

EFFECT OF VARIATION IN THE STRENGTH OF CONCRETE AND REINFORCING BARS ON THE BEHAVIOR OF RC BEAMS

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ABSTRACT

Reinforced concrete members are designed with specified code specifications. In general, the compressive strength of concrete and the yield strength of steel are assumed in the design process. Compressive strength of concrete depends on a number of factors and generally shows some degree of variation from the desired strength. On the other hand, reinforcing bars with higher yield strength than that recommended in the Bangladesh National Building Code is available in the market and being used in construction. Therefore, increase in yield strength of steel and decrease in compressive strength of concrete may have adverse effects on the flexural behavior of beams. This study includes the behavior of reinforced concrete beam due to this variation in strengths. This study shows that some certain beam turns into over-reinforced from under-reinforced state as well as compression controlled from tension-controlled state due to change in strengths. Besides, reduction in ductility is also observed due to strength variation in the properties of the major constituent materials. A complete theoretical analysis along with some experimental investigation is presented in this paper.

Keywords: Ductility; high-strength steel; BNBC; beam behavior

INTRODUCTION

The building construction industry is one of the emerging sectors of Bangladesh and reinforced concrete (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. Concrete and reinforcing bars are the chief constituent materials in RC buildings. 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). The important concern is 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). Therefore such increase in yield strength of steel and decrease in compressive strength of concrete may have adverse effects on the behavior of RC flexural members and the beam would not achieve adequate ductility under ultimate load. This study aims to focus on

1. the behavior of beams using TMT high strength structural steel bars and concrete having specified design strength.
2. the behavior of beams using TMT high strength structural steel bars and concrete having strength less than the specified design strength.

METHODOLOGY

The study is divided into two steps (i) analytical study with some typical beam sections (ii) experimental investigations. In each case ultimate load carrying capacity of the beam and ductility was measured.

Ductility is an important issue in the design of structure and structural member and 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

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

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

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

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.

In this article the curvature ductility was considered. The ductility factor was taken as the ratio of the curvature at yield and ultimate condition. The ductility can be estimated as shown below:

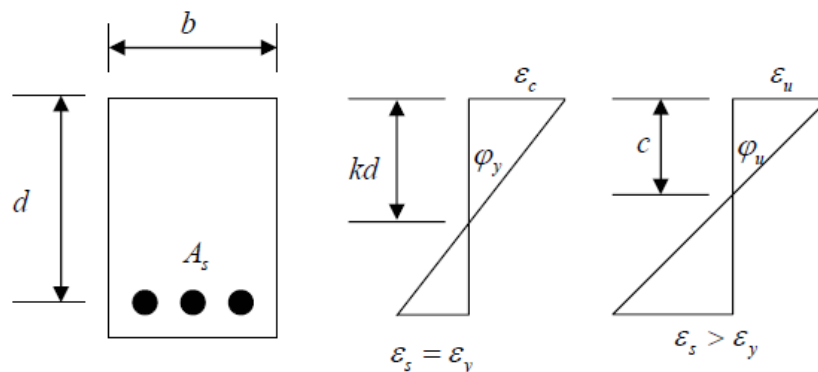


Fig. 1: Calculation of ductility

$$\text{The curvature at yield condition, } \phi_y = \frac{f_y}{E_s} \frac{1}{d(1-k)} \quad (3)$$

where, ϕ_y = curvature at yield condition, k = constant, E_s = modulus of elasticity of steel, d = effective depth of the beam.

$$\text{The curvature at ultimate condition, } \phi_u = \frac{\epsilon_u}{c} = \frac{\epsilon_u \beta_1}{a} \quad (4)$$

where, ϕ_u = curvature at ultimate condition, a = depth of rectangular compression stress block.

$$\text{Ductility } \mu = \frac{\phi_u}{\phi_y} = \frac{\epsilon_u}{f_y} \frac{d(1-k)}{a/\beta_1} \quad (5)$$

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.

NUMERICAL STUDY

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.

EXPERIMENTAL INVESTIGATION

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

Table 1: Numerical analysis results

Sl. No.	f'_c (ksi)	f_y (ksi)	Steel ratio	Balance d 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

out throughout the tests. The test was terminated when the specimen failed completely, i.e. when the resistance of the specimen dropped. The load-deflection plot and failure patterns are shown in Fig. 3 and 4 respectively.

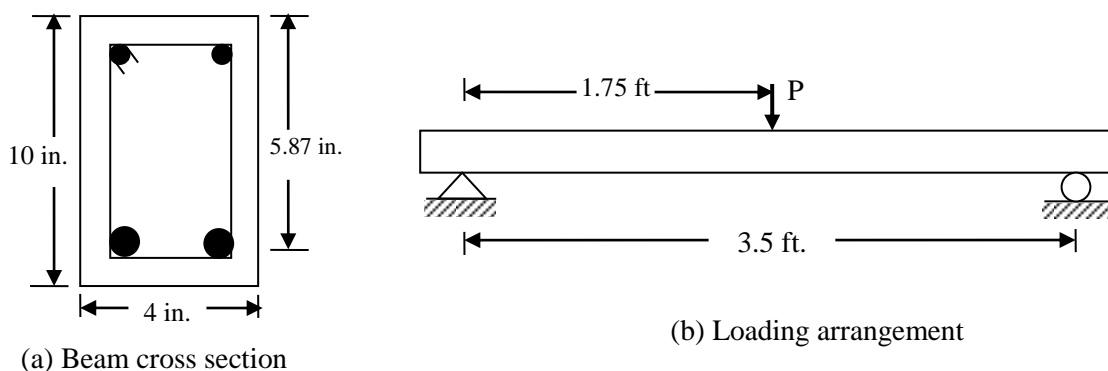


Fig. 2: Beam cross section and loading arrangement

Table 2: Properties of the beam specimen

Sl. No.	f'_c (ksi)	f_y (ksi)	Balance d 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	0.015 ₁	0.005 ₃	0.90	Tension	2.51	0.26	10.5
C2	2.97	72.5	0.016	0.012 ₇	0.004 ₀	0.66	Transition	1.74	0.18	12.1
C3	2.52	72.5	0.014	0.010 ₈	0.002 ₉	0.61	Transition	1.44	0.14	12.5

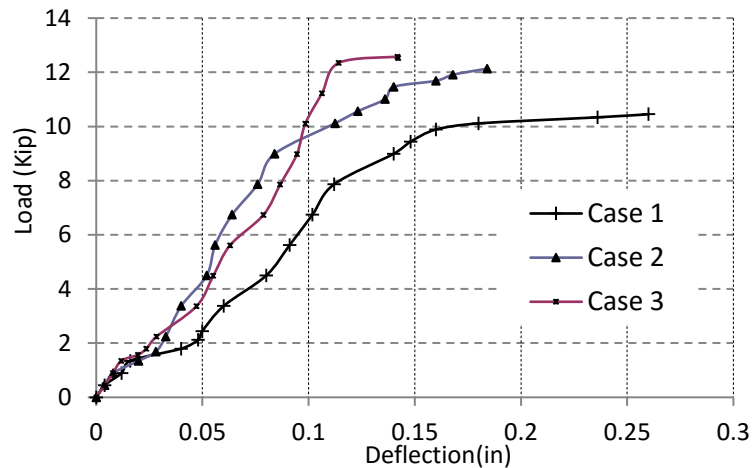


Fig. 3: Typical load- deflection curves

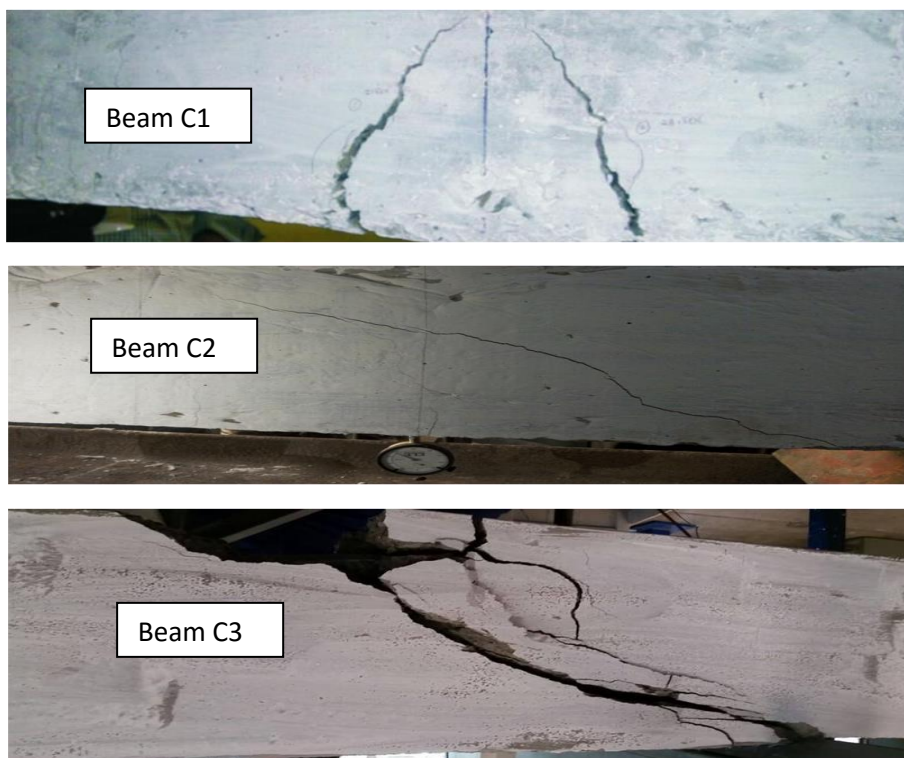


Fig. 4: Failure pattern of experimental beams

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.

CONCLUSIONS

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.

From the above, 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.

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