Effect of Variation in the Strength of Concrete and Reinforcing Bars on the Behavior of Reinforced Concrete Beam and Column

A. AMIN[1], N.H.M.K SERKER[2]

[1]Department of Civil Engineering, European University of Bangladesh, Bangladesh (aalaminruet10@gmail.com)
[2]Department of Civil Engineering, Rajshahi University of Engineering & Technology, Bangladesh (kamrujjaman.serker@ruet.ac.bd)

Abstract

Reinforced concrete structures are primarily formed with beams and columns. In general, the compressive strength of concrete and the yield strength of steel are specified in the design process. Compressive strength of concrete generally shows some degree of variation from the target strength. On the other hand, reinforcing bars with higher yield strength than that recommended in the Bangladesh National Building Code are being used in construction. Therefore, increase in yield strength of steel and decrease in compressive strength of concrete may have adverse effects on the behavior of beam and column. This study shows beam and column behavior due to the increase in yield strength up to 500W and reduction in compressive strength up to 2.5 ksi. Numerical and experimental study indicates that ductility as well as in ultimate moment capacity reduces due to variation in strengths in case of beam. However, the effect is not significant in case of column.

Keywords: *High-Strength Steel; Ductility; BNBC; Beam Failure; Longitudinal Reinforcement.*

1 Introduction

Reinforced concrete (RC) structures have become very popular in present era due to availability of materials, ease of construction and many other facts. In fact, the building construction industry is now an emerging sector of Bangladesh and RC building frames are the most popular choice in this regard. Recent earthquakes as well as some tragic incidents have raised the issue of performance of these buildings during an earthquake or under ultimate load. Since reinforcing bars are made in the factory its quality can be easily controlled and high strength steel bars are also available in the local market. The use of high-strength steel bars offers several advantages, such as the reduction of the reinforcement ratio, less cost for reinforcement placement, reduced reinforcement congestion, better concrete placement etc. On the other hand the quality of concrete is difficult to control and this job has become an impossible one in Bangladesh because of the crude construction technology and no-trained workers. Another important issue is the use of higher strength steel than that specified in the Bangladesh National Building Code (BNBC). BNBC (1993) adopted some of the ASTM Standards for structural steel and allowable yield strength of steel reinforcing bars was limited to 410 MPa (60 ksi). It is concerning that RC members are designed with Code specified maximum yield strength of 410 MPa and constructed with locally available higher grade steels such as thermo mechanically treated (TMT) high strength structural steel bars having yield strength up to 500 MPa or 72.5 ksi (Islam, 2010).So, the actual yield strength of the steel bars can exceed its nominal value by a significant factor, depending on the steel manufacturing processes. Such increase in yield strength may have adverse effects on the flexural behavior of beams that are designed as tension controlled. Design of a beam with higher yield strength has higher possibility to be an over-reinforced beam, thus the value of balanced reinforcement ratio becomes smaller than actual reinforcement ratio, which is never expected. Increased yield strength may reduce the ductility of steel, an essential property in seismic resisting as well as other structures (Mourad et. al, 2014) .The present study investigates the effect of using reinforced bars with yield strength exceeding its nominal values on the flexural behavior of beams or columns. This study aims to focus on the behavior of beams using TMT high strength structural steel bars and concrete having specified design strength and the behavior of beams using TMT high strength structural steel bars and concrete having strength less than the specified design strength.

2 Methodology

The study is divided into three steps (i) analytical study with some typical beam sections (ii) experimental investigations (iii) Analytical study with some typical column sections. In case of beam, ultimate load carrying capacity and ductility was measured and for column, longitudinal reinforcement was measured.

In accordance with the development of industrial society and the expansion of the magnitude of economies, structures have become larger and more complex. The safety and serviceability assessment of those complex structures necessitates the development of accurate and reliable methods and models for their analysis. To ensure the safety of structures in the case of earthquake, ductility of structure has become an important issue.

Ductility is defined as the ability of the material/member to sustain deformation beyond the elastic limit while maintaining a reasonable load carrying capacity until total failure (Pam et. al., 2001). Ductility is a valuable structural property as it allows stress redistribution and provides warning of impending failure. The ductility of a reinforced concrete beam depends on the amount of tension reinforcement, the amount of compression reinforcement and the strength and ductility of the materials used (Sarkar et. al., 1997).

Generally, reinforced concrete beams are under-reinforced by design, so that failure is initiated by yielding of the steel reinforcement, followed, after considerable deformation at no substantial loss of load carrying capacity, by concrete crushing and ultimate failure. That is a ductile mode of failure is desired and is ensured by designing the tensile reinforcement ratio to be substantially below the balanced ratio, which is the ratio at which steel yielding and concrete crushing occur simultaneously.

The mathematical expression of balanced reinforcement ratio (Nilson et. al., 2004) is

$$\rho_b = 0.85\,\beta_1 \frac{f'_c}{f_y}\frac{\epsilon_u}{\epsilon_u+\epsilon_y} \qquad (1)$$

where,

f'_c= compressive strength of concrete,

f_y= yield strength of steel,

ϵ_u= ultimate strain in concrete (usually taken as 0.003),

ϵ_y= yield strain of steel and

β_1 = constant depends on compressive strength of concrete. It is clear from Eq. (1) that for a particular beam section the balanced reinforcement ratio depends on the material properties. Besides upper limit of the reinforcement ratio has been introduced in the design Codes (e.g. ACI 318-05) to guarantee ductility

$$\rho_{max} = 0.85\,\beta_1 \frac{f'_c}{f_y}\frac{\epsilon_u}{\epsilon_u+0.004} \qquad (2)$$

The reinforcement ratio thus provides a measurement for ductility and the ductility corresponding to the maximum allowable reinforcement ratio provides a measure of the minimum acceptable ductility. The mode of failure is another important issue which is defined as a function of net tensile strain. The net tensile strain is the tensile strain in the extreme tension steel at nominal strength. According to ACI Code (2005), a beam section is said to be tension-controlled if the net tensile strain is equal to or larger than 0.005 and compression-controlled if the net tensile strain is equal to or less than 0.002. A section is in a transition region between compression- and tension-controlled sections.

Another important factor, the strength reduction factor, is also incorporated in the design of the reinforced concrete members which is essentially based on the deformation capability of the member. The strength reduction factor depends on the net tensile strain of the beam. The purposes of the strength reduction factor are (1) to allow for the probability of under-strength members due to variations in material strengths and dimensions (2) to reflect the degree of ductility and required reliability of the member under the load effects being considered and (3) to reflect the importance of the member in the structure (ACI 318-05, 2005). Design strength or usable strength of a member or cross section is the nominal strength multiplied by the strength reduction factor.

Although, both experimental and numerical study should be carried out here, experimental studies are expensive and time consuming and give us limited information. With the limited information, it is possible to show how strength variation affects the behavior of beam and column (Kwak et. al., 2012).

3 Behavior of Beam

Through some numerical analyses as well as some experimental study, the behavior of beam under the change in material strengths can be discussed.

3.1 Numerical study on beam

To understand the effect of the variation in chief constituent materials a numerical analysis was conducted on a beam section. A typical beam section (width = 12 inch, overall depth = 26 inch, effective depth = 22.5 inch) reinforced with three No.7 and two No. 9 bars was considered and analyzed. The analyses results are presented in Table 1. The beam section was analyzed considering two different grades of concrete to understand how the material strength affects the behavior of reinforced concrete beams. Balanced steel ratio, maximum steel ratio and ductility were calculated for each beam using the equations shown in the previous section and are presented in Table 1.

It is clear from Table 1 that the nominal strength of the beam increases as the yield strength of steel increases (Beams A2 and B2). However, the ultimate strength or the design strength of the beam may not increase in each case because the net tensile strain reduces appreciably. On the other hand, ductility of the member reduces with the inclusion of higher strength steel than that was primarily specified in the design. The minimum ductility may be obtained if the compressive strength of concrete decreases and the yield strength of the steel increase (Beams A3 and B3). The reduction in ductility is obvious and irrespective of concrete grade. Similarly, the net tensile strain reduces as the yield strength of the steel increases or the compressive strength of concrete reduces. Balanced steel ratio or the maximum steel ratio also decreases the yield strength of the steel increases or the compressive strength of concrete reduces.

Table 1. Numerical analysis results of beam specimen

Sl. No.	f'_c (ksi)	f_y (ksi)	Steel ratio	Balanced steel ratio	Max. steel ratio	Net tensile strain	Strength reduction factor	Mode of failure	Ductility	Nominal Moment Capacity (k-ft)	Ultimate Moment Capacity (k-ft)
A1	3.0	60.0	0.014	0.0214	0.0155	0.0050	0.90	Tension	2.24	356.7	321.0
A2	3.0	72.5	0.014	0.0163	0.0128	0.0033	0.76	Transition	1.53	413.2	315.0
A3	2.5	72.5	0.014	0.0136	0.0107	0.0024	0.68	Transition	1.24	392.5	265.0
B1	4.0	60.0	0.014	0.0285	0.0206	0.0077	0.90	Tension	3.07	374.4	337.0
B2	4.0	72.5	0.014	0.0217	0.0171	0.0059	0.90	Tension	2.10	439.0	395.1
B3	3.5	72.5	0.014	0.0190	0.0150	0.0048	0.69	Transition	1.79	428.0	295.0

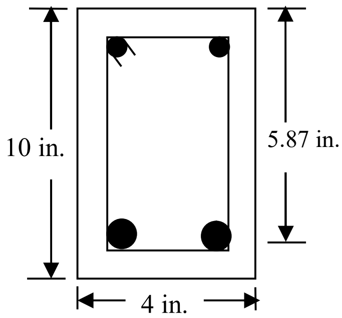
3.2 Experimental study on beam

To make the analysis more reliable, an experimental program was taken. Three rectangular singly reinforced concrete beams having dimensions 4in. x 10in. x 48in. (breadth x depth x length) were fabricated for testing. The beams were cast from normal strength concrete with cylinder compressive strength ranging from 2500 to 3000 psi. In order to study the effects of different materials strength yield strength of steel was also varied. The main bars (two No. 4 bars) were placed near the bottom of the beams. Near the top of the beams, two No. 3 bars (8 mm) bars were added as hanger bars for fixing the stirrups. All of the beams were simply supported at a span of 42 in. and were tested by subjecting them to monotonically applied point load at mid-span, as illustrated in Figure 2. Detailed properties of the beams are given in Table 2. During loading, the vertical deflections at mid-span of the beams were measured by a displacement dial gauge. Visual inspection of the cracks was carried out throughout the tests. The test was terminated when the specimen failed completely, i.e. when the resistance of the specimen dropped. The failure patterns and load-deflection plot are shown in Fig. 2 and 3 respectively.

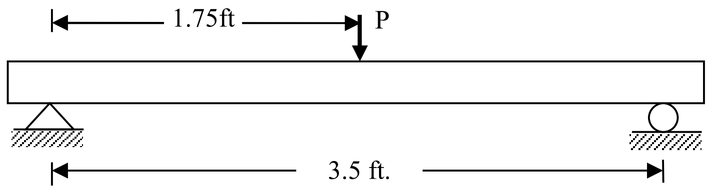
Experimental Results

The experimental program was designed in such a way that the variation of the material strengths on the behavior of beam can be studied. From the numerical study results it is clear that a section may turn into over-reinforced if the strength of concrete decreases or strength of steel increases. Therefore, the tension reinforcement may or may not yield before the concrete in the compression zone is crushed. If the strength of the materials remains the same as it was considered in the design the reinforcement ratio may lie below the allowable maximum amount as a result the tension reinforcement will yield before the concrete is crushed and the beam will fail in a ductile manner. If the reinforcement ratio becomes larger than the allowable maximum, the concrete will be crushed without prior yielding of the tension reinforcement and the beam will fail in a brittle manner.

Beam C1 was designed considering compressive strength of 3000 psi and yield strength of steel as 60,000 psi. Due to some limitations, measurement of strain of steel or concrete was not possible. It was expected from the previous numerical study that the use of higher strength steel or lower strength concrete will affect the behaviour of the beam significantly. From the experiment the ultimate load capacity of the beam was measured as 10.5, 12.1 and 12.5 kips for beam C1, C2 and C3 respectively. It is evident that the load carrying capacity of the beam has been increased after increasing the yield strength of steel. However, the ultimate load of beam C3 was larger than the expected. It is noteworthy that the deflection of the beam specimens reduces as the yield strength of steel increases or compressive strength of concrete decreases. The measured deflections are well correlated with the theoretical ductility. It is evident from the analytical study that there is a remarkable effect on the mode of failure of the beam and the beam which was initially designed as an under-reinforced section may turn into an over-reinforced section i.e. the beam may also fail by crushing of concrete instead of yielding of steel. The experimental beam also reflects the same as it can be seen from Figure 4.



(a) Beam cross section

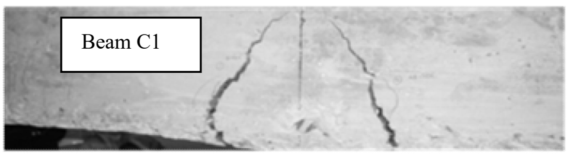


(b) Loading arrangement

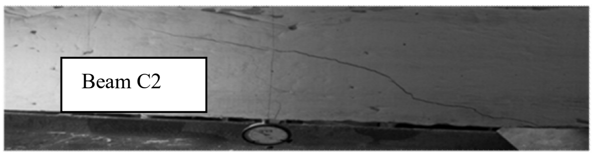
Figure 1. Beam cross section and loading arrangement

Table 2.Properties of the beam specimen

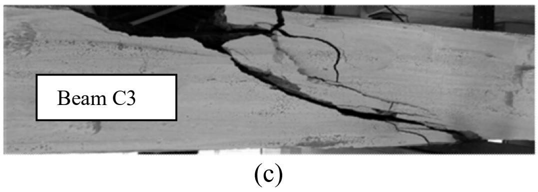
Sl. No.	f'_c (ksi)	f_y (ksi)	Balanced steel ratio	Max. steel ratio	Net tensile strain	Strength reduction factor	Mode of failure	Ductility	Deflection (in)	Ultimate Load (k)
C1	2.93	60.0	0.021	0.0151	0.0053	0.90	Tension	2.51	0.26	10.5
C2	2.97	72.5	0.016	0.0127	0.0040	0.66	Transition	1.74	0.18	12.1
C3	2.52	72.5	0.014	0.0108	0.0029	0.61	Transition	1.44	0.14	12.5



(a)



(b)



(c)

Figure 2. Failure pattern of beams (a) beam C1 (b) beam C2 (c) beam C3

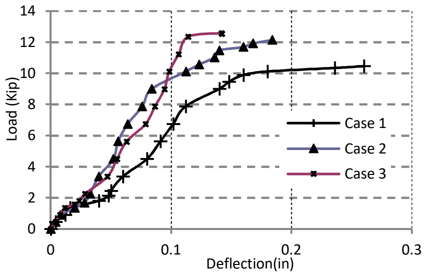


Figure 3. Load-deflection curves of experimental beams

4 Behavior of Column

Columns are structural element that transmits the weight of the structure above to other structural element below and are generally treated as compression member. In case of seismically active areas, columns may also be designed to resist lateral forces. Therefore, special attention should be given to their structural response under loading conditions. In previous section effect of variation in material strengths than that specified in the design process on a beam member has been discussed. The similar cases can be considered for different column sections and can be analyzed. For an axially loaded column the ultimate load that can be carried can easily be computed from

$$P = \alpha\emptyset(0.85f'_c\ A_g - A_{st}\ + A_{st}f_y) \qquad (3)$$

where α = 0.85, φ = 0.7 for spiral column and 0.65 for tied column, A_g = total area of concrete, A_{st} = area of reinforcing steel bars. In a column, concrete occupies the most areas and minimum area of steel should not be less than 1%. Therefore it can be estimated that the reduction in concrete strength will greatly affect the load carrying capacity of an axially loaded column. However, a column having axial load and bending the effect of reduced concrete strength and increased steel strength may have different result. Although column is primarily designed as a compression member almost all columns are subjected to bending moments in addition to axial loads. The behavior of such columns is not that much simple as it is in case of an axially loaded column. To estimate how a column behaves in such cases, a 20 in. X 12 in. column was considered in this study. Two different reinforcement ratios were considered. First case (D1, D2, D3) considers 4 No. 9 bars at four corners providing reinforcement ratio of 1.67% and second case (E1, E2, E3) considers 4 No. 7 bars at four corners providing reinforcement ratio of 1.0%. Interaction diagrams for these columns are produced for different combination of concrete and steel strengths and shown Figure 4. The results are also tabulated in Table 3. It is evident from Table 3 that the balance load is the highest when the specified materials are used and moment capacity increases if higher strength steel bars are used. The moment capacity as well as the corresponding load decreases if the concrete strength is lowered even though the steel strength is higher.

Table 3. Numerical analysis results of column specimen

Sl. No.	f'_c (ksi)	f_y (ksi)	Balanced condition		Tension failure		Compression failure		Zero eccentricity
			P_b	M_b	P_t	M_t	P_c	M_c	P_n
D1	3.0	60.0	272.3	3311.5	137.6	2824	520	2354	852.0
D2	3.0	72.5	238.6	3525.8	112.6	2005	547	2555	900.0
D3	2.5	72.5	214.0	3341.4	86.6	2818	476	2320	800.0
E1	3.0	60.0	262.3	2591.0	145.0	2160	478	1945	756.0
E2	3.0	72.5	231.0	2705.0	130	2271	494	2057	786.0
E3	2.5	72.5	161.5	2512.0	104	2382	424	1835	684.0

5 Conclusions

Recent earthquakes in different parts of Bangladesh as well as some tragic incidents have focused the issue regarding the performances of buildings. The performance of such buildings during an earthquake or ultimate loading conditions may depend on several factors. Strength of concrete and steel are chosen as the primary factors in this study and some numerical study results along with some experimental results are presented in this paper. From the results the following conclusions are drawn:

(i) in the design of a reinforced concrete beam, both the flexural strength and ductility need to be considered. However, more importance is usually given to the flexural strength and only a simple check is carried out to ensure that a certain minimum level of ductility is provided by keeping the beam under-reinforced. From the structural safety point of view, ductility is as important as strength. A good ductility would provide the beam with a much better chance of survival when it is overloaded, attacked by a severe earthquake or subjected to an accidental impact.
(ii) it is evident that the major factors affecting the flexural strength and ductility of a reinforced concrete beam section are the concrete grade, yield strength of steel and tension steel ratio. In the case of a singly reinforced section, at a fixed concrete grade, the use of a higher tension steel ratio leads to a higher flexural strength but a lower ductility. Hence, the increase in flexural strength is achieved by compromising ductility. When specified design strength and actual strength remain the same, then the steel ratio is below the allowable maximum steel ratio thus beam shows tension failure and produce higher deflection and ductility. When compressive strength remain the same but steel strength is increased, then beam shows larger nominal strength and produces relatively lower deformation and ductility. In case compressive strength is decreased but steel strength is increased which may be a common case in Bangladesh, the steel ratio increases and mode of failure of the beam is also changed and results lower deformation and ductility.

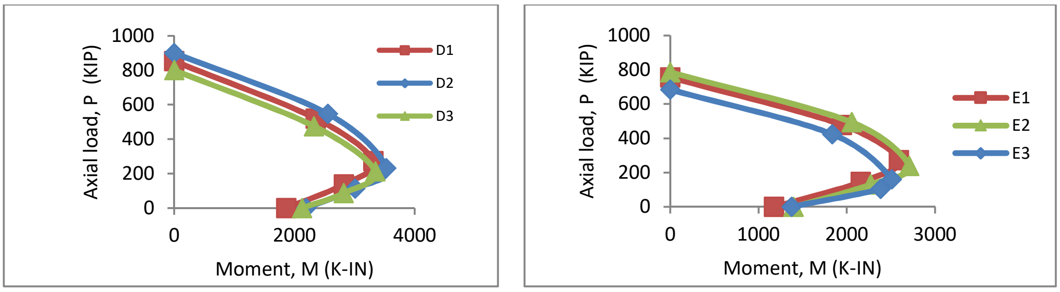


Figure 4. Interaction diagram of columns

(iii) column is a key structural element and its performance is greatly affected with the variation of concrete strength. In case of axially loaded column an increase in steel strength will increase the ultimate load carrying capacity. An increase in compressive strength will lead to a reduction in member size and an economy of materials while an increase in durability will lead to lower life-cycle cost. Brittleness increases as the concrete compressive strength increases. Low ductility of concrete is detrimental to its performance in areas of high seismic activity. However the ductility factor was not considered in this study.

References

ACI Committee 318. 2005.Building Code Requirements for Structural Concrete (ACI 318-05) and Commentary, American Concrete Institute, Farmington Hills, MI.

ASTM A615/A615M-09.(2009). Standard Specifications for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement, ASTM International, West Conshohocken, PA.

Bangladesh National Building Code. (1993). Housing and Building Research Institute, Dhaka, Bangladesh.

Islam, MA. 2010. Thermo Mechanically Treated Advanced Steels for Structural applications, Proceedings of MARTEC 2010, the International Conference on Marine Technology, 11-12December, 2010, Dhaka, Bangladesh.

Kwakand, H.G. and Kim, S. P., 2002.Nonlinear analysis of RC beams based on moment–curvature relation, 80 (2002) 615–62.

Nilson, AH; Darwin, D and Dolan, CW. 2004.Design of Concrete Structures, Thirteenth edition. McGraw Hill.

Sarkar, S;Adwan, O. and Munday JGL. 1997. High strength concrete: an investigation of the flexural behavior of highstrength rc beams. Structural Engineer, 75(7):115–121.

Mourad, S. Charif, A and Khan, MI., 2014.Flexural behavior of RC Beams with local steel - experimental investigation, IOS Press, doi:10.3233/978-1-61499-466-4-1038.

Price, KR, Fields, D and Lows, N., 2013.The Impact of High-Strength Reinforcing Steel on Current Design Practice, Charles Pankow Foundation Research Grant Agreement vol-01-13.