Evaluation of Properties of Steel Reinforcing Bars for Seismic Design

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SUMMARY:
Capacity design procedure for the earthquake-resistant reinforced concrete (RC) structures is effective when actual member capacities do not greatly exceed the assumed design capacities. Moreover, RC members are expected to undergo large inelastic deformations for adequate seismic energy dissipation. Since flexural capacity and post-yield behavior of an RC member is largely controlled by steel reinforcing bars, it places certain special requirements on their properties, such as, yield strength (YS), ultimate tensile strength to yield strength ratio (UTS/YS ratio) and elongation, which are sensitive to the method of rebar manufacturing. Flexural tests on thirty RC beams which used rebars of carefully controlled properties was conducted and it was observed that for dependable flexure behaviour, YS and UTS values should lie in a narrow band around values used in the member design. If these values are greater than the specified value, it may cause brittle shear failure instead of more ductile and desirable flexure mode of failure. Moreover, a high UTS/YS ratio equal to 1.25 is necessary to have dependable peak strength which is larger than the yield strength.

Keywords: Reinforcing steel bars, Earthquake-resistant design, Steel tensile/yield ratio, Elongation

1. INTRODUCTION

Earthquake-resistant design of reinforced concrete (RC) structures is based on maximizing energy absorbing capacity of various members without causing collapse. In order to ensure such an outcome, the capacity design procedures are used, which is effective when actual member capacities do not greatly exceed the design capacities and the pre-determined hierarchy of member strength is maintained (Paulay and Priestley, 1992). In addition, RC members are likely to experience large inelastic deformations and, therefore, adequate ductility is essential to avoid brittle failure mode and to enhance energy dissipation potential. Since strength and ductility related capacities in RC flexural members are largely controlled by steel reinforcing bars, it places certain special requirements on their properties, especially those controlling the inelastic portion of the stress-strain curve which largely depends on the method of rebar manufacturing besides metallurgical/chemical compositions of the steel used (Towl and Burrell, 2005; Brooke et al., 2005; McDermott, 1998; Macchi et al., 1996).

Two most common types of manufacturing process for reinforcing bars of higher strength using mild steel involve either cold-working or a heat treatment process. The process of *cold working* involves stretching and twisting of mild steel beyond yield plateau to obtain cold twisted deformed (CTD) bars of increased strength (*proof strength*), though it reduces the available ductility in the material. The other method uses a thermo-mechanical treatment (TMT) process in which red hot rebars are quenched through a series of water jets causing a hardened outer layer (martensite structure) surrounding softer core (ferrite-pearlite structure). The resulting rebars has higher yield strength than parent mild steel and is characterized with definite yield point, superior ductility, weldability and bendability. These bars are also referred as quenched and self-tempered (QST) or simply QT bars (Viswanatha, 2004; Viswanatha et al., 2004; Hare, 2005).

This study is concerned with the effect of reinforcing steel characteristics and their manufacturing process on the flexural behavior of beams upto failure, with an objective of identifying requirements of reinforcing bars for earthquake resistant construction. Thirty RC beams were tested with (a) five types of reinforcement differing in their yield strength (YS), ultimate tensile strength to yield strength ratio (UTS/YS ratio), elongation, manufacturing process (CTD vs. TMT) and degree of quality control (well controlled vs. poorly controlled).

2. EXPERIMENTAL PROGRAM AND DESCRIPTION OF BEAM SPECIMENS

Ten different types of beams (numbered as 1 to 10) were designed by varying the various parameters affecting rebar properties as shown in Table 1.1 and for each kind three specimens were prepared (identified as A, B and C). Therefore, each beam specimens is designated by its type number followed by a letter A, B and C. In total, thirty beams were tested to either failure or to the maximum displacement available with the actuator. All beams except Beam Set #10 were designed as over-reinforced section for a moment capacity of 90 kNm. Transverse reinforcements were provided to prevent shear failure at design moment capacity; however, two beam sets #8 & #9 were provided with shear stirrups at closer spacing to provide confinement of core concrete.

Table 1.1 Details of beams used in the study

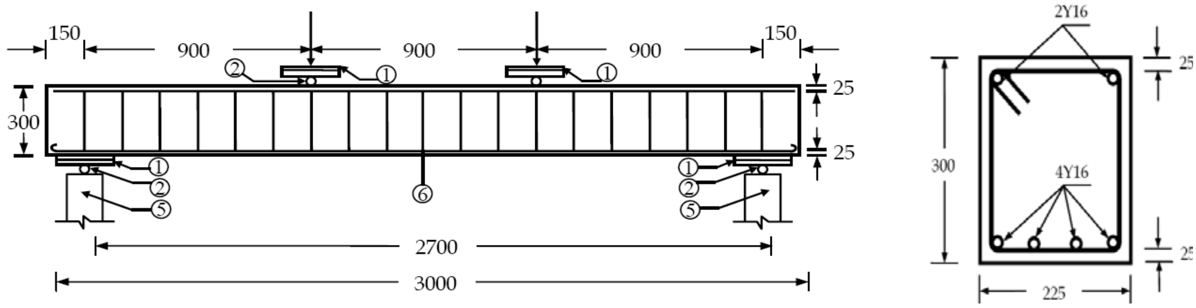
Sr. No.	Concrete Grade	YS (MPa)	UTS/YS Ratio	Rebar Type	Elong.	Reinforcement Details and Design Capacity		Comparison with Control Specimen
						Flexure	*Shear*	
1	M25	415	1.15	TMT	22%	A_{st} = 4Y16 A_{sc} = 2Y16 M_u = 68.3 kNm	One hoop Y6 at 150 mm c/c V_u = 79.2 kN	Control Specimen Standard
2	M35	415	1.15	TMT	22%	A_{st} = 4Y16 A_{sc} = 2Y16 M_u = 69.3 kNm	One hoop Y6 at 150 mm c/c V_u = 79.2 kN	Varying concrete grade keeping same M_c
3	M25	550	1.15	TMT	19%	A_{st} = 3Y16 A_{sc} = 2Y16 M_u = 68.1 kNm	One hoop Y6 at 150 mm c/c V_u = 74.9 kN	Using high strength steel keeping same M_c
4	M35	550	1.15	TMT	19%	A_{st} = 3Y16 A_{sc} = 2Y16 M_u = 69.0 kNm	One hoop Y6 at 150 mm c/c V_u = 76.5 kN	Varying concrete grade using high strength steel keeping same M_c
5	M25	415	1.10	CTD	11%	A_{st} = 4Y16 A_{sc} = 2Y16 M_u = 67.9 kNm	One hoop Y6 at 150 mm c/c V_u = 79.2 kN	Varying type of steel (CTD bars) keeping same M_c
6	M25	415	1.25	TMT	25%	Similar to 1	Similar to 1	Varying UTS/YS ratio and total rebar elongation keeping same M_c
7	M25	415	1.15	TMT	14%	Similar to 1	Similar to 1	Non-Standard TMT keeping same M_c
8	M25	415	1.15	TMT	22%	Similar to 1	One hoop Y6 at 100 mm c/c V_u = 97.3 kN	Confining beam section and using normal steel with same M_c
9	M25	550	1.15	TMT	19%	Similar to 3	One hoop Y6 at 100 mm c/c V_u = 93.1 kN	Confining beam section and using high strength steel with same M_c
10	M25	550	1.15	TMT	19%	A_{st} = 4Y16 A_{sc} = 2Y16 M_u = 90.0 kNm	One hoop Y6 at 150 mm c/c V_u = 79.2 kN	Varying M_c using high strength steel keeping same A_s

Note: M_c = Moment Capacity of Control Beam (Set #1); A_{st} = Area of bottom tension steel; A_{sc} = Area of top compression steel; M_u = Design moment capacity as per IS: 456; V_u = Design shear capacity as per IS 456:2000.

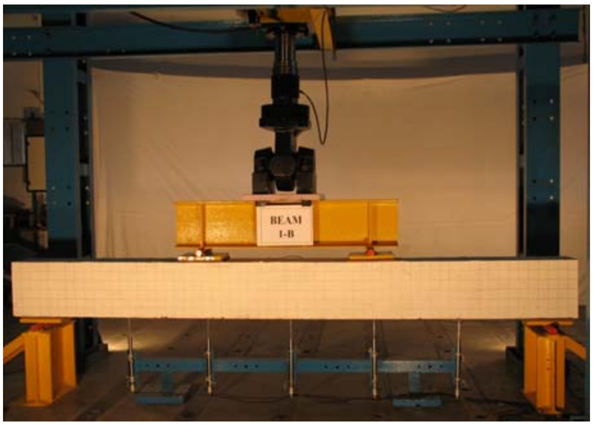
The dimensions of all concrete beams were kept as 3000×230×300 mm. Each concrete beams were reinforced with 16 mm dia. steel bars for tension and compression and a clear concrete cover of 25 mm was provided. For shear reinforcement 6 mm diameter bars at a spacing of 150 mm centre to centre were provided except Set # 8 & 9. In these beams 6 mm diameter bars with 100 mm centre to centre were provided. The details of test specimen and loading arrangement are shown in Fig. 2.1.

The beams were loaded in a four-point load arrangement which produces a constant bending moment over the central span. The load was applied through a 500 kN load/ 250 mm displacement capacity MTS servo-hydraulic actuator in displacement control at the rate of 0.075 mm per second till either beam failed or maximum useable stroke was reached in the actuator.

The instrumentation consisted of load cell and LVDT in the actuator arm for load and displacement measurement, which was also used for controlling the load application by MTS GT servo controller. A set of five LVDTs along the length of beam at its underside were installed as shown in Fig. 2.1b to measure the deflection of the beam. In addition, two strain gauges (Measurement Group, USA) were mounted on two bottom reinforcing bars at mid-span. All these sensors were connected to a System 5000 data acquisition system (Measurement Group, USA) for recording and storage.



(a)



(b)

Figure 2.1. (a) Geometric details of the beam and reinforcement layout and (b) Test setup for four point bending

3. MATERIAL PROPERTIES

3.1 Concrete

Two different grades of concrete, M25 and M35 were used which were prepared in a ready mix plant and delivered to the laboratory. The mix designs in the ratio of water: cement: fine aggregate: coarse aggregate were 1:2.63:4.53:7.76 for M25 and 1:3.1:2.82:7.06 for M35. The compressive strength of standard cubes and cylinder were determined on the day of testing of beams and are showin in Fig. 3.1. The ‘characteristic’ cube strength was estimated as 36.9 MPa for M25 and 44.0 MPa for M35 concrete. A total of 53 cubes were tested during the course of testing program. A set of 11 cylinders for M25 and 3 cylinders for M35 were also tested.

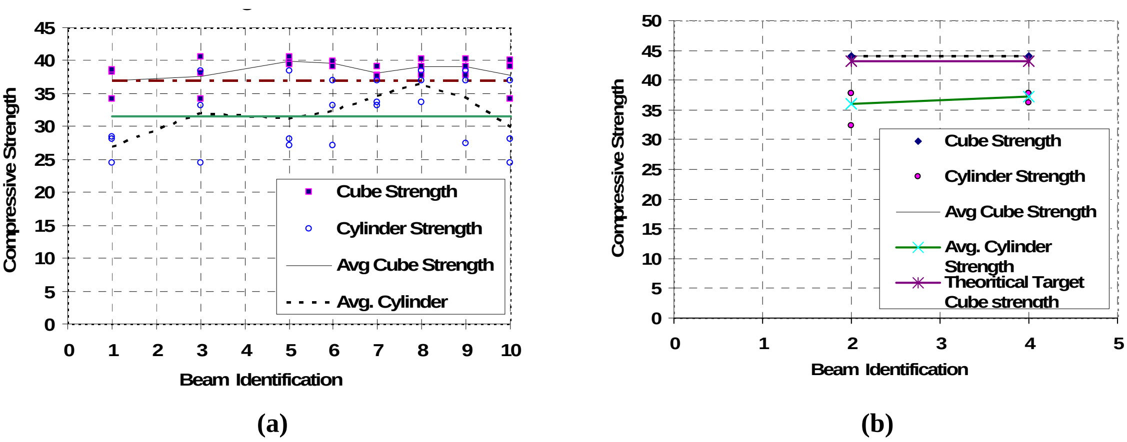


Figure 3.1. Compressive strength of concrete used in test specimens (a) M25 and (b) M35 grade of concrete

3.2 Steel reinforcing bars

Each reinforcing bar used in the beam specimens was tested in tension and results are shown in Fig. 3.2a-d. There were five different kinds of steel reinforcing bar used in the study based on their properties and degree of quality control exercised to ensure these properties and manufacturing process, i.e., TMT versus CTD, as summarized in Table 3.1.

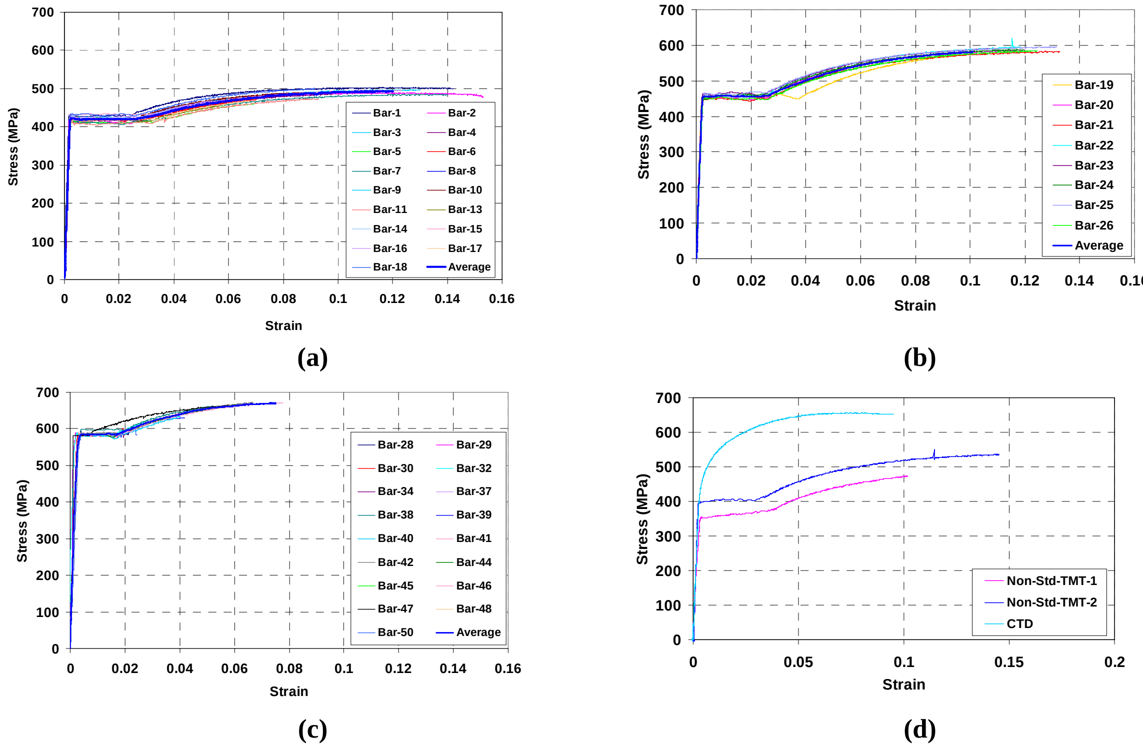


Figure 3.2 Stress-strain curves for 16 mm diameter rebars used in (a) Beam Sets # 1, 2, & 8 (YS=415 MPa, UTS/YS = 1.15, EL=22%) (b) Beam Sets # 6 (YS=415 MPa, UTS/YS = 1.25, EL=25%) (c) Beam Sets # 3, 4, 9, & 10 (YS=550 MPa, UTS/YS = 1.15, EL=19%) (d) Beam Sets # 5 & 7 for CTD and Non-Standard TMT bars of specified YS=415 MPa

It should be noted that *Type IV* and *V* reinforcing bars were produced with no control over UTS/YS ratio, as it was not part of the required specifications (BIS, 2008). Moreover, these reinforcing bars were believed not to be produced with the strict quality control to ensure compliance with relevant Indian Standards. As shown in Fig. 3.2d, 0.2% proof strength of CTD bar is 555 MPa against the required strength of 415 MPa. Similarly, for the non-standard TMT bars, the yield stress values were

354 MPa and 405 MPa, both less than the required minimum YS of 415 MPa. Reinforcing bars with specified yield strengths of 415 and 550 MPa are usually designated as Fe415 and Fe550, respectively.

Table 3.1 Specified Characteristics of Reinforcing Bars used in the study

Type	YS (MPa)	UTS/YS	Elongation (%)	Manufacturing Process
Type I	415	1.15	22	Standard TMT process
Type II	415	1.25	22	Standard TMT process
Type III	550	1.15	19	Standard TMT process
Type IV	415	Not specified	22	Non-Standard TMT process
Type V	415	Not specified	11	CTD process

4. RESULTS & DISCUSSION

As expected most beams behaved like under-reinforced beams wherein behavior was controlled by the tensile stress-strain behavior of steel rebars. However, in six cases, wherein provided flexural strength became greater than available shear strength, undesirable shear failure mode was observed. Fig. 4.1 shows the observed failure mode and cracking pattern of a representative beam (Series B) of each set.

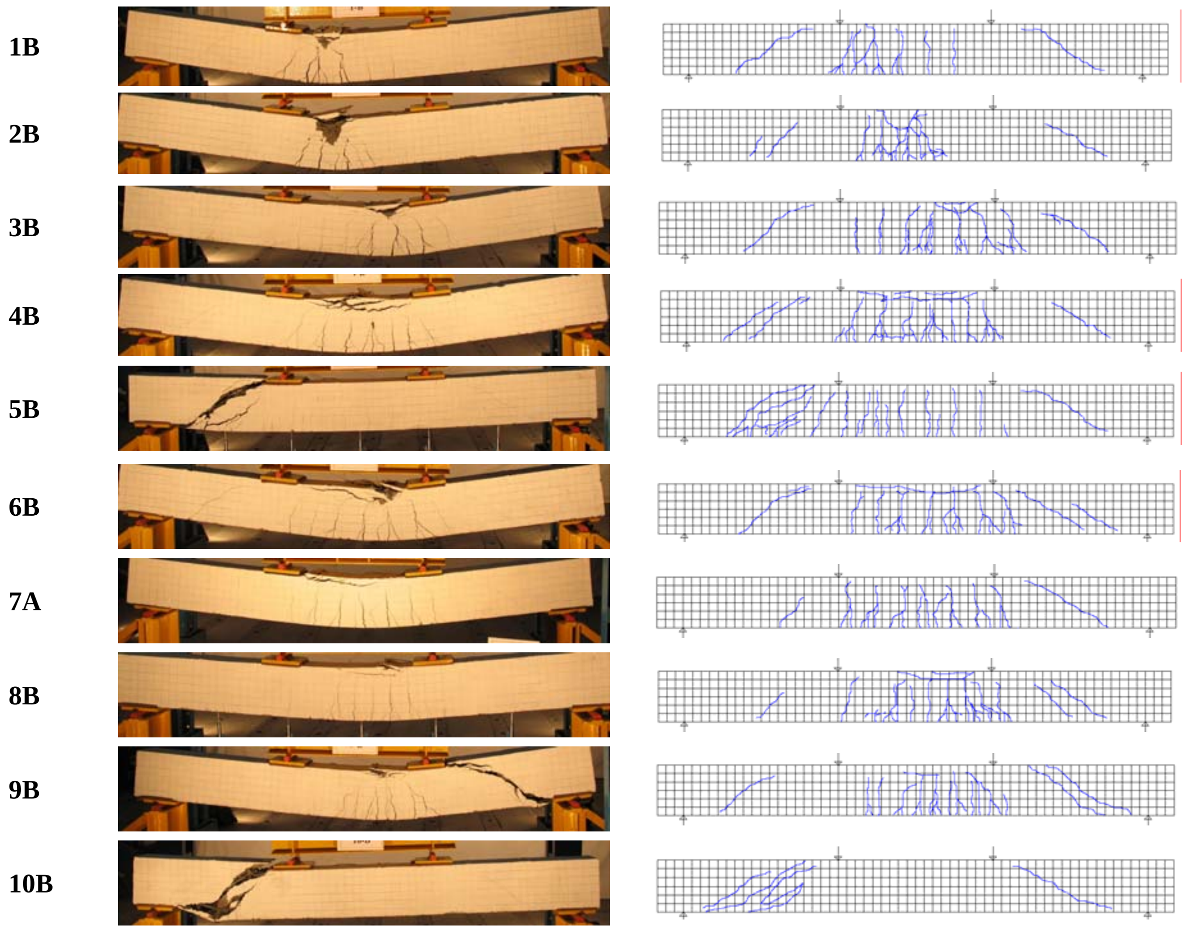


Figure 4.1 Beam specimens at the conclusion of the test (Series B of each set) and observed cracking pattern

A summary of observed results is provided in Table 4.1. It included loads corresponding to appearance of the first flexure crack (FCL), flexure yield load (YL), shear cracking initiation load (SCIL) and finally, the load corresponding to crushing of concrete in the compression region (CCL). A study of the observed pattern across various beams suggest that cracking load was almost similar because of no significant variation in concrete properties. The flexure yield strength was observed to be in proportion to the YS of their reinforcing bars. It should be noted that for beams using non-standard bars had lower yield loads. Similar trend was observed for the ultimate failure load (CCL). A large variation was noted across all beams for the load at which the first shear crack appeared (SCIL) and can be attributed to sub-standard bars used for stirrups.

Table 4.1 Summary of observed experimental data

Beam ID	**Specimens**	**Grade of Concrete**	**Specified YS (MPa)**	**Actual Properties of Reinforcing Steel Bars**				**Main bars**	**Stirrup**	**FCL (kN)**	**YL (kN)**	**SCIL (kN)**	**CCCL (kN)**
				YS (MPa)	**UTS (MPa)**	**UTS/ YS**	**%EL**						
1	A	M25	415	422	488	1.16	31.1	A_{st}= 4Y16 A_{sc}= 2Y16	6 mm @150 c/c	57	190	200	205
	B			421	499	1.18	28.9			68	191	192	214
	C			420	494	1.17	31.6			54	192	190	202
2	A	M35	415	421	491	1.17	30.0	A_{st}= 4Y16 A_{sc}= 2Y16	6 mm @150 c/c	58	186	170	192
	B			421	492	1.17	27.9			49	195	175	201
	C			421	490	1.16	30.3			40	197	170	203
3	A	M25	550	585	679	1.16	25.0	A_{st}= 3Y16 A_{sc}= 2Y16	6 mm @150 c/c	57	202	175	212
	B			587	681	1.16	27.0			46	199	177	226
	C			580	676	1.16	26.0			53	201	180	222
4	A	M35	550	585	681	1.16	26.0	A_{st}= 3Y16 A_{sc}= 2Y16	6 mm @150 c/c	67	197	177	211
	B			583	678	1.16	24.0			64	207	165	210
	C			555	646	1.16	22.0					168	
5	A	M25	415	476	656	1.38	13.3	A_{st}= 4Y16 A_{sc}= 2Y16	6 mm @150 c/c			209	
	B			476	656	1.38	13.3					203	
	C			476	656	1.38	13.3					180	
6	A	M25	415	456	590	1.29	26.6	A_{st}= 4Y16 A_{sc}= 2Y16	6 mm @150 c/c	54	203	165	214
	B			455	587	1.29	29.2			60	207	201	218
	C			455	591	1.30	27.5			62	212	200	226
7	A	M25	415	405	550	1.35	32.9	A_{st}= 4Y16 A_{sc}= 2Y16	6 mm @150 c/c	60	174	180	179
	B									50	146		168
	C			354	474	1.33	24.7			54	162	163	182
8	A	M25	415	422	495	1.17	31.2	A_{st}= 4Y16 A_{sc}= 2Y16	6 mm @100 c/c	57	191	187	190
	B			422	500	1.18	30.3			50	190	204	200
	C			421	489	1.16	29.8			59	189	194	193
9	A	M25	550	584	682	1.17	24.0	A_{st}= 3Y16 A_{sc}= 2Y16	6 mm @100 c/c	56	184	180	178
	B			581	679	1.17	25.0			60	193	194	210
	C			586	682	1.16	25.0			57	199	199	214
10	A	M25	550	567	670	1.18	23.0	A_{st}= 4Y16 A_{sc}= 2Y16	6 mm @150 c/c	56	256	158	257
	B			583	680	1.17	24.0					195	
	C			589	680	1.15	23.0					185	

4.1 Effect of YS of steel rebars

Behavior of beams with high strength Fe550 rebars is similar to that of beams with Fe415 steel rebars when they are suitably designed, as suggested by comparing Beam Set #1 with #4 as shown in Fig. 4.2 (ignoring the anomalous behavior of Beam 4-C). Use of Fe550 rebar reduced the amount of tension steel reinforcement to three bars in contrast to four bars of Fe415, taking advantage of its high tensile strength. However, when amount of steel reinforcement was not adjusted for higher strength of Fe550 and simply 4 bars of Fe415 design (Beam Set #1) was replaced by four bars of Fe550 (Beam Set #10), the observed behavior of two of three beams was very different. These beams expectedly reached higher loads but failed much early in the brittle shear mode, because the shear stirrup design was not revised for the expected higher shear demand. However, the shear failure was completely avoided in Beam Set #9 despite Fe550 rebars due to the presence of increased amount of shear reinforcement.

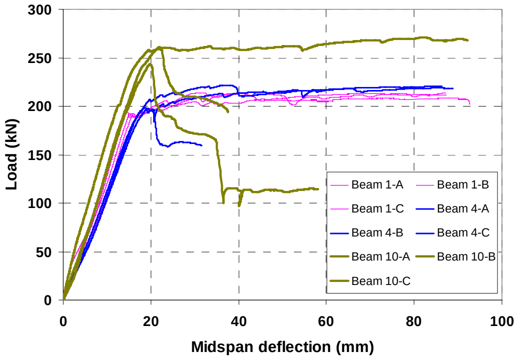
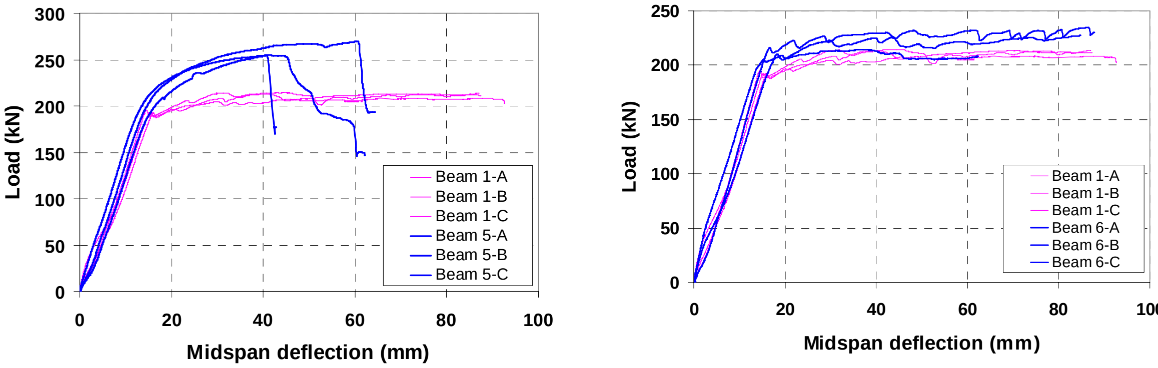


Figure 4.2 Effect of yield strength of steel rebars on beams with M25 and M35 concrete

4.2 Effect of different process of rebar manufacturing (CTD vs. TMT)

CTD reinforcing bar produced by cold twisting process has no definite yield point and as standards do not put an upper limit on yield strength (0.2% proof strength), the actual yield strength can be much higher than the required yield strength. As shown in Fig. 4.3 (a), load–deformation curves for Beam Set #5 with CTD bars show no definite yield point and reached much higher load in the excess of 250 kN which is about 20% higher than beams with standard Fe415 TMT bars. Such large flexural strength for these beams were due to higher strengths of CTD bars and it changed the expected failure mode from flexure to shear. All three beams of Set #5 failed in shear mode, because the design shear capacity was exceeded before the flexural strength is reached. As a result, the beams failed prematurely and suddenly at much lower displacement, nearly half of what the control beam could reach. This poor performance has serious implications for seismic applications as higher strength of rebar may induce undesirable shear mode of failure and reduced deformation capacity of beam which limits the energy dissipation potential.



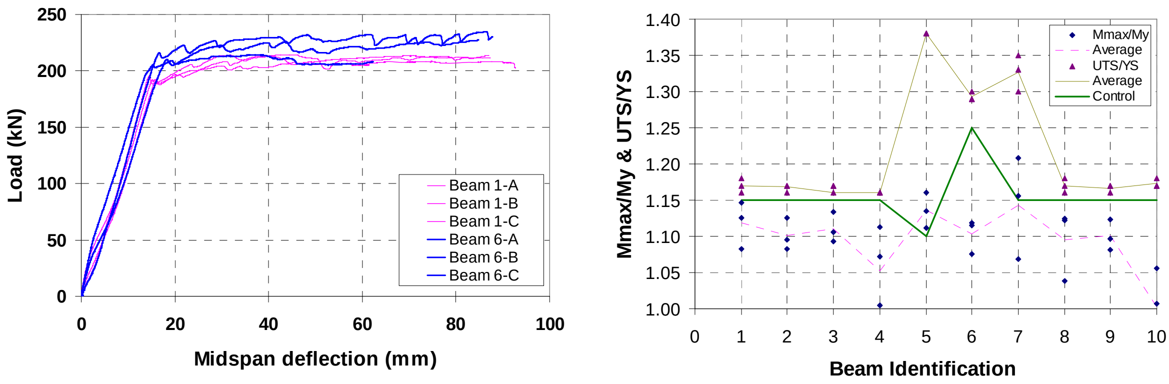
(a) (b)

Figure 4.3 Effect of ‘uncontrolled’ strength properties: (a) CTD rebars (b) Non-standard TMT bars

The non-standard TMT bars manufactured with poor quality control have yield strengths often below the minimum specified value. Use of such reinforcing bar results in lower strength than expected design values and may result in unsafe member/structure. Larger variability observed in their tensile stress-strain curves is also reflected in load-deformation response of beams as shown in Fig. 4.3(b).

4.3 Effect of UTS/YS Ratio

Ensuring a minimum UTS/YS ratio is important as the maximum strength capacity of structural member should be distinct from its yield strength. This helps in realizing the assumed failure mechanism and distributing inelastic activities across various elements of a structure. Typically a higher ratio of 1.25 is preferred over more common 1.15. As shown in Fig. 4.4(a), Beam Set #6 with higher UTS/YS ratio of 1.25 could reach higher peak strength in comparison to control specimens with UTS/YS ratio of 1.15; however, they also had higher yield strength too, which may not be desirable. This response is direct consequence of properties of *Type II* steel rebars which have typically higher actual YS values than *Type I* rebars for the same specified YS value. In Fig. 4.4(b), the ratio of observed maximum moment to yield moment of all beams is compared against UTS/YS ratio of rebars and it is interesting to note that moment ratio is always lower than UTS/YS ratio. Moreover, higher moment ratio was observed with higher UTS/YS ratio rebars. Therefore, it appears that for significantly larger maximum moment from the yield moment, a higher UTS/YS ratio of 1.25 is more suitable. However, such *Type II* rebars have a little disadvantage in terms of increased yield moments.



(a) (b)

Figure 4.4 Effect of UTS/YS ratio on (a) load-deformation behavior, and (b) ration of max. to yield moment

4.4 Effect of Rebar Elongation

Elongation of rebars in beams due to applied loading was difficult to measure. Maximum strains measured by strain gauges placed at mid-span are local strain values and can not be used to estimate the elongation. An indirect method was used to estimate elongation of rebars which is based on the comparing the deformed length of reinforcing bar in the constant moment region to initial length of 900 mm (Rai et al., 2010). This 'uniform' total strain for each beam specimen is shown in Fig. 4.5.

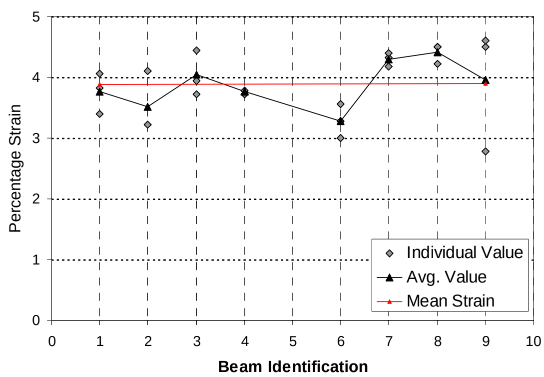


Figure 14. 'Uniform' total strain in bottom rebars at ultimate condition

It is interesting to note that observed elongation values varied from a minimum of 2.78% to a maximum of 4.5% for all beam specimens, with an average value of 3.9%. The localized strain values can be higher than these values. However, it appears that maximum elongation reached in any of the specimens can be easily met by both CTD and TMT bars. Also, the observed demands are smaller than minimum elongation specified by most international codes for reinforcing bars.

5. SUMMARY AND CONCLUSIONS

Based on the experimental observations and data presented in above sections, the following broad conclusions can be drawn:

1. A strict control on YS value of rebars is essential as it determines the strength of member in variosr behavioral modes. If the YS value is greater than the specified value, it may cause premature failure of beam in an undesirable failure mode, such as brittle shear failure instead of more ductile and desirable flexure mode. If YS is lower than the specified value, as observed in the case of non-standard TMT bars, the yield strength will be lower than the expected design value and thus reducing the margin of safety and increasing risk of premature failure.
2. A strict control on UTS value of rebars is also a must. If it is not controlled, the behavior of beam can change rather dramatically to undesirable shear mode of failure, as seen for CTD rebars.
3. A high UTS/YS ratio is necessary to have dependable peak strength greater than the yield value. Beams with standard TMT bars of UTS/YS ratio of 1.25 were better than those with UTS/YS ratio equal to 1.15. However, the rebars with higher UTS/YS ratio had a higher yield strength causing the yield moments to be greater than expected values.
4. Beams with high YS (550 MPa) rebars exhibited similar behavior as low YS (415 MPa) rebars as long as the beam was designed keeping in mind of its effects on other aspects of the beam behavior.
5. Elongation capacity of rebars does not appear to be a significant issue as the observed average maximum demands, about 4%, can be easily met by most reinforcing bars. However, this observation is based on crude estimation of elongation which needs to be further substantiated.
6. The results of this study also demonstrate the inadequacy of the IS 1786 (BIS, 2008) specifications as it has no provisions to control higher values of YS, minimum UTS/YS ratio, an upper limit of UTS to limit overstrength and higher uniform elongation to prevent premature fracture.

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