] Raka I G. P., Tavio, and Astawa M. D., State-of-the-Art Report on Partially-Prestressed Concrete Earthquake-Resistant Building Structures for Highly-Seismic Region, Procedia Engineering, Elsevier, Vol. 95, 2014, pp. 43–53.

[3] Tavio and Kusuma B., Investigation of Stress-Strain Models for Confinement of Concrete by Welded Wire Fabric, Procedia Engineering, Elsevier, Vol. 14, 2011, pp. 2031–2038.

[4] Pudjisuryadi P. and Tavio, Performance of Square Reinforced Concrete Columns Externally Confined by Steel Angle Collars under Combined Axial and Lateral Load, Procedia Engineering, Elsevier, Vol. 125, 2015, pp. 1043–1049.

[5] Tavio and Kusuma B., Stress-Strain Model for High-Strength Concrete Confined by Welded Wire Fabric, Journal of Materials in Civil Engineering, ASCE, Vol. 21, No. 1, 2009, pp. 40–45.

[6] Machmoed, Tavio, and Raka I G. P., Potential of New Innovative Confinement for Square Reinforced Concrete Columns, IOP Conf. Series: Journal of Physics, No. 1469, ID 012027, 2020, pp. 1–7.

[7] Sabariman B., Soehardjono A., Wisnumurti, Wibowo A., and Tavio, Stress-Strain Behavior of Steel Fiber-Reinforced Concrete Cylinders Spirally Confined with Steel Bars, Advances in Civil Engineering, Vol. 2018, ID 6940532, 2018, pp. 1–8.

[8] Pudjisuryadi P. and Tavio, Axial Compressive Behavior of Square Concrete Columns Externally Collared by Light Structural Steel Angle Sections, International Journal of Applied Engineering Research, Vol. 11, No. 7, 2016, pp. 4655–4666.

[9] Mander J. B., Priestley M. J., dan Park, R, Theoretical Stress-Strain Model for Confined Concrete, Journal of Structural Engineering, ASCE, V. 114, No. 8, 1988, pp.1804–1826.

[10] Cusson D. and Paultre P., High-Strength Concrete Columns Confined by Rectangular Ties, Journal of Structural Engineering, ASCE, V. 120, No. 3, 1994, pp.783–804.

[11] Cusson D. and Paultre P. Stress-Strain Model for Confined High-Strength Concrete, Journal of Structural Engineering, ASCE, Vol. 121, No. 3, 1995, pp. 468–477.

[12] Razvi, S. R. and Saatcioglu M., Confinement Model for High-Strength Concrete, Journal of Structural Engineering, ASCE, Vol. 125, No. 3, 1999, pp. 281–289.

[13] Li B., Park R., and Tanaka H., Stress-Strain Behavior of High-Strength Concrete Confined by Ultra-High- and Normal-Strength Transverse Reinforcements, ACI Structural Journal, Vol. 98, No. 3, 2001, pp. 395–406.

[14] Legeron F. and Paultre P., Uniaxial Confinement Model for Normal and High-Strength Concrete Columns, Journal of Structural Engineering, ASCE, Vol. 129, No. 2, 2003, pp. 241–252.

[15] Paultre P. and Légeron F., Confinement Reinforcement Design for Reinforced Concrete Columns, Journal of Structural Engineering, ASCE, Vol. 134, No. 5, 2008, pp. 738–749.

[16] Khatulistiani U., Tavio, and Raka I G. P., Influence of Steel Bars for External Confinement on Compressive Strength of Concrete, International Journal of GEOMATE, Vol. 20, No. 82, 2021, pp. 146–152.

[17] Rautenberg M., Pujol S., Tavallali H., Lepage A., Cyclic Response of Concrete Columns Reinforced with High-Strength Steel, Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering, Toronto, Ontario, Canada, 2010, Paper No. 996.

[18] Tavio and Kusuma B., Strength and Ductility Enhancement of Reinforced HSC Columns Confined with High-Strength Transverse Steel, Proceedings of the Eleventh East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-11), Taipei, Taiwan, 2008, pp. 350–351.

[19] Mast R. F., Dawood. M, Rizkalla S. H., and Zia P., Flexural Strength Design of Concrete Beams Reinforced with High-Strength Steel Bars, ACI Structural Journal, Vol. 105, No. 5, 2008, pp. 570–577.

[20] Bae S., Bayrak O., and Williamson E., What do We Know about the Performance-Based Design of Columns, 13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada, 2004, Paper No. 997.

[21] ASTM Subcommittee 05, Standard Specification for Deformed and Plain, Low-Carbon, Chromium, Steel Bars for Concrete Reinforcement (ASTM A1035/A1035M-20), ASTM International, Vol. 01.04, 2020, 7 pp.

[22] Japanese Standards Association, Steel Bars for Concrete Reinforcement (JIS G3112:2020 (E)), Japanese Industrial Standards, 2020, 15 pp.

[23] Cheng M. Y. and Giduquio B. M., Cyclic Behavior of Reinforced Concrete Flexural Members using High-Strength Flexural Reinforcement, ACI Structural Journal, V. 111, No. 4, 2014, pp. 893–902.

[24] Komite Teknis 77-01, Baja Tulangan Beton (SNI 2052:2017), Badan Standardisasi Nasional, 2017, 13 pp.

[25] ACI Committee 318, Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary on Building Code Requirements for Structural Concrete (ACI 318R-19), American Concrete Institute, 2019, 623 pp.

[26] Tavio, Anggraini R., Raka I G. P., and Agustiar, Tensile Strength/Yield Strength (TS/YS) Ratios of High-Strength Steel (HSS) Bars, AIP Conference Proceedings, Vol. 1964, 2018, ID 020036.

[27] Anggraini R., Tavio, Raka I G. P., and Agustiar, Stress-Strain Relationship of High-Strength Steel (HSS) Reinforcing Bars, AIP Conference Proceeding, Vol. 1964, 2018, ID 020025.

[28] Agustiar, Tavio, Raka I G. P., and Anggraini R., Evaluation of Higher-Strength Steel Reinforcing Bar Elongation for Seismic Design According to Various Standard Specifications, AIP Conference Proceedings, Vol. 2059, 2019, ID 020033.

[29] Anggraini R., Tavio, Raka I G. P., and Agustiar, Flexural Capacity of Concrete Beams Reinforced with High-Strength Steel Bars under Monotonic Loading, International Journal of GEOMATE, Vol. 20, No. 77, 2021, pp. 173–180.

[30] Agustiar, Tavio, Raka I G. P., and Anggraini R., Behavior of Concrete Columns Reinforced and Confined by High-Strength Steel Bars, International Journal of Civil Engineering and

Technology, Vol. 9, No. 7, 2018, pp. 430–436.
[31] Anggraini R., Tavio, Raka I G. P., and Agustiar, Experimental Load-Drift Relations of Concrete Beams Reinforced and Confined with High-Strength Steel Bars under Reversed Cyclic Loading, ASEAN Engineering Journal, Vol. 11, No. 4, 2021, pp. 56–69.
[32] ASTM Subcommittee 05, "Standard Specification for Deformed and Plain Low-Alloy Steel Bars for Concrete Reinforcement (ASTM A706/A706M-16), ASTM International, Vol. 01.04, 2016, 7 pp.
[33] Subkomite Teknis 91-01-S4, Persyaratan Beton Struktural untuk Bangunan Gedung dan Penjelasan (SNI 2847:2019), Badan Standarisasi Nasional, 2019, 695 pp.
[34] ACI Committee 318, Building Code Requirements for Structural Concrete (ACI 318M-14) and Commentary on Building Code Requirements for Structural Concrete (ACI 318RM-14), American Concrete Institute, 2014, 623 pp.