Research Article

Experimental Study and Reliability Analysis of Flexural Capacity of RC Beams Reinforced with 600 MPa Grade Steel

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Flexural capacity of beams reinforced with 400 or 500 MPa grade steel can be accurately estimated by using equations provided in design codes. Recently, 600 MPa grade steel has evolved in the construction industry, and the applicability of existing equations for this grade of steel should be verified by performing experimental investigation. By conducting tests on concrete beams reinforced with 600 MPa grade high-strength steel, this study investigates the flexural performance for different concrete strength grades and different reinforcement ratios. Flexural capacities of concrete beams reinforced with 400 MPa, 500 MPa, and 600 MPa grade steel are analyzed based on equations in various codes and based on experimental studies in the literature. Furthermore, this study performs reliability analysis and verifies the three design values of 600 MPa grade steel yield strength in relation to the experimental performance and recommends the appropriate design values of 600 MPa grade steel yield strength. Research results show that when the measured values of yield strength of the steel bars and concrete strength are used, the ratio of the measured failure moment value to the calculated value for various beams based on different codes is nearly 1.0, demonstrating the high degree of fitting. Finally, the reliability analysis shows that the design yield strength of the 600 MPa grade high-strength steel bars should be taken as 520 MPa.

1. Introduction

In recent years, use of high-strength steel bars has improved the performance of concrete structures and reduced the amount of steel bars. High-strength steel bars (with yield strength > 500 MPa) have evolved as a new type of environmentally friendly building materials [1–4]. In the United States, South Korea, Canada, and Japan, 70% of the steel reinforcement in reinforced concrete has the strength of 400 MPa and above 25% has the strength of 500 MPa. In Germany, France, and the United Kingdom, the amount of the 500 MPa steel bar has reached 70% of the total reinforcement, and the construction industry is demanding for the 600 MPa steel bar. Based on the data of steel processing, saving 10 million tons of steel is equivalent to saving 18 million tons of iron ore, saving 6.5 million tons of standard coal, and reducing a large amount of exhaust gas and dust

emissions. Therefore, the application of high-strength reinforcement can not only save energy and resources but also reduce emissions. In addition, new materials and environmentally friendly materials have always been the goal pursued by engineers and researchers [5–7]. High-strength steel with yield strength (f_y) greater than 500 MPa has been developed in several markets worldwide [8]. Development of high-strength steel with different grades has been extensively studied all over the world, such as steel grade 600 MPa [9], steel grade 700 MPa [10], steel grade 700 MPa [11], steel grade 780 MPa [12], and steel grade 800 MPa [13]. Hao et al. [14] studied the mechanical properties and microstructure of HRB600 steel bars (600 MPa grade) after subjecting to high temperature. Zhang et al. [15] studied the mechanical properties of steel fiber concrete at high temperatures. Saleem et al. [16] studied the bonding and deformation properties of reinforced concrete (RC) that used steel with

the yield strength of 690 MPa. Harries et al. [17] believed that the application of high-strength steel bars in concrete can achieve significant economic benefits. Barclay and Kowalsky [18] studied the seismic performance of high-strength RC columns, and the results showed that RC columns with steel having the yield strength of 550 MPa behaved similar to columns with steel having yield strength of 420 MPa steel bars in terms of the early stage of yield, length of plastic hinge, and capacity consumption. However, the yield strength of RC columns having 550 MPa grade steel was markedly improved. The characteristic of steel bar fracture appears under low deformation. Zhang et al. [19] found that high-strength concrete columns with HRB600 steel bars possessed good hysteretic behavior, deformability, and energy dissipation capacity as well as seismic resilience. Aldabagh and Alam [20] found that high-strength steel (HSS), i.e., ASTM A1035 grade 690, has been gaining popularity in the last two decades due to its considerably higher strength and corrosion resistance. Baek et al. [21] revealed that the shear friction resistance of grade 600 MPa (87 ksi) reinforcing bars was greater than that of 400 MPa (58 ksi) reinforcing bars. Li et al. [22] found that the combination of concrete with C80 grade and steel bars with HRB600 grade was a reasonable match for strength.

Definition of high-strength grade differs from specifying institutions. For instance, the International Organization for Standardization Standard ISO6935-2-2015 stipulates the high-strength steel bar grades as B600A-R, B600B-R, and B600C-R, the American standard ASTM A615-18el stipulates the high-strength steel grade as 100 ksi (690 MPa), the Korean standard KSD3504-2011 stipulates the high-strength steel grade as SD600 and SD700, the Singapore standard SS 560-2016 stipulates high-strength steel bar grades as B600A, B600B, and B600C, and the Chinese standard GB/T1499.2-2018, Part 2 of steel for RC, hot-rolled ribbed steel bar stipulates the high-strength steel bar as HRB600 [23]. However, the formulas for calculating the bearing capacity of RC beams made with high-strength steel bars are not the same in various countries, and even, the formulas used by different industries are sometimes different in the same country. For example, in China, reinforcing steel is produced with different standards, namely, GB 50010 [24], DL/T 5057 [25], SL/T 191 [26], JTJ 267 [27], JTG D62 [28], and TB10002.3 [29]. The applicability of equations developed for 400 MPa and 500 MPa steel bars has been generally deemed applicable for high-strength bars by various countries. However, experimental verification is necessary to determine whether high-strength steel bars based on different standards are suitable to be used as 600 MPa steel bars and whether the bars possess sufficient safety reserves. Determining the properties of materials through experiments is also a common method used by researchers [30–36]. In addition, the grades of steel bars are updated quickly, and the codes often lag behind. The current Chinese code GB 50010 Design Code for Concrete Structures stipulates that the highest yield strength of ordinary stressed steel bars is 500 MPa. Therefore, the applicability of high-strength steel bars should be urgently recognized in such codes; otherwise, it will affect its application in engineering.

TABLE 1: Main physical and mechanical properties of cement.

Compressive strength (MPa)				Flexural strength (MPa)				Density (kg/m ³)	
P.O42.5		P.O52.5		P.O42.5		P.O52.5		P.O42.5	P.O52.5
3 d	28 d	3 d	28 d	3 d	28 d	3 d	28 d	3043	3244
22.3	49.4	26.5	57.7	5.2	9.1	6.5	9.8		

Researchers have identified the safe design value of 600 MPa steel bars. However, researchers are not unanimous about the yield strength of the 600 MPa steel bar, and this causes inconvenience in design. Chen et al. [37] and Rong et al. [38] studied the flexural performance of RC beams with 600 MPa grade steel under concentrated load. The research results showed that the bending failure mode was the same as that of ordinary reinforced (HRB500 and HRB400) concrete beams. The flexural bearing capacity could still be calculated according to the equations for the flexural bearing capacity of the normal RC section specified in the current codes. When the design tensile strength of the 600 MPa grade steel bar was set to 500 MPa, sufficient safety reserve was maintained. However, Zhang et al. [39] suggested that when the yield strength of 600 MPa grade steel bars was taken as 520 MPa, the equation for design of concrete structures (GB 50010) could be safely used for calculating flexural bearing capacity of RC beams with 600 MPa steel bars. In order to study the applicability of codes from various countries in the design of RC beams with high-strength steel bars, this research experimentally investigates the flexural bearing capacity of beams with 600 MPa high-strength reinforcement and different strengths of concrete and combines the test results with those of other scholars to analyze the bearing capacity of RC beams. Finally, the reliability of the three design values (500 MPa, 520 MPa, and 545 MPa) of 600 MPa grade steel yield strength is verified in relation to the experimental results, and the appropriate design value of 600 MPa grade steel yield strength is selected.

2. Experimental Study for RC Beams with 600 MPa Steel Bars

2.1. Material. Four concrete grades were used in this experiment, denoted by C30, C40, C50, and C60. Physical and mechanical properties of cement are shown in Table 1 (Chinese standard GB 175 2007 [40]). Fine aggregate used in this experiment was river sand with the maximum size of 2.5 mm. Material properties of the river sand are presented in Table 2. Coarse aggregate used in this experiment was crushed aggregate, and its properties are shown in Table 3. A high-range water-reducing admixture was used to achieve good workability. Concrete mixture proportion for the four grades of concrete can be found in Table 4.

The size, reinforcement arrangement, and material properties of tested beams are listed in Table 5. In the table, f_{cu} (average value from three cubes with the dimensions of 150 mm × 150 mm × 150 mm) is the cube compressive strength and f_{ts} (average value from three cubes with the dimensions of 150 mm × 150 mm × 150 mm) is the splitting

TABLE 2: Machine-made sand.

Apparent density (kg/m ³)	Sediment percentage	Bulk density (kg/m ³)	Fineness modulus
2700	0.5	1610	2.6

TABLE 3: Coarse aggregate.

Apparent density (kg/m ³)	Sediment percentage	Bulk density (kg/m ³)	Particle size distribution (mm)
2710	0.3	1630	5–20

TABLE 4: Concrete mixture proportion.

Mixture	Cement, (kg/m ³)	Water, (kg/m ³)	w/c	Aggregate (kg/m ³)			Sand (kg/m ³)	High-range water-reducing admixture (kg/m ³)
				5 to 10 (mm)	10 to 16 (mm)	16 to 20 (mm)		
C30	378 (no. 42.5)	189	0.50	491	328	273	758	1.89
C40	473 (no. 42.5)	189	0.40	491	328	273	670	3.31
C50	473 (no. 52.5)	189	0.40	491	328	273	698	3.31
C60	630 (no. 52.5)	189	0.30	458	305	254	624	5.04

TABLE 5: Size and reinforcement and material properties of tested beams.

RC beam number	Width b /mm	Depth h /mm	Effective span l_0 /mm	Concrete cover c /mm	Steel ratio ρ /100%	Reinforcement					Concrete	
						A_s /mm ²	f_y /MPa	E_s /GPa	f_{cu} /MPa	f_{ck} /MPa	f_{ts} /MPa	$E_c \times 10^4$ /MPa
600-C30-1-1	200	350	2550	30	0.8	509	645.02	195	37.65	26.36	1.97	3.80
600-C30-1-2	200	350	2550	30	0.8	509	645.02	195	37.65	26.36	1.97	3.80
600-C30-2-1	200	350	2550	30	0.5	308	635.71	198	37.65	26.36	1.97	3.80
600-C30-2-2	200	350	2550	30	0.5	308	635.71	198	37.65	26.36	1.97	3.80
600-C40-1-1	200	350	2550	30	0.8	509	645.02	195	42.55	32.19	2.69	3.70
600-C40-1-2	200	350	2550	30	0.8	509	645.02	195	42.55	32.19	2.69	3.70
600-C40-2-1	200	350	2550	30	0.5	308	635.71	198	42.55	32.19	2.69	3.70
600-C40-2-2	200	350	2550	30	0.5	309	635.71	198	42.55	32.19	2.69	3.70
600-C50-1-1	200	350	2550	30	0.8	509	645.02	195	53.00	33.28	3.40	3.70
600-C50-1-2	200	350	2550	30	0.8	509	645.02	195	53.00	33.28	3.40	3.70
600-C50-2-1	200	350	2550	30	0.5	308	635.71	198	53.00	33.28	3.40	3.70
600-C50-2-2	200	350	2550	30	0.5	308	635.71	198	53.00	33.28	3.40	3.70
600-C60-1-1	200	350	2550	30	0.8	509	645.02	195	67.14	62.31	3.35	4.10
600-C60-1-2	200	350	2550	30	0.8	509	645.02	195	67.14	62.31	3.35	4.10
600-C60-2-1	200	350	2550	30	0.5	308	645.02	198	66.31	61.75	3.35	4.10
600-C60-2-2	200	350	2550	30	0.5	308	645.02	198	66.31	61.75	3.35	4.10
400-C60-1-1	200	350	2550	30	0.8	509	428.07	200	67.14	62.31	3.35	4.10
400-C60-1-2	200	350	2550	30	0.8	509	428.07	200	67.14	62.31	3.35	4.10

tensile strength. Similarly, f_{ck} (average value from three prisms with the dimensions of 150 mm × 150 mm × 300 mm) is the prism compressive strength and E_c (average value from three prisms with the dimensions of 150 mm × 150 mm × 300 mm) is the elastic modulus.

2.2. Design and Test of RC Beams. In this experiment, 8 groups (2 beams from each group based on the concrete grade) of RC beams were tested. All beams were cast using 600 MPa grade reinforcing steel. 2 RC beams with C60 grade concrete and the steel grade of 400 MPa were cast as a control group. As shown in Figure 1, the two points of the midspan section were symmetrically loaded to form an 800 mm pure bending section. The load application was based on the design bending moment of the purely bent section. The concrete beam was tested under static loading with consideration of the effects of the beam's own weight and the loading equipment. The load values at all levels were controlled by the readings of the data acquisition system connected to the sensor.

2.3. Stress-Strain Curves of 600 MPa Steel Bar. In this study, 600 MPa grade reinforcement was used as longitudinal reinforcement of the test beam. Figure 3 shows the stress-strain curve of the 600 MPa rebar as obtained from a test. The stress-strain curve of the 600 MPa steel bar shows three stages with a clear yield plateau: elasticity, yielding, and stress hardening. Yield strength f_y and ultimate strength f_u of the 600 MPa rebar with different diameters were between 635.71 MPa and 645.02 MPa, and 819.92 MPa to 840.38 MPa, respectively. The Chinese standard GB50010-2010 specifies the measured maximum force total elongation A_{gt} of steel bars should not be less than 9%. The measured A_{gt} of 600 MPa grade steel bars was 10.3%.

2.4. Failure Mode and Load-Deformation Curves of RC Beam. The actual failure mode of the RC beam belongs to proper-reinforced beam failure. As shown in Figure 4, the actual failure state of the test beam is shown that the beam has obvious plastic deformation and fracture precursor before failure. In addition, the load-deformation curves show typical three stage of proper-reinforced beam failure, as shown in Figure 5. The deformation of the specimen increased linearly before cracking. When the external load reached the cracking bending moment M_{cr} ((20%–30%) M_u), one or several initial cracks appeared in the pure bending section of the RC beam, the deformation curves exhibited an abrupt transition point, and the slopes of the curves began to decrease. With a further increase in load, when the strength of the 600 MPa steel bar reached its yield strength, the deformation of the specimens increased sharply, a second and more obvious inflection point appeared on the load-deformation curve, and the concrete in the RC beam was crushed. Therefore, the 600 MPa steel RC beam is the balanced-reinforced beam.

As shown in Figure 5, when the strength grade of concrete was the same, the bearing capacity of the specimen

increased with an increase in reinforcement ratio. On the other hand, the ductility of specimens decreased with an increase in the reinforcement ratio. When the ratio of reinforcement was the same, the bearing capacity of the specimen increased with an increase in the concrete strength grade.

3. Results and Discussion

3.1. Analytical Ultimate Bearing Capacity Based on Codes from Various Countries. The calculation methods for the bearing capacity from various Chinese standards are based on the test results of 335 MPa, 400 MPa, and 500 MPa RC beams. Whether the method is applicable to the calculation of the bearing capacity of 600 MPa RC beams is still uncertain. This needs to be verified based on the test data of 600 MPa RC beams.

By comparing the bearing capacity equations of various national codes (GB 50010-2010 [24], SL 191-2008 [26], DL/T5057-2009 [25], JTG D62-2004 [27], ACI 318-2014 [41], EN1992-1-1 [42], CRC Press LLC, 1999 [43], BS5400-4 [44, 45], EN1991-2 [46], and AASHTO LRFD Bridge Design Specification [47]), it can be found that the calculation methods for the bearing capacity of rectangular cross section RC beams in the current Chinese codes and European and American codes are consistent in expression and symbolic connotation. However, there are subtle differences in the strength calculation and height calculation methods of the concrete equivalent rectangular stress diagram. Therefore, the actual measured value of the bearing capacity of 400 MPa, 500 MPa, and 600 MPa RC beams and the calculated values based on various codes are compared and analyzed to verify their applicability.

3.2. Analysis of Moment of Resistance of Beams with 400 MPa Grade Steel. The literature [48–53] reports flexural performance tests of concrete beams reinforced with 400 MPa grade steel, and the relevant information of the specimens is shown in Table 6.

In order to verify the applicability of the bearing capacity equations of the existing national codes, measured flexural bearing capacity of RC beams is compared with the calculated value based on various codes. The comparison of the measured value M_u and the calculated value M_{uc} is shown in Table 7 and Figure 6. It can be seen that all codes have good accuracy for the calculation of the flexural bearing capacity of concrete beams using 400 MPa grade steel bars ($\mu = 1.01\text{--}1.17$ and $\delta = 0.08\text{--}0.1$).

3.3. Analysis of Moment of Resistance of Beams with 500 MPa Grade Steel. References [52, 54–60] conducted flexural performance tests of concrete beams reinforced with 500 MPa grade steel. The relevant information of the specimens is shown in Table 8. In order to verify the applicability of the bearing capacity equations of the existing national codes, measured flexural bearing capacity of RC beams is compared with the calculated value based on various codes. The comparison of the measured value M_u of

FIGURE 1: Geometry of RC beams.

FIGURE 2: Actual RC beams with 600 MPa steel bars and the test device.

FIGURE 3: Stress-strain curves of 600 MPa steel bars.

the flexural bearing capacity of the test beams with 500 MPa steel bars and the calculated value M_{uc} based on different codes is shown in Table 9 and Figure 7. It can be seen that all codes have good accuracy for the calculation of the bending bearing capacity of 500 MPa RC beams ($\mu = 1.01\text{--}1.22$ and $\delta = 0.09\text{--}0.11$).

3.4. Analysis of Moment of Resistance of Beams with 600 MPa Grade Steel. Several studies [39, 52, 53, 61] conducted

flexural performance tests of RC beams reinforced with 600 MPa grade steel. The relevant information of the RC beams in those studies is shown in Table 10. In order to verify the applicability of the bearing capacity equation in the current national standard, results from the experiment in this study are compared with the measured values of the flexural bearing capacity of RC beams in the literature and with the calculated value based on the national standard. Measured value M_u of the flexural bearing capacity of the RC beam reinforced with 600 MPa grade steel is compared with

FIGURE 4: Actual failure mode of the RC beam.

the calculated value M_{uc} based on various codes as shown in Table 11 and Figure 8. Due to the differences in the size of the members designed by different scholars and the properties of the materials used in the experiment and other influencing factors during the experiment, the results have certain differences but the difference is small. The average value μ of the ratio between the measured value and the calculated value of the ultimate bearing capacity based on the codes is 1.10~1.27, and the dispersion coefficient δ is 0.07~0.08. As shown in Figure 8, the measured values of the ultimate bearing capacity of RC beams with 400 MPa and 500 MPa grade steel are in good agreement with the calculated values of various codes. The data of the configuration of RC beams with 600 MPa grade steel and the configuration of RC beams with 400 MPa and 500 MPa grade steel are similar (the ratio of the measured value of the flexural bearing capacity of RC beams to the calculated values of various codes is around 1.0 for all cases), and the dispersion coefficients are small. In general, the measured value of the ultimate bearing capacity of 600 MPa RC beams coincided with the ultimate bearing capacity calculated from various codes. Therefore, the existing equations in the Chinese code are still applicable to RC beams reinforced with high-strength (600 MPa) steel.

4. Reliability Analysis of Bearing Capacity

For an RC beam using 600 MPa grade steel, the design values of the yield strength of reinforcement taken by different scholars are different, such as 500 MPa and 520 MPa. In order to determine the appropriate yield strength design value of the 600 MPa grade steel bar in a design specification, this study took the basis of the experiment and the reference standard GB 50010 [24]. The material subentry coefficients as per the standard are 1.1, 1.1, and 1.15, respectively, for the 335 MPa, 400 MPa, and 500 MPa grade steel (yield strength design value of the steel bar determined by many engineering practice and the material subentry coefficient is the ratio of the standard value to the design value of yield strength). Accordingly, the trial design value of the yield strength of 600 MPa grade steel was taken as 500 MPa, 520 MPa, and 545 MPa, corresponding to the material subentry coefficients of 1.1, 1.15, and 1.2, respectively. Reliability analysis was performed to determine the most

appropriate value. On the basis of the experimental study, the reliability analysis of the above three values was carried out to further select the design value of yield strength which would meet the requirements of both strength and reliability.

In the reliability analysis of the flexural bearing capacity of the 600 MPa RC beam, the known function is shown in equation (1), where the structural resistance R obeys the log-normal distribution and the dead load S_G obeys the normal distribution. The load S_Q obeys the extreme value type I distribution [62]. The most commonly used method for reliability calculation is the first-order second-moment method, including the center point method and the checking point method. The center point method does not take into account the probability distribution of variables, while the JC method (checking point method) can handle other random variables of probability distributions [63, 64]. In order to consider the probability distribution and correlation of random variables, this paper used the JC method to calculate the reliability of the flexural bearing capacity of 600 MPa RC beams and used MATLAB software to solve the problem:

$$R - S_G - S_Q = 0. \quad (1)$$

4.1. Reliability Index of Beams with Different Yield Strength Values of Steel Bars. In order to select the most suitable design value of the steel bar, the reliability index was calculated for different strength design values for the steel bar. In the process of determining the reliability index, statistical parameters of various loads of RC beams were referred to the specifications GB 50153 [65] and GB 50009 [66]. The standard value of moment of resistance was calculated by taking the reinforcement strength of 600 MPa and substituting it into the bending bearing capacity formula of GB 50010. Minimum ratio of the dead load to the variable load was determined under the condition that only the self-weight was considered as the dead load. According to the determined calculation parameters, the JC method was used to calculate the reliability index of RC beams.

As shown in Figure 9, for a given constant load to variable load ratio ρ , the reliability index of each RC beam was basically the same for different yield strength values of

FIGURE 5: The load-deformation curves for RC beams.

steel. When dead load was the controlling load, that is, when ρ was less than 2.8, the reliability index of the beam increased continuously with an increase in ρ value and with an increased rate. When the loading was dominated by the variable load, that is, when ρ was greater than 2.8, the reliability index still increased to a certain extent as the value of ρ increased. When ρ was approximately 7, the reliability index reached its peak, after which the reliability index decreased marginally and then gradually stabilized. The

reliability index of each RC beam was different for different design values of steel yield strength. Generally speaking, the reliability decreased as the design yield strength increased. For the steel with the strength of 600 MPa, when the design yield strength was taken as 500 MPa, the reliability was the largest and it was followed by 520 MPa, and the smallest reliability index was observed corresponding to the yield strength of 545 MPa. For beams with a concrete strength grade of C60, two types of steel bars, namely, HRB600 and

TABLE 6: Details of beams with 400 MPa steel bars.

Data sources	RC beam number	b/mm	h/mm	l_0/mm	c/mm	$\rho/100\%$	A_s/mm^2	Reinforcement				Concrete	
								f_y/MPa	E_s/GPa	F_{cu}/MPa	F_{ck}/MPa	f_{ts}/MPa	$E_c \times 104/\text{MPa}$
[48]	SB-1	200	400	2210	30	0.9	628	470	200	18.80	14.30	1.99	2.47
	SB-2	200	400	2210	30	0.7	509	533	200	23.50	17.90	2.24	2.72
	SB-3	200	400	2210	30	0.6	461	493	200	15.50	11.80	1.78	2.25
[49]	L-1	200	400	3300	30	0.9	628	450	200	29.67	19.84	1.42	2.97
	L-2	200	400	3300	30	1.3	928	455	200	33.53	22.42	1.48	3.09
	L-3	200	400	3300	30	1.3	942	457	200	24.32	16.26	1.25	2.76
	L-4	200	400	3300	30	0.9	628	485	200	27.64	18.48	1.36	2.89
	TL-1	200	400	4300	30	0.9	628	465	200	27.38	18.50	1.36	2.88
	TL-2	200	400	4300	30	0.9	628	475	200	22.22	14.68	1.18	2.66
[50]	L-1	152	304	1800	30	0.5	226	504	200	47.75	28.64	2.44	3.32
	L-2	150	304	1800	30	0.8	339	504	200	40.90	27.50	2.38	3.28
	L-3	153	305	1800	30	1.2	509	479	200	42.75	28.64	2.44	3.32
	L-4	150	305	1800	30	1.2	509	458	200	41.00	27.47	2.38	3.28
	L-5	151	304	1800	30	—	308	448	200	42.80	28.68	2.44	3.32
	L-6	149	305	1800	30	1.3	509	479	200	44.60	29.88	2.50	3.36
[51]	B4A	180	300	3000	30	0.5	226	405	—	41.60	27.8	2.8	3.31
	B4B	180	300	3000	30	0.7	339	405	—	41.60	27.8	2.8	3.31
	B4C	180	300	3000	30	1.1	515	452	—	41.60	27.8	2.8	3.31
	B4D	180	300	3000	30	1.5	716	452	—	41.60	27.8	2.8	3.31
[52]	L7	250	400	3400	35	1.5	1521	360	200	—	14.3	1.432	3.0
	L8	250	400	3400	35	1.5	1521	360	—	—	23.1	1.89	3.45
	L9	250	400	3400	35	1.5	1521	360	200	—	27.5	2.04	3.6
[53]	LW-5	200	400	3000	25	2.0	1473	445	—	29.1	19.5	2.22	—

Note. Symbol “—” means that the parameter has no relevant data in the literature.

HRB400, were used. The curve of the reliability of RC beams with ρ value is shown in Figure 10. When the design yield strength of the HRB600 steel bar was taken as 500 MPa and 520 MPa, the reliability of the beam was greater than that when the HRB400 steel bar was used. However, when the design yield strength of the HRB600 steel bar was 545 MPa, the reliability of the beam was less than that of the beam using the HRB400 steel bar.

The minimum reliability index can reflect the reliability performance of the component under the most unfavorable conditions, so statistical analysis was necessary to determine the minimum reliability index of the beam. Table 12 shows the minimum value of the reliability index of the C60 test beams under different conditions. For C60 beams equipped with HRB600 steel bars, the minimum reliability index corresponding to the reinforcement ratio of 0.005 was greater than the index corresponding to the reinforcement ratio of 0.008. For a given reinforcement ratio, the minimum reliability index decreased with an increase in the design yield strength of the steel bar. This study calculated the average value of the minimum reliability index corresponding to HRB600 RC beams under different reinforcement ratios. When the design yield strength was 520 MPa, the minimum reliability index average value was 3.172, which is closest to the code specified value and basically meets the reliability criterion. The failure

probabilities of the HRB400 RC beam and that of the HRB600 RC beam with the design yield strength of 500 MPa and 520 MPa were comparable to the standard failure probability. When the design yield strength of the HRB600 steel bar was taken as 545 MPa, the beam's failure probability was an order of magnitude smaller than the normative failure probability.

When designing the bearing capacity of a beam, considering that the beam should have sufficient safety protection, the design value of the bearing capacity of the component is generally less than the ultimate bearing capacity. Table 13 compares the measured value of the bearing capacity for all test beams with the calculated value when design yield strength of the steel bars was taken as 520 MPa. As shown in the table, the calculated value of the ultimate bearing capacity of each test beam obtained from the existing Chinese code <cite> equation is less than the actual measured value of the ultimate bearing capacity, demonstrating a larger safety reserve ($\mu=1.36\sim1.59$ and $\delta=0.05\sim0.06$).

On the basis of the experiment and practice, 500 MPa, 520 MPa, and 545 MPa were selected as the possibly appropriate design value of yield strength of the 600 MPa grade reinforcement. Reliability analysis showed that 500 MPa and 520 MPa met the reliability requirements. Moreover, use of 520 MPa as the design value showed a large strength surplus

TABLE 7: Comparison of experimental flexural bearing capacity M_u with M_{uc} calculated by different codes for beams with 400 MPa steel bars.

Data sources	RC beam number	GB50010-2010 M_u/M_{uc}	SL191-2008 M_u/M_{uc}	DL/T5057-2009 M_u/M_{uc}	JTG D62-2012 M_u/M_{uc}	ACI318-2014 M_u/M_{uc}
Test	400-C60-1-1	1.14	1.14	1.14	1.14	1.14
	400-C60-1-2	1.07	1.07	1.07	1.07	1.07
	SB-1	1.17	1.17	1.17	1.17	1.21
[48]	SB-2	0.98	0.98	0.98	0.98	1.00
	SB-3	1.06	1.06	1.06	1.06	1.09
[49]	L-1	0.97	0.97	0.97	0.97	0.99
	L-2	0.95	0.95	0.95	0.95	0.98
	L-3	0.99	0.99	0.99	0.99	1.03
	L-4	1.00	1.00	1.00	1.00	1.02
	TL-1	1.06	1.06	1.06	1.06	1.08
	TL-2	1.10	1.10	1.10	1.10	1.13
[50]	L-1	1.09	1.09	1.09	1.09	1.10
	L-2	1.09	1.09	1.09	1.09	1.11
	L-3	1.04	1.04	1.04	1.04	1.06
	L-4	1.08	1.08	1.08	1.08	1.10
	L-5	1.08	1.08	1.08	1.08	1.09
	L-6	1.12	1.12	1.12	1.12	1.14
[51]	B4A	0.98	0.98	0.98	0.98	0.99
	B4B	0.93	0.93	0.93	0.93	0.94
	B4C	0.89	0.89	0.89	0.89	0.90
	B4D	0.93	0.93	0.93	0.93	0.95
[52]	L7	0.90	0.90	0.90	0.90	0.95
	L8	0.89	0.89	0.89	0.89	0.91
	L9	0.88	0.88	0.88	0.88	0.90
[53]	LW-5	1.10	1.10	1.10	1.10	1.16
μ	—	1.02	1.02	1.02	1.02	1.04
δ	—	0.08	0.08	0.08	0.08	0.08
Data sources	RC beam number	EN 1992-1-1 M_u/M_{uc}	BS5400-4 M_u/M_{uc}	AASHEO M_u/M_{uc}	EN1991-2 2003 M_u/M_{uc}	CRC PRESS M_u/M_{uc}
Test	400-C60-1-1	1.23	1.31	1.14	1.14	1.14
	400-C60-1-2	1.15	1.22	1.07	1.06	1.07
	SB-1	1.17	1.35	1.21	1.17	1.21
[48]	SB-2	0.98	1.13	1.00	0.98	1.00
	SB-3	1.06	1.22	1.09	1.06	1.09
[49]	L-1	0.97	1.12	0.99	0.97	0.99
	L-2	0.95	1.09	0.98	0.95	0.98
	L-3	0.99	1.14	1.03	0.99	1.03
	L-4	1.00	1.15	1.02	1.00	1.02
	TL-1	1.06	1.21	1.08	1.06	1.08
	TL-2	1.10	1.26	1.13	1.10	1.13
[50]	L-1	1.09	1.25	1.10	1.09	1.10
	L-2	1.09	1.25	1.11	1.09	1.11
	L-3	1.04	1.19	1.06	1.04	1.06
	L-4	1.08	1.24	1.10	1.08	1.10
	L-5	1.08	1.24	1.09	1.08	1.09
	L-6	1.12	1.29	1.14	1.12	1.14
[51]	B4A	0.98	1.13	0.99	0.95	0.99
	B4B	0.93	1.07	0.94	0.88	0.94
	B4C	0.89	1.02	0.90	0.81	0.90
	B4D	0.93	1.07	0.95	0.82	0.95
[52]	L7	0.90	1.04	0.95	0.90	0.95
	L8	0.89	1.02	0.91	0.89	0.91
	L9	0.88	1.01	0.90	0.88	0.90
[53]	LW-5	1.10	1.15	1.16	1.13	0.98
μ	—	1.03	1.17	1.04	1.01	1.04
δ	—	0.09	0.08	0.08	0.10	0.08

Note. M_u in the table is the measured ultimate flexural bearing capacity and M_{uc} is the calculated value of ultimate flexural bearing capacity obtained by taking the measured yield strength of reinforcement from the current code formulas.

FIGURE 6: Continued.

FIGURE 6: Comparison of experimental flexural bearing capacity M_u with M_{uc} calculated by different codes for beams with 400 MPa steel bars.

TABLE 8: Details of beams with 500 MPa steel bars.

Data sources	RC beam number	b/mm	h/mm	l_0/mm	c/mm	$\rho/100\%$	Reinforcement			Concrete			
							A_s/mm^2	f_y/MPa	E_s/GPa	f_{cu}/MPa	f_{ck}/MPa	f_{ts}/MPa	$E_c \times 10^4/\text{MPa}$
[54]	LW1	200	400	3200	30	0.8	603	567.3	210	43.4	27.3	2.66	3.33
	LW2	200	400	3200	30	0.8	603	567.3	210	47.8	30.4	2.79	3.42
	LW3	200	400	3200	30	0.8	603	567.3	210	56.2	34.3	2.97	3.55
	LW4	200	400	3200	30	1.3	982	502.8	210	43.4	27.3	2.66	3.33
	LW5	200	400	3200	30	1.3	982	502.8	210	47.8	30.4	2.79	3.42
	LW6	200	400	3200	30	1.3	982	502.8	210	56.2	34.3	2.97	3.55
	LW7	200	400	3200	30	2.1	1608	522.5	210	47.8	30.4	2.79	3.42
[55]	FB1	200	400	3000	30	0.4	339	515	211	23.3	15.6	1.96	2.71
	FB2	200	410	3000	30	0.6	509	567	213	28.1	18.8	2.18	2.91
	FB3	200	399	3000	30	1.2	982	537	205	25.7	17.2	2.07	2.82
	FB4	200	403	3000	30	0.4	339	515	211	33.4	22.3	2.39	3.09
	FB5	200	401	3000	30	0.6	509	567	213	33.5	22.4	2.4	3.09
	FB6	200	405	3000	30	1.2	982	537	205	32.1	21.5	2.34	3.05
	FB7	200	395	3000	30	0.4	339	515	211	40.6	27.1	2.67	3.27
	FB8	200	406	3000	30	0.6	509	567	213	40.7	27.2	2.67	3.28
	FB9	200	402	3000	30	1.2	982	537	205	40.3	27	2.65	3.27
[56]	B5F1	250	400	3600	30	0.7	603	549.5	200	—	22.74	2.16	3.11
	B5F2	250	400	3600	30	1.1	982	495	200	—	22.74	2.16	3.11
	B5F3	250	400	3600	30	0.7	603	549.5	200	—	36.2	2.77	3.55
	B5F4	250	400	3600	30	1.1	982	495	200	—	36.2	2.77	3.55

TABLE 8: Continued.

Data sources	RC beam number	b/mm	h/mm	l_0/mm	c/mm	$\rho/100\%$	Reinforcement			Concrete			
							A_s/mm^2	f_y/MPa	E_s/GPa	f_{cu}/MPa	f_{ck}/MPa	f_{ts}/MPa	$E_c \times 10^4/\text{MPa}$
[57]	LW1	204	400	3200	30	0.8	603	567.3	200	41.3	27.3	2.66	3.29
	LW2	202	400	3200	30	0.8	603	567.3	200	45.5	30	2.79	3.38
	LW3	202	400	3200	30	0.8	603	567.3	200	53.5	34.3	2.97	3.51
	LW4	199	400	3200	30	1.3	982	502.8	200	41.3	27.3	2.66	3.29
	LW5	200	400	3200	30	1.3	982	502.8	200	45.5	30	2.79	3.38
	LW6	199	400	3200	30	1.3	982	502.8	200	53.5	34.3	2.97	3.51
	LW7	200	400	3200	30	2.2	1608	522.5	200	45.5	30	2.79	3.38
[58]	L1	202	405	3200	30	0.6	462	525	200	21.42	14.33	1.87	2.62
	L2	204	400	3200	30	0.8	603	550	200	21.42	14.33	1.87	2.62
	L3	198	401	3200	30	1.0	760	530	200	21.42	14.33	1.87	2.62
	L4	201	402	3200	30	1.3	982	505	200	21.42	14.33	1.87	2.62
	LX1-A	200	402	3200	30	0.6	462	525	200	22.1	14.78	1.91	2.65
	LX2-A	199	402	3200	30	0.8	603	550	200	22.1	14.78	1.91	2.65
	LX3-A	202	400	3200	30	1.0	760	530	200	22.1	14.78	1.91	2.65
	LX4-A	201	403	3200	30	1.3	982	505	200	22.1	14.78	1.91	2.65
	LX1-B	203	402	3200	30	0.6	462	525	200	21.01	14.05	1.86	2.6
	LX2-B	200	401	3200	30	0.8	603	550	200	21.01	14.05	1.86	2.6
	LX3-B	203	400	3200	30	1.0	760	530	200	21.01	14.05	1.86	2.6
	LX4-B	202	401	3200	30	1.3	982	505	200	21.01	14.05	1.86	2.6
[59]	L1-A	149	305	2800	30	0.2	100	540	200	27.96	18.7	2.47	2.91
	L1-B	253	305	2800	30	0.2	100	540	200	27.96	18.7	2.47	2.91
	L1-C	150	303	2800	30	0.2	100	540	200	42.67	28.54	3.11	3.32
	L2-A	152	310	2800	30	1.0	399	502	200	46.31	30.97	3.26	3.39
	L2-B	150	308	2800	30	1.0	399	502	200	49.51	33.11	3.38	3.45
	L3-A	150	315	2800	30	1.4	599	502	200	48.34	32.33	3.33	3.43
	L3-B	150	301	2800	30	1.5	599	502	200	42.7	28.56	3.11	3.32
	L4-A	151	303	2800	30	2.2	799	502	200	52.1	34.84	3.47	3.49
	L4-B	152	306	2800	30	2.2	799	502	200	52.1	34.84	3.47	3.49
	L5-A	149	303	2800	30	2.8	999	502	200	46.75	31.27	3.27	3.4
	L5-B	148	305	2800	30	2.8	999	502	200	46.75	31.27	2.27	3.4
[60]	B-N2	200	250	3080	26	1.2	509	530	—	—	48.61	3.69	2.46
	B-N3	200	250	3080	26	1.8	763	530	—	—	48.61	3.69	2.46
	B-N4	200	250	3080	26	2.4	1018	530	—	—	48.61	3.69	2.46
	B-M2	200	250	3080	26	1.2	509	530	—	—	78.5	5.05	3.54
	B-M3	200	250	3080	26	1.8	763	530	—	—	78.5	5.05	3.54
	B-M4	200	250	3080	26	2.4	1018	530	—	—	78.5	5.05	3.54
	B-H2	200	250	3080	26	1.2	509	530	—	—	102.4	5.59	3.84
	B-H3	200	250	3080	26	1.8	763	530	—	—	102.4	5.59	3.84
	B-H4	200	250	3080	26	2.4	1018	530	—	—	102.4	5.59	3.84
[52]	L4	250	400	3400	35	1.3	1257	435	200	—	14.3	1.432	3
	L5	250	400	3400	35	1.3	1257	435	200	—	23.1	1.89	3.45
	L6	250	400	3400	35	1.3	1257	435	200	—	27.5	2.04	3.6

Note. Symbol “—” means that the parameter has no relevant data in the literature.

when checked for a strength criterion. According to the analysis results, the strength utilization ratio of reinforcement was considered to meet the requirements of strength and reliability, and hence, the appropriate design yield strength of the 600 MPa grade steel bar was selected as 520 MPa.

4.2. Reliable Indicators of Beams under Different Concrete Strength Grades. In the reliability calculation, parameters are divided into deterministic variables and random variables. The deterministic random variables include geometric

parameters and design parameters, such as cover thickness and reinforcement ratio. The random variables are load and material parameters, such as concrete strength, reinforcement strength, constant load, and variable load [67–69]. It can be seen from the above analysis that the influence of constant load and variable load on the reliability index of the beam is such that the reliability index of the test beam increased with an increase in the constant load to variable load ratio. When the load ratio reached a certain value, the reliability index of the beam became approximately constant. In order to study the influence of the concrete strength grade on the reliability index, the index was calculated for RC

TABLE 9: Comparison experimental flexural bearing capacity M_u with M_{uc} calculated by different codes for beams with 500 MPa steel bars.

Data sources	RC beams number	GB50010 -2010	SL191 -2008	DL/T5057 -2009	JTG D62-2012	ACI 318-2014
		M_u/M_{uc}	M_u/M_{uc}	M_u/M_{uc}	M_u/M_{uc}	M_u/M_{uc}
[54]	LW-1	0.93	0.93	0.93	0.93	0.95
	LW-2	1.01	1.01	1.01	1.01	1.02
	LW-3	1.18	1.18	1.18	1.18	1.19
	LW-4	0.99	0.99	0.99	0.99	1.02
	LW-5	1.00	1.00	1.00	1.00	1.02
	LW-6	1.00	1.00	1.00	1.00	1.02
	LW-7	1.06	1.06	1.06	1.06	1.10
[55]	FB-1	1.10	1.10	1.10	1.10	1.12
	FB-2	0.89	0.89	0.89	0.89	0.91
	FB-3	1.07	1.07	1.07	1.07	1.12
	FB-4	1.12	1.12	1.12	1.12	1.13
	FB-5	1.10	1.10	1.10	1.10	1.12
	FB-6	1.01	1.01	1.01	1.01	1.04
	FB-7	1.20	1.20	1.20	1.20	1.21
	FB-8	1.09	1.09	1.09	1.09	1.11
	FB-9	1.18	1.18	1.18	1.18	1.22
[56]	B5F1	1.17	1.17	1.17	1.17	1.18
	B5F2	1.22	1.22	1.22	1.22	1.25
	B5F3	1.09	1.09	1.09	1.09	1.10
	B5F4	1.20	1.20	1.20	1.20	1.22
[57]	LW-1	0.94	0.94	0.94	0.94	0.96
	LW-2	1.05	1.05	1.05	1.05	1.06
	LW-3	1.19	1.19	1.19	1.19	1.21
	LW-4	1.03	1.03	1.03	1.03	1.05
	LW-5	1.02	1.02	1.02	1.02	1.04
	LW-6	1.01	1.01	1.01	1.01	1.03
	LW-7	1.08	1.08	1.08	1.08	1.12
[58]	L1	1.01	1.01	1.01	1.01	1.04
	L2	1.17	1.17	1.17	1.17	1.21
	L3	1.16	1.16	1.16	1.16	1.21
	L4	1.13	1.13	1.13	1.13	1.20
	LX1-A	1.01	1.01	1.01	1.01	1.03
	LX2-A	1.11	1.11	1.11	1.11	1.15
	LX3-A	1.18	1.18	1.18	1.18	1.23
	LX4-A	1.17	1.17	1.17	1.17	1.23
	LX1-A	0.97	0.97	0.97	0.97	0.99
	LX2-A	1.09	1.09	1.09	1.09	1.13
	LX3-B	1.19	1.19	1.19	1.19	1.24
	LX4-B	1.15	1.15	1.15	1.15	1.22
[59]	L1-A	1.18	1.18	1.18	1.18	1.19
	L1-B	1.16	1.16	1.16	1.16	1.17
	L1-C	1.32	1.32	1.32	1.32	1.32
	L2-A	1.07	1.07	1.07	1.07	1.09
	L2-B	1.05	1.05	1.05	1.05	1.07
	L3-A	1.03	1.03	1.03	1.03	1.06
	L3-B	1.09	1.09	1.09	1.09	1.12
	L4-A	0.94	0.94	0.94	0.94	0.97
	L4-B	0.98	0.98	0.98	0.98	1.01
	L5-A	0.93	0.93	0.93	0.93	0.97
	L5-B	0.89	0.89	0.89	0.89	0.93
[60]	B-N2	1.07	1.07	1.07	1.07	1.09
	B-N3	1.03	1.03	1.03	1.03	1.05
	B-N4	0.99	0.99	0.99	0.99	1.01
	B-M2	1.04	1.04	1.04	1.04	1.05
	B-M3	0.98	0.98	0.98	0.98	0.99
	B-M4	0.97	0.97	0.97	0.97	0.99
	B-H2	1.01	1.01	1.01	1.01	1.02
	B-H3	1.00	1.00	1.00	1.00	1.01
[52]	B-H4	0.99	0.99	0.99	0.99	1.00
	L4	0.93	0.93	0.93	0.93	0.97
	L5	0.86	0.86	0.86	0.86	0.89
	L6	0.87	0.87	0.87	0.87	0.89
μ	—	1.06	1.06	1.06	1.06	1.09
δ	—	0.09	0.09	0.09	0.09	0.09

TABLE 9: Continued.

Data sources	RC beams number	EN1992-1-1 M_u/M_{uc}	BS5400-4 M_u/M_{uc}	AASHEO M_u/M_{uc}	EN1991-2 2003 M_u/M_{uc}	CRC PRESS M_u/M_{uc}
[54]	LW-1	0.93	1.07	0.95	0.93	0.95
	LW-2	1.01	1.16	1.02	1.01	1.02
	LW-3	1.18	1.35	1.19	1.18	1.19
	LW-4	0.99	1.14	1.02	0.99	1.02
	LW-5	1.00	1.15	1.02	1.00	1.02
	LW-6	1.00	1.15	1.02	1.00	1.02
	LW-7	1.06	1.21	1.10	1.06	1.10
[55]	FB-1	1.10	1.27	1.12	1.10	1.12
	FB-2	0.89	1.02	0.91	0.89	0.91
	FB-3	1.07	1.23	1.12	1.07	1.12
	FB-4	1.12	1.28	1.13	1.12	1.13
	FB-5	1.10	1.27	1.12	1.10	1.12
	FB-6	1.01	1.16	1.04	1.01	1.04
	FB-7	1.20	1.38	1.21	1.20	1.21
	FB-8	1.09	1.25	1.11	1.09	1.11
	FB-9	1.18	1.36	1.22	1.18	1.22
[56]	B5F1	1.17	1.37	1.18	1.17	1.18
	B5F2	1.22	1.41	1.25	1.22	1.25
	B5F3	1.09	1.25	1.10	1.09	1.10
	B5F4	1.20	1.38	1.22	1.20	1.22
[57]	LW-1	0.94	1.08	0.96	0.94	0.96
	LW-2	1.05	1.20	1.06	1.05	1.06
	LW-3	1.19	1.37	1.21	1.19	1.21
	LW-4	1.03	1.18	1.05	1.03	1.05
	LW-5	1.02	1.17	1.04	1.02	1.04
	LW-6	1.01	1.16	1.03	1.01	1.03
	LW-7	1.08	1.24	1.12	1.08	1.12
[58]	L1	1.01	1.16	1.04	1.01	1.04
	L2	1.17	1.35	1.21	1.17	1.21
	L3	1.16	1.33	1.21	1.16	1.21
	L4	1.13	1.30	1.20	1.13	1.20
	LX1-A	1.01	1.16	1.03	1.01	1.03
	LX2-A	1.11	1.28	1.15	1.11	1.15
	LX3-A	1.18	1.36	1.23	1.18	1.23
	LX4-A	1.17	1.34	1.23	1.17	1.23
	LX1-B	0.97	1.12	0.99	0.97	0.99
	LX2-B	1.09	1.25	1.13	1.09	1.13
	LX3-B	1.19	1.37	1.24	1.19	1.24
	LX4-B	1.15	1.33	1.22	1.15	1.22
[59]	L1-A	1.18	1.36	1.19	1.18	1.19
	L1-B	1.16	1.34	1.17	1.16	1.17
	L1-C	1.32	1.51	1.32	1.32	1.32
	L2-A	1.07	1.23	1.09	1.07	1.09
	L2-B	1.05	1.21	1.07	1.05	1.07
	L3-A	1.03	1.19	1.06	1.03	1.06
	L3-B	1.09	1.25	1.12	1.09	1.12
	L4-A	0.94	1.03	0.97	0.94	0.97
	L4-B	0.98	1.12	1.01	0.98	1.01
	L5-A	0.93	1.07	0.97	0.93	0.97
	L5-B	0.89	1.02	0.93	0.89	0.93
[60]	B-N2	1.07	1.23	1.09	1.07	1.09
	B-N3	1.03	1.18	1.05	1.03	1.05
	B-N4	0.99	1.13	1.01	0.99	1.01
	B-M2	1.04	1.20	1.05	1.04	1.05
	B-M3	0.98	1.12	0.99	0.98	0.99
	B-M4	0.97	1.12	0.99	0.97	0.99
	B-H2	1.01	1.16	1.02	1.01	1.02
	B-H3	1.00	1.15	1.01	1.00	1.01
[52]	B-H4	0.99	1.14	1.00	0.99	1.00
	L4	0.93	1.07	0.73	0.93	0.87
	L5	0.86	0.99	0.75	0.99	0.83
	L6	0.87	1.00	0.78	1.03	0.84
μ	—	1.06	1.22	1.01	1.06	1.08
δ	—	0.09	0.09	0.11	0.09	0.10

Note. M_u in the table is the measured ultimate flexural bearing capacity and M_{uc} is the calculated value of ultimate flexural bearing capacity obtained by taking the measured yield strength of reinforcement from the current code formulas.

FIGURE 7: Continued.

FIGURE 7: Comparison of experimental flexural bearing capacity M_u with M_{uc} calculated by different codes for beams with 500 MPa steel bars.

beams reinforced with 600 MPa grade steel and having the concrete grade of C40, C50, and C60. The reliability analysis of the flexural bearing capacity of RC beam was calculated by considering the design yield strength of the steel bar as 520 MPa.

As shown in Figures 11 and 12, the trend of change in ρ - β curve corresponding to different concrete strength grades was basically the same for the two reinforcement ratios of 600 MPa grade steel. Generally speaking, the reliability index of the beam increased with an increase in the strength of concrete, but the increase was not large.

The curve of the minimum value of the reliability index of the beam with different concrete strength grades is shown in Figure 13. The trend of change in the minimum value of the reliability index of the beam under different reinforcement ratios was basically the same. With an improvement in the concrete strength grade, the minimum value of the reliability index increased; when the reinforcement ratio is small, the minimum value of the reliability index of the beam is larger.

Table 14 shows the statistical parameters of the minimum reliability index corresponding to different concrete

strength grades of the test beams. The average value of the minimum reliability index of the test beams with a reinforcement ratio of 0.005 was 3.172 for each concrete strength grade. The average value of the minimum reliability index corresponded to the failure probability of 7.57×10^{-4} . The average value of the minimum reliability index for different concrete grades with a reinforcement ratio of 0.008 was 3.148, and the average value of the minimum reliability index corresponded to the failure probability of 8.23×10^{-4} . The overall average minimum reliability index of the test beam (irrespective of the reinforcement ratio) was 3.160, and the corresponding failure probability was 7.89×10^{-4} . These values are close to the code specified values. The coefficient of variation of the minimum reliability index corresponding to different concrete strength grades was negligibly small, indicating that the minimum reliability index was less affected by the concrete strength grade and had good stability. The analysis of the minimum reliability index of the beams with different concrete strength grades further verified that the design yield strength of the 600 MPa grade steel bar should be taken as 520 MPa to meet the reliability requirements.

TABLE 10: Details of beams with 600 MPa steel bars.

Data sources	RC beam number	b/mm	h/mm	l_0/mm	c/mm	$\rho/100\%$	Reinforcement			Concrete			
							A_s/mm^2	f_y/MPa	E_s/GPa	F_{cu}/MPa	F_{ck}/MPa	f_{ts}/MPa	$E_c \times 10^4/\text{MPa}$
[39]	L-5	200	400	3200	30	1.3	982	622	—	54.67	35.3	2.80	3.52
	L-7	200	400	3200	30	1.3	982	622	—	54.67	35.3	2.80	3.52
	L-8	200	400	3200	30	1.0	763	654	—	54.67	35.3	2.80	3.52
	L-9	200	400	3200	30	0.7	509	654	—	54.67	35.3	2.80	3.52
	L-10	200	400	3200	30	1.0	763	654	—	67.42	45.49	3.68	3.68
	L-11	200	400	3200	30	0.7	509	654	—	67.42	45.49	3.68	3.68
[61]	LW-1	200	400	3200	30	—	509	654	—	54.27	35.11	3.02	—
	LW-2	200	400	3200	30	—	509	654	—	67.42	43.27	3.09	—
	LW-3	200	400	3200	30	—	763	654	—	54.27	35.11	3.02	—
	LW-4	200	400	3200	30	—	763	654	—	67.42	43.27	3.09	—
	LW-5	200	400	3200	30	—	982	622	—	54.27	35.11	3.02	—
	LW-6	200	400	3200	30	—	982	622	—	67.42	43.27	3.09	—
[53]	LW1	200	400	3000	25	0.8	603	645	—	19.5	19.5	2.22	—
	LW2	200	400	3000	25	0.8	603	645	—	31.2	31.2	2.85	—
	LW3	200	400	300	25	1.4	982	610	—	19.5	19.5	2.22	—
	LW4	200	400	3000	25	1.4	982	610	—	31.5	31.2	2.85	—
[52]	L-1	250	400	3400	35	1.1	1140	500	200	—	14.3	1.43	3.0
	L-2	250	400	3400	35	1.1	1140	500	200	—	23.1	1.89	3.45
	L-3	250	400	3400	35	1.1	1140	500	200	—	27.5	2.04	3.6

Note. Symbol “—” means that the parameter has no relevant data in the literature.

TABLE 11: Comparison of experimental flexural bearing capacity M_u with M_{uc} calculated by different codes for beams with 600 MPa steel bars.

Data sources	RC beam number	GB50010-2010	SL191 -2008	DL/T5057-2009	JTG D62-2012	ACI318-2014
		M_u/M_{uc}	M_u/M_{uc}	M_u/M_{uc}	M_u/M_{uc}	M_u/M_{uc}
Test	600-C30-1-1	1.16	1.16	1.16	1.16	1.18
	600-C30-1-2	1.15	1.15	1.15	1.15	1.17
	600-C30-2-1	1.20	1.20	1.20	1.20	1.22
	600-C30-2-2	1.19	1.19	1.19	1.19	1.20
	600-C40-1-1	1.06	1.06	1.06	1.06	1.08
	600-C40-1-2	1.04	1.04	1.04	1.04	1.06
	600-C40-2-1	1.10	1.10	1.10	1.10	1.11
	600-C40-2-2	1.25	1.25	1.25	1.25	1.27
	600-C50-1-1	1.04	1.04	1.04	1.04	1.06
	600-C50-1-2	1.10	1.10	1.10	1.10	1.12
	600-C50-2-1	1.16	1.16	1.16	1.16	1.17
	600-C50-2-2	1.19	1.19	1.19	1.19	1.20
	600-C60-1-1	1.08	1.08	1.08	1.08	1.09
	600-C60-1-2	1.07	1.07	1.07	1.07	1.08
	600-C60-2-1	1.20	1.20	1.20	1.20	1.20
	600-C60-2-2	1.20	1.20	1.20	1.20	1.20
[39]	L-5	1.16	1.16	1.16	1.16	1.29
	L-7	1.11	1.11	1.11	1.11	1.24
	L-8	1.14	1.14	1.14	1.14	1.24
	L-9	1.13	1.13	1.13	1.13	1.19
	L-10	1.13	1.13	1.13	1.13	1.19
	L-11	1.11	1.11	1.11	1.11	1.15
[61]	LW-1	1.13	1.13	1.13	1.13	1.14
	LW-2	1.14	1.14	1.14	1.14	1.15
	LW-3	1.14	1.14	1.14	1.14	1.16
	LW-4	1.13	1.13	1.13	1.13	1.15
	LW-5	1.12	1.12	1.12	1.12	1.14
	LW-6	1.13	1.13	1.13	1.13	1.15

TABLE 11: Continued.

Data sources	RC beam number	GB50010-2010 M_u/M_{uc}	SL191 -2008 M_u/M_{uc}	DL/T5057-2009 M_u/M_{uc}	JTGD62-2012 M_u/M_{uc}	ACI318-2014 M_u/M_{uc}
[53]	LW1	1.13	1.13	1.13	1.13	1.16
	LW2	1.05	1.05	1.05	1.05	1.07
	LW3	1.08	1.08	1.08	1.08	1.13
	LW4	1.06	1.06	1.06	1.06	1.09
[52]	L-1	0.92	0.92	0.92	0.92	0.97
	L-2	0.90	0.90	0.90	0.90	0.93
	L-3	0.89	0.89	0.89	0.89	0.91
μ	—	1.11	1.11	1.11	1.11	1.14
δ	—	0.07	0.07	0.07	0.07	0.08
Data sources	RC beam number	EN1992-1-1 M_u/M_{uc}	BS5400-4 M_u/M_{uc}	AASHEO M_u/M_{uc}	EN1991-2 2003 M_u/M_{uc}	CRC PRESS M_u/M_{uc}
Test	600-C30-1-1	1.14	1.33	1.18	1.10	1.18
	600-C30-1-2	1.13	1.32	1.17	1.09	1.17
	600-C30-2-1	1.19	1.38	1.22	1.17	1.22
	600-C30-2-2	1.20	1.37	1.20	1.18	1.20
	600-C40-1-1	1.06	1.22	1.08	1.04	1.08
	600-C40-1-2	1.04	1.20	1.06	1.02	1.06
	600-C40-2-1	1.10	1.27	1.11	1.09	1.11
	600-C40-2-2	1.25	1.44	1.27	1.24	1.27
	600-C50-1-1	1.04	1.19	1.06	1.01	1.06
	600-C50-1-2	1.10	1.27	1.12	1.07	1.12
	600-C50-2-1	1.16	1.34	1.17	1.14	1.17
	600-C50-2-2	1.19	1.37	1.20	1.17	1.20
	600-C60-1-1	1.08	1.24	1.09	1.08	1.09
	600-C60-1-2	1.07	1.23	1.08	1.07	1.08
	600-C60-2-1	1.20	1.37	1.20	1.20	1.20
	600-C60-2-2	1.20	1.37	1.20	1.20	1.20
[39]	L-5	1.24	1.33	1.19	1.16	1.19
	L-7	1.20	1.28	1.14	1.11	1.14
	L-8	1.20	1.31	1.16	1.14	1.16
	L-9	1.17	1.29	1.14	1.13	1.14
	L-10	1.17	1.30	1.14	1.13	1.14
	L-11	1.13	1.28	1.12	1.11	1.12
[61]	LW-1	1.13	1.30	1.14	1.13	1.14
	LW-2	1.14	1.31	1.15	1.14	1.15
	LW-3	1.14	1.31	1.16	1.14	1.16
	LW-4	1.13	1.30	1.15	1.13	1.15
	LW-5	1.12	1.28	1.14	1.12	1.14
	LW-6	1.13	1.30	1.15	1.13	1.15
[53]	LW1	1.13	1.30	1.16	1.13	1.16
	LW2	1.05	1.20	1.07	1.05	1.07
	LW3	1.08	1.24	1.13	1.08	1.13
	LW4	1.06	1.22	1.09	1.06	1.09
[52]	L-1	0.92	1.06	0.97	0.92	0.97
	L-2	0.90	1.04	0.93	0.90	0.93
	L-3	0.89	1.02	0.91	0.89	0.91
μ	—	1.12	1.27	1.13	1.10	1.13
δ	—	0.08	0.07	0.07	0.07	0.07

Note. M_u in the table is the measured ultimate flexural bearing capacity and M_{uc} is the calculated value of ultimate flexural bearing capacity obtained by taking the measured yield strength of reinforcement from the current code formulas.

FIGURE 8: Continued.

FIGURE 8: Comparison of experimental flexural bearing capacity M_u with M_{uc} calculated by different codes for beams with 600 MPa steel bars.

FIGURE 9: Continued.

FIGURE 9: ρ - β Variation curve of each test beam.

FIGURE 10: Comparison of the ρ - β variation curve of the test beam 600-C60-1 and 400-C60-1.

TABLE 12: The minimum reliable indexes and failure probability of the C60 test beam under different conditions.

Rebar category	f_y	Minimum reliable index		Average	Probability of failure	Code value	
		Reinforcement rate 0.008	Reinforcement rate 0.005			β	p_f
HRB400	360	3.062	—	3.095	9.83×10^{-4}	3.2	6.87×10^{-4}
	500	3.281	3.302	3.291	4.99×10^{-4}		
HRB600	520	3.163	3.181	3.172	7.57×10^{-4}		
	545	3.023	3.036	3.030	1.22×10^{-3}		

TABLE 13: Comparison of experimental flexural bearing capacity M_u with M_{uc} calculated by code of 520 MPa for the reinforcement design strength.

RC beam number	EN1992-1-1	BS5400-4	AASHEO	EN1991-2 2003	CRC PRESS
	M_u/M_{uc}	M_u/M_{uc}	M_u/M_{uc}	M_u/M_{uc}	M_u/M_{uc}
600-C30-1-1	1.40	1.40	1.44	1.40	1.42
600-C30-1-2	1.39	1.39	1.42	1.39	1.41
600-C30-2-1	1.29	1.45	1.33	1.29	1.31
600-C30-2-2	1.27	1.43	1.30	1.27	1.29
600-C40-1-1	1.27	1.29	1.30	1.27	1.28
600-C40-1-2	1.35	1.27	1.38	1.35	1.36
600-C40-2-1	1.33	1.34	1.36	1.33	1.34
600-C40-2-2	1.32	1.52	1.35	1.32	1.32
600-C50-1-1	1.45	1.27	1.49	1.45	1.47
600-C50-1-2	1.43	1.35	1.47	1.43	1.45
600-C50-2-1	1.34	1.41	1.37	1.34	1.35
600-C50-2-2	1.52	1.45	1.56	1.52	1.53
600-C60-1-1	1.41	1.33	1.45	1.41	1.42
600-C60-1-2	1.45	1.32	1.48	1.45	1.46
600-C60-2-1	1.46	1.45	1.49	1.45	1.46
600-C60-2-2	1.46	1.45	1.49	1.45	1.46
M	1.38	1.38	1.42	1.38	1.40
Δ	0.05	0.05	0.05	0.05	0.05

TABLE 13: Continued.

RC beam number	EN1992-1-1 M_u/M_{uc}	BS5400-4 M_u/M_{uc}	AASHEO M_u/M_{uc}	EN1991-2 2003 M_u/M_{uc}	CRC PRESS M_u/M_{uc}
600-C30-1-1	1.38	1.61	1.42	1.35	1.42
600-C30-1-2	1.37	1.60	1.41	1.34	1.41
600-C30-2-1	1.44	1.49	1.47	1.27	1.47
600-C30-2-2	1.45	1.46	1.45	1.25	1.45
600-C40-1-1	1.29	1.46	1.31	1.24	1.31
600-C40-1-2	1.27	1.55	1.29	1.31	1.29
600-C40-2-1	1.34	1.53	1.35	1.33	1.35
600-C40-2-2	1.52	1.51	1.53	1.32	1.53
600-C50-1-1	1.27	1.67	1.28	1.42	1.28
600-C50-1-2	1.35	1.65	1.36	1.40	1.36
600-C50-2-1	1.41	1.54	1.42	1.32	1.42
600-C50-2-2	1.45	1.75	1.46	1.50	1.46
600-C60-1-1	1.33	1.62	1.34	1.39	1.34
600-C60-1-2	1.32	1.66	1.32	1.42	1.32
600-C60-2-1	1.46	1.67	1.46	1.45	1.46
600-C60-2-2	1.46	1.67	1.46	1.45	1.46
M	1.38	1.59	1.40	1.36	1.40
Δ	0.05	0.05	0.05	0.06	0.05

Note. M_u in the table is the measured ultimate flexural bearing capacity and M_{uc} is the calculated value of ultimate flexural bearing capacity obtained by taking the measured yield strength of reinforcement from the current code formulas.

FIGURE 11: ρ - β Curve of different concrete strength grades with the reinforcement rate of 0.005. FIGURE 12: ρ - β Curve of different concrete strength grades with the reinforcement rate of 0.008.

FIGURE 13: Concrete strength grade- $\beta_{\min}$ curve.

TABLE 14: Statistical parameters of the minimum reliable index.

Reinforcement rate	μ_{β}	δ_{β}	μ_{p_f}	μ'_{β}	δ'_{β}	μ'_{p_f}	β	p_f	μ'_{p_f}/p_f
0.005	3.172	0.002	7.57×10^{-4}						
0.008	3.148	0.003	8.23×10^{-4}	3.160	0.005	7.89×10^{-4}	3.2	6.87×10^{-4}	1.15

Note. μ_{β} is the average reliability index of concrete different strength grades corresponding to the reinforcement ratio; δ_{β} is the coefficient of variation of different concrete strength grades corresponding to the reinforcement ratio; μ_{p_f} is the failure probability of the concrete different strength grades corresponding to the reinforcement rate; μ'_{β} is the average value of the overall reliability index; δ'_{β} is the coefficient of variation of the overall reliability index; μ'_{p_f} is the overall average failure probability; β is the reliability index in code; and p_f is the failure probability in code.

5. Conclusion

This paper investigated the flexural bearing capacity of concrete beams reinforced with high-strength steel bars (600 MPa) and concrete of different strengths. Combined with the test data, this study analyzed the applicability of the equations for calculating the flexural capacity an RC beam with 600 MPa grade reinforcement as per different national codes. The reliability of the proposed method of analysis was checked against the experimental performance. The conclusions are as follows:

- (1) The expressions and symbols of the equations for calculating the flexural capacity of the normal section of reinforced concrete beams are consistent in various countries, but there are slight differences in the strength calculation and height calculation methods of the equivalent rectangular stress diagram of concrete.
- (2) The calculated values of ultimate bearing capacity of RC beams based on codes of different countries were compared with the measured values of ultimate bearing capacity. Equations and calculation procedures that are used to calculate the flexural capacity of beams reinforced with 400 MPa or 500 MPa grade steel could also be used for beams reinforced with 600 MPa grade steel.
- (3) On the basis of the experiment, reliability analysis was performed for different design values of yield strength of the 600 MPa grade steel bar. Combined with the

experimental results and considering the utilization ratio of steel bar strength, the design value of yield strength of the steel bar was selected to be 520 MPa.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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