International Journal of GEOMATE, Jan., 2021, Vol.20, Issue 77, pp. 173-180
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2020.77.j2005
Geotechnique, Construction Materials and Environment

FLEXURAL CAPACITY OF CONCRETE BEAMS REINFORCED WITH HIGH-STRENGTH STEEL BARS UNDER MONOTONIC LOADING

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

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

*Corresponding Author, Received: 28 Sep. 2020, Revised: 28 Nov. 2020, Accepted: 12 Dec. 2020

ABSTRACT: This paper presents the flexural capacity of reinforced concrete beams designed with high-strength steel bars. Reinforced concrete beams with steel bars f_y = 550 MPa are designed to have flexural strength like beams with steel bar f_y 420 MPa. According to ACI 318M-19, the high-strength steel bars (f_y = 550 MPa) are allowed to use as the reinforcing steel, which previously unpermitted. This study was conducted to represent the possibility of using high-strength steel bars as reinforcement. There are five sample beams that design with various diameters (13 and 19 mm) and strength (f_y 420 and 550 MPa) of longitudinal reinforcement. These beams were placed on two simple supported and undergo monotonic loads at two points-load. It is reviewed the flexural capacity of beams with high-strength steel bars involve load capacity, moment, and beam deflection. Also, the behavior of beams when receiving loads in terms of the relationship between load and deflection. Based on the research, beams with a high-strength steel bar can accept higher loads than normal beams by a difference of about 16-18%. While at the same deflection condition, which is 100 mm, beams with high strength reinforcement can achieve a higher load of around 18 percent. Beam with high-strength steel bars showed flexural behavior that was not much different from the normal-strength steel bars because it did not show brittle collapse. It proves that high-strength steel bars can be used on reinforced concrete structural elements if it satisfies the requirements specified in the code.

Keywords: Beam, Flexure, High-strength steel bar, Monotonic loading, Reinforced concrete.

1. INTRODUCTION

Reinforced concrete design in the location where the earthquakes often occur requires great reinforcement and confinement details to provide adequate ductility of the structure. It causes the reinforcement density, so the process of workability is more complicated, and construction financing more expensive. [1-5]

One attempt to overcome this problem is to use high-strength steel bars to reduce the density of reinforcement that must be installed. Reducing the reinforcement density can improve concrete performance, simplify workability, reduce assembly time, and reduce construction costs. [1-5]

Now, the production of steel bars has grown rapidly. The United States has produced reinforcing steel with a strength of more than 690 MPa, as explained in ASTM A1035 [6] that there are two grades of high-strength steel bars Grade 80 and 100.

The Japanese state is capable of producing steel bars up to grade f_y 1000 MPa. While in Indonesia, high-strength steel bars that can be produced only reaches strength around f_y 500 MPa. It is explained in SNI 2052:2017 [7].

The production of high-strength steel bars is still bound by applicable regulations because there are requirements for the use of high-strength steel bars in reinforced concrete detailing [8,9]. ACI 318M-14 [10] mentions that as a longitudinal reinforcement, the strength of the steel bar is restricted in its use not to exceed f_y 420 MPa, and as a transversal reinforcement, it cannot exceed f_y 700 MPa.

This limitation aims to achieve adequate ductility in the structure, but there were changes in ACI 318-19 [11]. This code mentions that the use of high-strength steel bars has been permitted. In its use, high-strength steel bars are limited by three requirements as mentioned in ACI 318M-14 [10] and ACI 318-19 [11]. The reinforcing bars for special moment frames (earthquake resistant) must satisfy three requirements when used. Those requirements are tensile and yield strength (t_s and f_y), tensile-yield strength ratio (t_s/y_s), and elongation. The tensile-yield strength ratio must not be less than 1.25, and the elongation value must not be less than 10%, 12%, and 14% for certain diameters. These requirements will guarantee that reinforced concrete beams can maintain the curvature ductility [10,11]. Tavio, Anggraini, Raka, and Agustiar [12], conducted research related to the tensile-yield strength ratio. The results showed that high-strength steel bars produced a slightly lower tensile-yield strength ratio than normal-strength steel bars. Agustiar, Tavio, Raka, and Anggraini [13], with f_y 550 MPa can reach 13-16% for diameter 10-19 mm and 15%-17% for diameter 22-32 mm.

There is a reason why high-strength steel bars, specially produced in Indonesia, needs to be further evaluated. This study aims to demonstrate the use of high-strength reinforcing steel as longitudinal and transverse reinforcement in reinforced concrete beams that are subjected to monotonic loads.

2. RESEARCH SIGNIFICANCE

Structural ductility is the ability of a structure to experience deflection due to load without damage. Ductility in the structure is very necessary, especially in earthquake-prone areas. These are because the earthquake load is an alternating load, that makes the structure experience repeated deformation. All applicable regulations mention the importance of ductility in the design because if the structure is ductile, the structure can absorb energy. The structure ductility allows the structure to experience a large deformation with a slight decrease in strength.

There are several methods to improve structural ductility, such as providing confinement to structural elements or using reinforcing steel that has high elongation. The use of Welded Wire Fabric (WWF) as reinforcement can improve the strength of concrete and structural ductility. By installing a detailed longitudinal reinforcement and the number of WWF grids will significantly increase strength and ductility. Increased strength can reach around 50%-110%, while ductility increases about 4-10 times compared with structures that do not use confinement. The improvement due to the use of WWF on each variable was increased strength and ductility [14].

The previous research has been developed using an analytical stress-strain model for concrete confined by high-strength steel [15]. It evaluated the three-parameter of the stress-strain curve. It indicated that the proposed modeling is good enough for the conditions of the increased stress-strain curve. While for the downward curve, the proposed model is not consistent.

In the past, the use of reinforcing steel must comply with the provisions of ASTM A615 / 615M-08 [16]. It is Grade 40 (280 MPa), Grade 60 (420 MPa), and Grade 75 (520 MPa). Reinforcement grade 60 has a minimum yield strength of 420 MPa with yield plates clearly shown in the stress-strain diagram [16]. ACI ITG-6R [17] allows the use of steel bars with specific yield strength, f_y, more than 420 MPa, but the f_y value limited must be less than 550 MPa or the stress corresponding to a strain value of 0.0035. ACI also limits the specific strength, f_y, for screw reinforcement used as shear reinforcement up to 420 MPa. There is the specified yield strength, f_y, which is used as reinforcement confinement (ties or spiral) on the compressed member. ACI allows the use of specific strengths, f_y, up to a maximum of 690 MPa [17].

High-strength steel bars have the potential to be used in reinforced-concrete construction, but there are still some limitations in their use. ACI 318M-14 [10] allows the use of steel bars Grade 60,000 (414 MPa) as longitudinal reinforcement in earthquake-resistant structures, while lateral reinforcement is permitted up to grade 100 (690 MPa) higher than the permitted may be used on longitudinal reinforcement. Meanwhile, in the most recent ACI, which is ACI 318-19, improvements have been made to these restrictions. ACI 318-19 has mentioned that the reinforcing steel for the moment design and axial strength of the special moment frame is permitted up to f_y 552 MPa strength. For the special structural wall, it is permissible to use reinforcement with strength up to Grade 100,000 (690 MPa). It shows that the high-strength steel bar has begun to use [11].

The stress-strain diagram of high-strength steel bars (f_y 550, 650, and 700 MPa) differs from Grade 60 (f_y 420 MPa). The shape does not have a clear yield plate boundary. The high-strength steel bars have a minimum specific strength value (f_y > 420 MPa), which can determine based on the 0.2% offset method. While reinforcing steel with grade < 60 is always determined based on the observation of yield points that are clear in the stress-strain diagram.

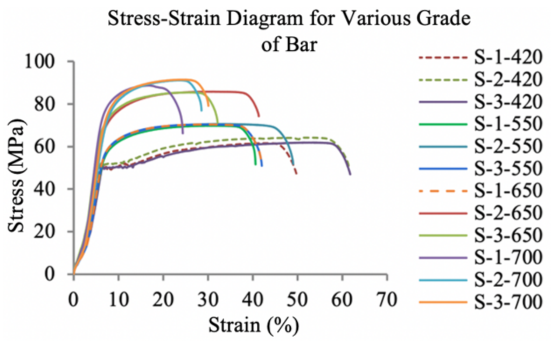

Fig 1. Stress-strain diagrams of several steel bar grades [18]

The grade 700 MPa achieves the highest

specific strength value compared to the strength of other steel bars (550 and 650). However, the strain can reach only 30%. While for the grade f_y 420 MPa, the lowest compared to other qualities but can achieve a longer stretch, reaching up to 60%. It shows that if the reinforcing bar has a high grade, it will have a high enough specific strength but not too long stretch value. That is because the elongation of high-strength steel bars is lower than low grade. The condition causes high-strength steel bars cannot be used directly in construction without strength improvement [18].

Now ASTM 615M-20 [19] provides requirements for reinforcing steel used in reinforced concrete elements. According to ASTM A615-20, there are several grades of steel, namely Grade 40 (f_y 280 MPa), 60 (f_y 420 MPa), 75 (f_y 520 MPa), 80 (f_y 550 MPa), and 100 (f_y 690 MPa). All of these classifications must satisfy the requirements of tensile strength, yield strength, strain, and bending. According to those requirements, the specifications in the research that have been conducted with not fully met the requirements satisfactorily. Further research is needed to implement it in the field.

3. METHODOLOGY

This research has been conducted by testing five samples of reinforced concrete beams. The shape and dimension of the beams are designed based on previous studies with some adjustments.

The beams have been designed with a cross-section dimension of 200 × 300 mm and a span length of 2550 mm. The beams will receive a monotonic load with two loading points. That is shown in Fig. 2.

The five samples beam were designed with two diameters of longitudinal reinforcement (13 and 19 mm) and two grades of reinforcement strength (f_y 420 and 550 MPa). Besides these, beams are also designed with transverse reinforcement with a diameter of 10 mm and with two different grades, which is, f_y 420 and 550 MPa. The transverse reinforcement is installed with two types of reinforcement spacing. It is 100 mm in one-third of the span length on the left and right of the beam and a distance of 200 mm in one-third of the span length in the middle (between two loading points). It is as shown in Fig. 2. In this study, the compressive strength of concrete used was the same for all beams, its normal compressive strength f_c' 30 MPa. It is as presented in Table 1.

Table 1. Design concrete strength and design data of reinforcing steel bars for beam specimens

Specimen ID	Con-crete	Longitudinal reinforcing bars		Transversal reinforcing bars	
	f_c' (MPa)	f_y (MPa)	diameter (mm)	f_y (MPa)	diameter (mm)
M1		420	3D19	420	10
M2		550	3D19	420	10
M3	30	550	3D13	420	10
M4		550	3D13	550	10
M5		550	3D19	550	10

Monotonic loading tests were applied to the beam specimens using the Universal Testing Machine (UTM). To read the load, a load cell was attached between the ram stroke and spreader beam from the beginning of loading until the beam failed in flexure and continued further until the beam capacity dropped to a minimum of 20% of its corresponding maximum load. The deflections were measured by the transducers which were located at the soffit of the beam midspan and two load points. The data obtained from the experimental tests included the load and deflection at maximum load and the end of testing.

Figure 3 shows the beam specimen during testing under monotonic loading with transducers mounted in front and at the backside of the beam, and the soffit of beam midspan.

Fig 3. Beam specimen during testing

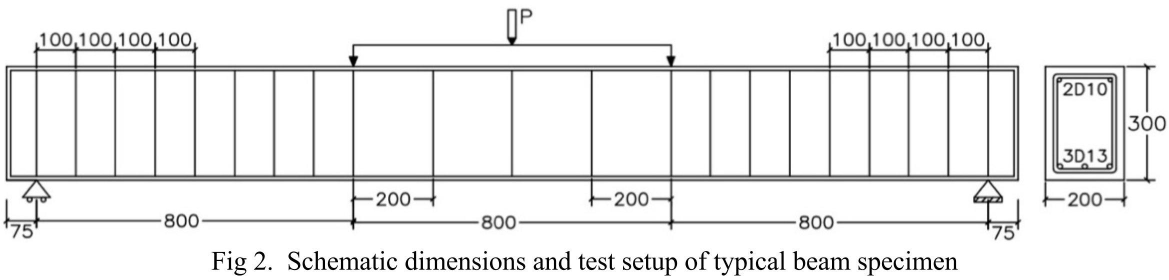

Fig 2. Schematic dimensions and test setup of typical beam specimen

4. RESULTS AND DISCUSSIONS

The research results were obtained with laboratory testing in the form of maximum loading and deflection of five sample beams. Those beams were supported with simple support. The result of maximum loading and final loading can be seen in Table 2.

Table 2. Maximum load and load at the end of testing

No.	Specimen ID	P_{max} (kN)	$P_{end\ of\ testing}$ (kN)
1	M1	223.1	111.6
2	M2	263.1	130.5
3	M3	137.2	68.6
4	M4	140.9	70.6
5	M5	259.6	129.8

Table 2 shows that beam M2 can reach the highest maximum load compared to other beams. There is because beam M2 has been designed with a high-strength steel bar (f_y 550 MPa) and a 19 mm diameter. Beam M1 as a control beam, that is designed with the same diameter (19 mm) but with a different grade steel reinforcement (f_y 420 MPa), can achieve a maximum load lower than beam M2. Beam M5 has been designed with the same diameter (19 mm) and grade (f_y 550 MPa) for longitudinal and transverse reinforcement. That beam can reach a maximum load slightly lower than beam M2. It is because those beams have a different strength at the transversal reinforcement. Beam M2 and M5 which used high-strength steel bars can achieve a higher maximum load than the control beam (M1) by a difference of about 16.4% and 17.9%, respectively. It is because beam M2 and M5 that used high-strength steel bars have higher strength than the normal-strength reinforcing beams so that the maximum load capacity that can be achieved is higher. Meanwhile, beam M3 and M4, which were designed using high-strength reinforcing steel but with a smaller area, 45% compared to that of M1, achieved maximum load which was lower than that of beam M1. The differences were found to be 38.5% and 36.8%, respectively.

Besides the maximum load (P_{max}), the last loading when the beam collapses at the end of testing ($P_{end\ of\ testing}$) can be seen in Fig. 4, which shows the difference between both of them. Figure 4 also shows that all beams can accept the load until the end of the test. The end of testing is designed until 50% of the maximum load can be achieved.

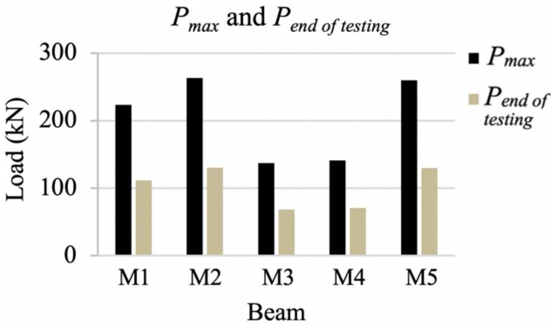

Fig 4. Comparison of P_{max} and $P_{end\ of\ testing}$

The M2 and M5 beams, which are designed with a high-strength reinforcement diameter of 19 mm, can survive until the end of the test without experiencing brittle collapse. It is indicated that the beams using high-strength steel bars had sufficient ductility. These beams can withstand further loading and maintained long deformation. Besides beam M3 and M4, which are designed with a high-strength longitudinal reinforcement diameter of 13 mm, also can survive until the end of testing but with a smaller load. This illustration shows that beam M3 and M4 with lower reinforcement ratios tend to deflect greater after yielding with slow degradation of load-carrying capacity than others. Due to safety reasons and to prevent the instruments from any damages, the tests were designed to be terminated if the load drops to approximately $0.5P_{\max}$, which is already considered to be unstable in load-carrying capacity and might be failed abruptly at any time.

This study also observed the deflection of reinforced concrete beams beside the maximum load. Table 3 shows the deflection in the middle span of the beam. The reading of deflection does when the maximal loading occurs and at the end of the test. Beams M2 and M5, which have been designed with yield strength steel bars of f_y 550 MPa and 19 mm diameter, achieve deflection of less than 20 mm. While beams M3 and M4, which have been designed with yield strength steel bars f_y of 550 MPa and 13 mm diameter, achieve deflection better than beams M2 and M5, it is around 33 mm. Beam M1, as a control beam, can reach almost the same deflection as beams M2 and M5. It is because beams M1, M2, and M5 are designed with the same diameter, even though the grade used is different.

When the maximum load occurs, M2 and M5 beams experience lower deflection than the M1 beam. It is because M2 and M5 beams that use high-strength reinforcing steel have higher strength so that they can maintain deformation compared to M1 beams. One of the factors affecting the flexural capacity of the beam is the strength of the reinforcement. It also relates to the load that can be accepted. It can be seen that the M2 and M5 beams can achieve a higher load than the M1 beam.

Table 3. Deflections at midspan of the beams

No.	Specimen ID	P_{max} (kN)	Deflection at maximal load (mm)	Deflection at the end of testing (mm)
1	M1	223.1	20.30	225.06
2	M2	263.1	19.95	203.85
3	M3	137.2	60.50	350.04
4	M4	140.9	33.25	354.10
5	M5	259.6	19.20	200.65

It can be seen that beam M3 can withstand until the deflection reached approximately 350 mm at the end of testing. It was the highest deflection achieved by beam M3 as compared to the other four beams. Beam M2 and M5, which have been designed with the same strength and diameter of longitudinal steel bars could attain deflection greater than that of beam M1. It is because beams with high-strength reinforcement provide better ductility in maintaining longer deformation. From all the tests, it can be seen that all the beams can successfully carry the load without any sign of collapse

The other research also conducted a similar study. The study shows that beams with high-strength reinforcing bars can reach a higher flexure capacity than beams with normal-strength steel bars [1, 20].

The deflection differences in each beam can be presented in the form of bar charts. Figure 5 shows the comparison of the deflections of all test beams. The diagram shows the deflection difference of each beam for maximum and at the end of loading.

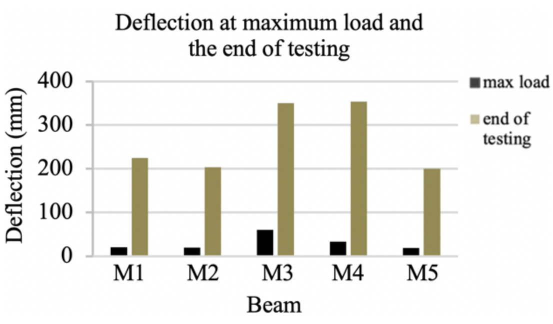

Fig 5. Comparison of deflections at maximum loads and end of testing

Besides, as one of the parameter comparisons for each beam, there is also observed the load when deflection 100 mm. Table 4 shows the load when the deflection reaches 100 mm. Beams M2 and M5, which have been designed with high-strength steel bar diameter 19 mm, can achieve loads better than beam M1 as the control beam. Whereas beam M3 and M4 achieved lower load compared to beam M1 since they used the smaller diameter of steel bars, i.e.13 mm.

Table 4. Experimental loads at 100-mm deflection

No.	Specimen ID	P_{max} (kN)	P at deflection 100 mm (kN)
1	M1	223.1	210.0
2	M2	263.1	227.1
3	M3	137.2	132.3
4	M4	140.9	135.6
5	M5	259.6	219.8

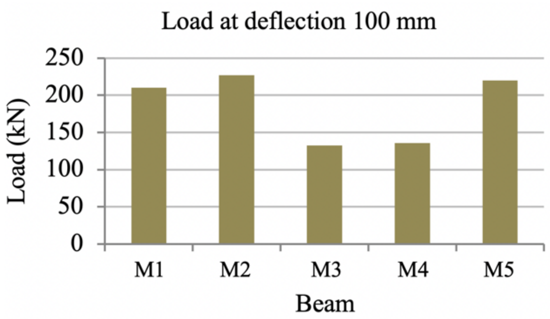

Fig 6. Loads at 100-mm deflection

According to Fig. 6, beams 2 and 5 which have reinforcement with a diameter of 19 mm can carry higher loads than beam M1 with the same diameter but different in the strength of steel bars. It can be seen that the deviation of load carrying capacity becoming obvious (8 percent) at the deflection of about 100 mm. It shows that high-strength steel bars can withstand the load. The beam M3 and M4 could carry loads lower than beam M1 when the deflection reached 100 mm. The difference was about 35 percent. This is due to the difference in bar diameter used in the beams. Beam M3 and M4 had reinforcement ratios of about 45% lower than beam M1.

Table 5. Bending moments at maximum loads and end of testing

No.	Specimen ID	M_{max} (kN-m)	$M_{end\ of\ testing}$ (kN-m)
1	M1	89.24	84.00
2	M2	105.20	90.84
3	M3	54.88	52.92
4	M4	56.36	54.24
5	M5	103.84	87.92

Table 5 above shows the bending moments achieved at the maximum and end of testing. It can be seen that beam M2 and M5 can carry a higher load than beam M1. The differences are about 16.4% and 18%, respectively. However, beam M3 and M4 are capable to reach a bending moment capacity lower than beam M1. The difference is about 36-38%.

The moment and load from the test results can be compared with the moment and load when calculating the initial design. Table 6 shows the comparison of the load, while Table 7 shows the comparison of the moment between experimental and theoretical.

Table 6. Comparison of experimental and theoretical loads

No.	Specimen ID	P_{max}		Differen-ces
		Experimental (kN)	Theoretical (kN)	%
1	M1	223.1	201.25	10.857
2	M2	263.1	250.93	4.810
3	M3	137.2	132.45	3.586
4	M4	140.9	132.45	6.380
5	M5	259.6	250.93	3.455

Table 7. Comparison of experimental and theoretical bending moments

No.	Specimen ID	M_{max}		Differen-ces
		Experimental (kN-m)	Theoretical (kN-m)	%
1	M1	89.24	80.50	10.807
2	M2	105.24	100.37	4.812
3	M3	54.88	52.98	3.624
4	M4	56.26	52.98	6.455
5	M5	103.84	100.37	3.417

Based on Tables 6 and 7, it can be seen that the maximum experimental load (P_{max} experimental) is slightly better than the maximal theoretical load that calculates at the initial design (P_{max} theoretical). The difference between the theoretical and experimental load that occurs is not very large. This also occurs at the maximum moment for experimental and theoretical.

The difference between the experimental and the theoretical calculations is presented in Fig. 7. It can be seen that the difference between the theoretical and experimental load and maximum moment of the beam occurs between 3-10%. The biggest-difference occurs in beams with normal reinforcement strength (f_y 420 MPa), while beams with a high-strength steel bar (f_y 550 MPa) have smaller differences.

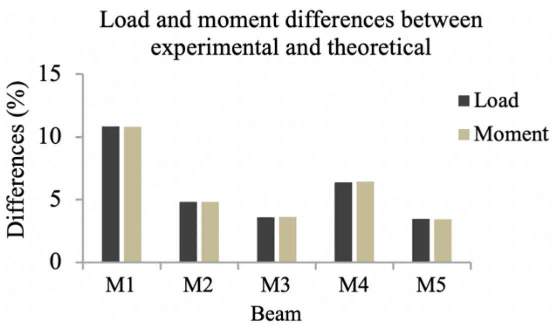

Fig 7. Comparison of experimental and theoretical loads and bending moments

These results indicate that the design that was carried out at the beginning was as expected. Also, these results indicate that the beams did not experience unexpected collapse, which is: brittle collapse. The analysis carried out at the beginning used a theoretical approach with the assumption that the elastic material conditions are still satisfactory.

The load and deflection of the entire beam sample show a relationship. The relationship is shown in Fig. 8. The beam designed with a longitudinal reinforcement diameter of 19 mm has almost the same maximum load. Beam M2 and M5, which have been designed with high-strength steel bars (f_y 550 MPa), have almost the same shape. Whereas beam M1 as a control beam has a slightly different shape. There is a sharp decrease after the maximum load occurs in beam M2 and M5. While beam M1 can still maintain its shape in a more stable condition even though the maximal load has been exceeded. It is due to the mechanical characteristics of high-strength steel bars used in beams M2 and M5.

Whereas beam M3 and M4 show different shapes with beams M1, M2, and M5 because beams M3 and M4 use longitudinal reinforcing steel with different diameters, both use 13 mm reinforcement diameters with the same strength that is f_y 550 MPa. Beams M3 and M4 have a different-strength in the transverse reinforcement used. The use of different strengths of transverse reinforcement is less influential in terms of load capacity and deflection. This is due to the load capacity and deflection are mainly affected by longitudinal reinforcement. The relationship between load and deflection can indicate the ductility of the structure. It can be seen that the beam M1 can maintain deformation to a long condition than the beam M2 and M5 that have a sharp-decreased curved shape. It means those beams cannot withstand the loads. Besides, beam

M3 and M4 can withstand the loads. It illustrates the ductility of each beam.

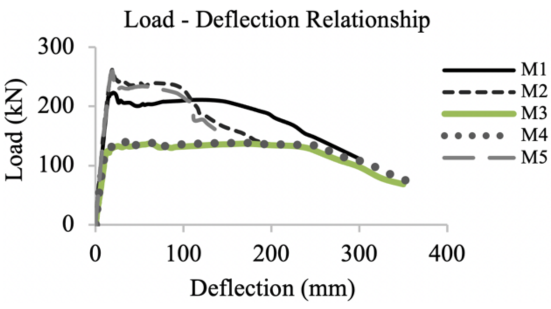

Fig 8. Load-deflection relationships

Based on this analysis, it appears that only two parameters have been analyzed here. There are still many other parameters that need to be analyzed to ensure the possibility of using high-strength steel bars in reinforced concrete design. So that further research is required to find out how to get a high-strength steel bar with good mechanical characteristics so that it can be used on reinforced concrete beams.

5. CONCLUSIONS

Based on the research results, it can be concluded that high-strength steel bars (f_y 550 MPa) used as longitudinal reinforcement for beams can sustain the load without experiencing any sudden collapse. Beams with high-strength reinforcing steel (M2 and M5) achieved a higher maximum load than the control beam (M1) with a difference of around 16.4 and 17.9%, respectively. Meanwhile, beam M2 and M3 which used high-strength reinforcing steel with an area of 45% lower than beam M1 achieved a lower maximum load. The differences were 38.5% and 36.8%, respectively. Beams with high-strength reinforcing steel (M2 and M5) were capable of resisting higher bending moments than the control beam (M1), while beam M3 and M4 resisted smaller bending moments than beam M1.

Beams with high-strength reinforcing steel can maintain load-deformation capacity. The high-strength reinforced beams survived throughout the loading tests without any brittle collapse even up to large deflections. At the deflection of 100 mm, beams with high-strength reinforcement (M2 and M5) could attain higher loads than the control beam with differences in load capacity of about 8.1% and 4.7%, respectively. Beam M3 and M4 reached a lower load capacity than beam M1 by the differences of about 37% and 35.4%, respectively.

It indicates that high-strength steel bars can be applied to reinforced concrete. These require some adjustments to ensure that the structure has adequate ductility and behavior as required by the regulations.

For further research, other research is still needed, especially to determine the ductility of reinforced concrete beams with high-strength steel bars. It is to know the possible use of high-strength steel bars in the reinforced concrete beam.

6. ACKNOWLEDGMENTS

The authors would like to extend their sincere gratitude for all the supports received, particularly from PT. Tunggal Jaya Steel, PT. Bhirawa Steel, and PT. Varia Usaha Beton.

7. REFERENCES

[1] 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, Issue 5, 2008, pp. 570-577.

[2] Faza S., Kwok J., Salah O., Application of High-Strength and Corrosion-Resistant ASTM A1035 Steel Reinforcing Bar in Concrete High-Rise Construction, CTBUH 8th World Congress, Dubai, 2008.

[3] Seliem H. M., Hosny A., Rizkalla S., Zia P., Briggs M., Miller S., Darwin D., Browning J., Glass G. M., Hoyt K., Donnely K., and Jirsa J. O., Bond Characteristics of ASTM A1035 Steel Steel bars, ACI Structural Journal, Vol. 106, Issue 4, 2009, pp. 530-539.

[4] Soltani A., Harries K. A., Bahram M. S., Russel H. G., and Miller R. A., Fatigue Performance of High-Strength Reinforcing Steel, Journal of Bridge Engineering, Vol. 17, Issue 3, 2012, pp. 454-461.

[5] Ruternberg J. M., Pujol S., Tavallali H., and Lepage A., Drift Capacity of Concrete Columns Reinforced with High-Strength Steel, ACI Structural Journal, Vol. 110, Issue 2, 2013, pp. 307-317.

[6] ASTM A1035/A1035M-20, Standard Specification for Deformed and Plain, Low-Carbon, Chromium, Steel Bars for Concrete Reinforcement, West Conshohocken, PA: ASTM International, 2020, pp. 7.

[7] SNI 2052:2017, Baja Tulangan Beton, Jakarta: Badan Standardisasi Nasional (BSN), 2017, pp. 13.

[8] Li Y., Cao S., Liang H., Ni X., and Jing D., Axial Compressive Behavior of Concrete Columns with Grade 600 MPa Reinforcing Bars, Engineering Structures, Vol.172, 2018, pp. 497-507.

[9] Dehkordi S. A., Mostofinejad D., and Alaee P.,

Effects of High-Strength Reinforcing Bars and Concrete on Seismic Behavior of RC Beam-Column Joints, Engineering Structures, Vol. 183, 2019, pp. 702-719.
[10] ACI 318M-14, Building Code Requirements for Structural Concrete (ACI 318M-14) and Commentary on Building Code Requirements for Structural Concrete (ACI 318RM-14), Farmington Hills, MI: American Concrete Institute, 2014.
[11] ACI 318-19, Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary on Building Code Requirements for Structural Concrete (ACI 318R-19), Farmington Hills, MI: American Concrete Institute, 2019.
[12] Tavio, Anggraini R., Raka I G.P., and Agustiar, Tensile strength/yield strength (TS/YS) ratios of high-strength steel (HSS) steel bars, AIP Conference Proceedings, Vol. 1964, 020036, 2018.
[13] 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, 020033, 2019.
[14] Tavio, Kusuma B., and Suprobo P., Experimental Behavior of Concrete Columns Confined by Welded Wire Fabric as Transverse Reinforcement under Axial Compression, ACI Structural Journal, Vol. 109, Issue 3, 2012, pp. 339-348.
[15] Tavio, Suprobo P., and Kusuma B., Strength and Ductility Enhancement of reinforced HSC Columns Confined with High-strength Transverse Steel, Eleventh East Asia-Pacific Conference on Structural Engineering & Construction (EASEC-11), Taiwan, 2008.
[16] ASTM A615/A615M-08, Standard Specification for Deformed and Plain Carbon-Steel for Concrete Reinforcement, West Conshohocken, PA: ASTM International, 2008, pp. 5.
[17] ACI ITG-6R-10, Design Guide for the Use of ASTM A1035/A1035M Grade 100 (690) Steel Bars for Structural Concrete, Farmington Hills, MI: American Concrete Institute, 2010.
[18] Anggraini R., Tavio, Raka I G.P., and Agustiar, Stress-Strain Relationship of High-strength Steel (HSS) Reinforcing Bars, AIP Conference Proceeding, Vol. 1964, 020025, 2018.
[19] ASTM A615/A615M-20, Standard Specification for Deformed and Plain Carbon-Steel for Concrete Reinforcement, West Conshohocken, PA: ASTM International, 2020, pp. 8.
[20] Kelly D. J., Lepage A., Mar D., Restrepo J. I., Sanders J.C., and Taylor A.W., Use of High Strength Reinforcement for Earthquake Resistant Concrete Structures, The 10th U.S. National Conference on Earthquake Engineering, Anchorage, Alaska, 2014.