Fire resistance of locally produced 500W structural steel bars

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Abstract. Steel has been used for many decades in structural applications because of its good combination of mechanical properties. In recent years in Bangladesh the demand for TMT 500W steel bars has increased profoundly, for its higher strength and good ductility. But fire remains one of the serious potential risks to most buildings and structures. To understand the effect of fire on mechanical properties of steel bars at elevated temperature a locally produced 500W TMT bar of 8 mm diameter has been investigated. Both macroscopy and microscopy were carried out to reveal different zones such as hardened case, soft core and transition zone in the cross-section and microstructure respectively of the steel bars in the as received condition. Finally, high temperature tensile tests were conducted at 500°C, 600°C, 650°C in steady state method at a strain rate of 0.5mm/min and the results at these 3 temperatures were noted. Data generated from the room temperature and high temperature tensile tests were compared. The test results demonstrated that the high temperature severely degrades the tensile strength of the 500W TMT steel bars and they can hardly bear any load at temperature above 600°C.

Keywords: TMT steel bar, Fire resistance, High temperature mechanical properties, Coefficient of reduction

1. Introduction

Concrete is a weak material in tension and cracks when the principle tensile stress exceeds its tensile strength. Consequently, concrete is reinforced to enable it to resist these stresses. Steel is the most popular reinforcement in concrete for its excellent mechanical properties. High strength structural steel (HSSS) usually refers to steels with nominal yield strength not less than 460 MPa. Compared with conventional mild structural steel, the application of HSSS could reduce the total steel consumption and emission of carbon dioxide in building industry.

Steel has excellent strength properties at ambient temperature, however, like other materials; steel loses its strength and stiffness with temperature. The yield strength of steel is reduced to about half at 550°C. At 1000 °C, the yield strength is 10 percent or less [1]. Near-total depletion of stress occurs at approximately 1,204°C [2]. Because of its high thermal conductivity, the temperature of unprotected internal steelwork normally will vary little from that of the fire [1]. Young’s Modulus does not decrease with temperature as rapidly as does yield strength [1].

If the duration and the intensity of the fire are large enough, the load bearing resistance can fall to the level of the applied load resulting in the collapse of the structure [3]. Thus, load bearing of steel decreases...
when steel or composite structure is subjected to a continuous fire action. However, the failure of the World Trade Centre on 11th September 2001 and, in particular, of building WTC7 alerted the engineering profession to the possibility of connection failure under fire conditions [4]. The structural response of buildings to fire conditions has been the focus of intensive research activity in recent years. For composite steel/concrete buildings, this has been driven by the motivation to achieve more cost-effective designs and, more generally, by the need to attain a greater understanding of the underlying behavioural mechanisms that occur in fire.

Although sufficient data on the elevated temperature properties of concrete exist in the literature, the studies related to elevated temperature properties of steel bars are limited [5] which emphasises the need of more investigative work in this area. This paper presents the results of experimental testing which was conducted on the steel bars available in the local market in Bangladesh to determine their properties at high temperatures. The data of chemical composition, yield and tensile strength and strain and elongation of the tested bars are compared and the differences are discussed.

The presented data are essential to develop realistic models of the capacity of fire exposed buildings to the applied loads. The presented study is unique in its nature in that there is no published contribution to date (to the best of authors’ knowledge) which has been carried out to assess the temperature dependent mechanical properties of steel bars available in Bangladesh. The parameters of the study included the local 500W rebar brands and heating temperatures.

2. Experimental

2.1 Samples

3 local brands of 500WTMT of same diameter of 8 mm as raw material. The samples were marked as Sample 1, 2 and 3. The samples of necessary sizes were cut from them for composition, tensile and metallographic and high temperature tests.

2.2 Composition Test

Three samples of about 150 mm were cut, each being of separate brand. Finally, they were tested on Optical Emission Spectroscopy (OES) and chemical composition was determined.

2.3 Tensile Test

Three samples of about 260 mm were cut from each brands of rebar. 200 mm was selected as gauge length for each of the sample. Each sample was then weighed on weight taking machine and density was assumed as 7.8 gm /cc. Then from the equation given below, diameter for each of the sample measured. The samples were subjected to tensile test in UH-500kN SHIMADZU, tensile testing machine and after the test the two detached parts of each of the tested sample were placed in contact in the fractured portions to measure the change in gauge length, thereby to measure the % elongation. From the machine data, stress vs strain graph was plotted in excel for each sample.

2.4 High temperature Tensile Test

For high temperature tensile test 3 samples of about 180mm length was cut from each brand of rebar. Then each rebar sample was made plate at each corner for holding in high temperature machine and 80mm length at the centre was selected as gauge length. In the machine test specimen was heated by the oven up-to the maximum expected temperature. Then the specimen was held at that temperature for a particular time (15 minutes). For my experiment the high temperature tensile tests were carried out at 500°C, 600°C and 650°C temperatures in steady state method with a constant strain rate of 0.5mm/min.
3. Results and discussion

3.1 Composition of the as received samples

The following composition data were obtained in OES spectroscopy for the 3 samples:

**Table 1: Chemical Compositions of re-bars**

| Sample | Element proportion (%) | Fe   | C    | Si   | Mn   | P    | S    | Cr   | Mo   | V    | Nb   | Cu   |
|--------|-------------------------|------|------|------|------|------|------|------|------|------|------|------|
| 1      |                         | 98.46| 0.21 | 0.19 | 0.71 | 0.01 | 0.02 | 0.08 | 0.011| 0.002| 0.001| 0.22 |
| 2      |                         | 98.60| 0.244| 0.25 | 0.81 | 0.008| 0.02 | 0.01 | 0.002| 0.001| 0.002| 0.001|
| 3      |                         | 98.60| 0.24 | 0.20 | 0.81 | 0.03 | 0.01 | 0.01 | 0.002| 0.001| 0.001| 0.001|

The chemical analysis of the as received bars of all 3 samples was carried out by spectroscopy. These data of chemical composition of reinforcing bars may become helpful in explaining changes that take place in steel at high temperatures. About 30 elements were identified using OES machine. Of these, C, Mn, P, Cr, Ti and Co are the important elements which have a direct influence on strength, ductility and hardenability of steel. The proportions of the aforementioned elements in the control specimens are given in Table 1.

Carbon is the principal element which provides both strength and ductility to steel. [6-9]. According to ASTM A706 maximum carbon percentage in structural steel is 0.18%. All 3 sample we tested has greater carbon percentage which is the main reason for their greater strength. Manganese (Mn) was found to be in the range of 0.71-0.81 which is well within the range of ASTM A706 standard of 1.60% (maximum). The higher Mn content may partly responsible for better ductility of the samples. Phosphorus contents in steel are limited to a maximum .04 as higher phosphorus affects steels ductility [7]. It is noted in Table 1, that phosphorus contents in the bars comply with the requirements given in the respective standards. Addition of niobium up to 0.025 percent [8][10] enhances strength without any loss of ductility. The addition of 0.3-0.5 percent [9] copper improves strength and corrosion resistance of steel. Again the addition of sulphur is detrimental to the mechanical properties. The amount of Nb, Cu, S is well within the standards and are very small to have any significant effect on the steel properties. Molybdenum (0.04-0.06 per cent) [9-10] can increase elevated temperature strength and corrosion resistance of steel. But molybdenum in the TMT bars is significantly less than the recommended proportion in the above.

3.2 Mechanical Properties

The mechanical properties of all 3 samples at deferent temperatures and there change with temperature are shown from table 2-6.

**Table 2: Mechanical properties of Sample 1 different temperatures**

| Temperature(°C) | Yield Strength (in MPa) | UTS (in MPa) | Young’s Modulus (in MPa) | % Elongation |
|-----------------|-------------------------|--------------|--------------------------|--------------|
| 25              | 526.35                  | 609.3        | 210.52                   | 12.6         |
| 500             | 265                     | 303.2        | 51.96                    | 16.3         |
| 600             | 102.1                   | 109.5        | 40.3                     | 22.7         |
| 650             | 70                      | 72.3         | 35                       | 27.1         |
Table 3: Mechanical properties of Sample 2 different temperatures

| Temperature(°C) | Yield Strength (in MPa) | UTS (in MPa) | Young’s Modulus (in MPa) | % Elongation |
|----------------|-------------------------|--------------|--------------------------|--------------|
| 25             | 562.17                  | 671.7        | 151.94                   | 13           |
| 500            | 202                     | 221.2        | 57.77                    | 14.1         |
| 600            | 120                     | 147.44       | 46.1                     | 21           |
| 650            | 85.6                    | 88           | 42.8                     | 23.6         |

Table 4: Mechanical properties of Sample 3 different temperatures

| Temperature(°C) | Yield Strength (in MPa) | UTS (in MPa) | Young’s Modulus (in MPa) | % Elongation |
|----------------|-------------------------|--------------|--------------------------|--------------|
| 25             | 590.8                   | 703.6        | 252.17                   | 11.4         |
| 500            | 175                     | 322.3        | 76.1                     | 16.4         |
| 600            | 77                      | 98           | 48                       | 27.4         |
| 650            | 88                      | 89           | 44                       | 38.1         |

Table 5: Average Mechanical properties of all 3 samples at different temperatures

| Temperature(°C) | Average Yield Strength (in MPa) | Average UTS (in MPa) | Average Young’s Modulus (in MPa) | Average Elongation (in percentage) |
|----------------|---------------------------------|----------------------|----------------------------------|----------------------------------|
| 25             | 559.77                          | 661.33               | 204.88                           | 12.33                            |
| 500            | 214                             | 282.23               | 61.94                            | 15.6                             |
| 600            | 99.73                           | 118.31               | 44.82                            | 23.7                             |
| 650            | 81.2                            | 83.1                 | 40.6                             | 29.6                             |

Table 6: Percentage change of mechanical properties of all 3 samples at elevated temperature compared to room temperature

| Temperature(°C) | Reduction in Percentage Yield Strength (%) | UTS (%) | Young’s Modulus (%) | Elongation (%) |
|----------------|--------------------------------------------|---------|---------------------|----------------|
| 500            | 61.77                                      | 57.32   | 69.77               | 26.52          |
| 600            | 82.2                                       | 82.1    | 78.12               | 92.91          |
| 650            | 85.5                                       | 87.45   | 80.21               | 140.1          |

Figure 1 shows the stress versus strain curve for samples at high temperatures. The curves for as received samples are also shown for comparison purposes. No strain hardening is observed for the samples at high temperatures like for samples at ambient (25°C).
Figure 1. Stress vs Strain curves of tested rebars at elevated temperatures; (a) Sample 1, (b) Sample 2 and (c) Sample 3

3.3 Yield Strength

Figure 1 shows yield plateau for all three samples tested at room temperature. However, the yield plateau has disappeared at temperatures 500°C, 600°C and 650°C. Moreover, in Figure 2(b), the yield strengths of all the samples decreased with increasing temperature. The reduction of yield strength occurs because of requiring reduced level of energy for movement of dislocation at high temperatures [1]. Figure 3 (b) illustrates the normalised yield strength (ratio of yield strength at high and room temperatures for a certain sample) which represents the coefficient for the reduction of yield strength. This is also called the reduction factor. The high temperature yield strength can be calculated by multiplying coefficient with the yield strength at room temperature. It is seen in Figure 3(b) that “Reduction Factor” is similar for all the three types of bars used in this study. Bar yield strength becomes nearly 15% yield strength at room temperature at 650°C.
3.4 *Ultimate tensile strength*

The ultimate capacity of the bar corresponds to maximum stress on the rebar stress–strain curve. Distinct differences in the behaviours of the bars in the strain hardening region are seen in Figure 1. Strain hardening in the bars became negligible after 500°C. Figure 3(a) illustrates the normalised ultimate strength ratio of ultimate strength at high and room temperatures for a certain sample, which is the coefficient for the reduction or reduction factor of rebars ultimate strength. It is seen in Figure 3(a) that the curves for reduction factor of UTS follow a pattern similar to reduction factor of YS.
3.5 Modulus of Elasticity

The elastic modulus of the bar at elevated temperature was calculated as tangent modulus of the initial linear elastic part of the stress–strain curve (Figure 2). Figure 3(a) illustrates the coefficient for the reduction or reduction for of re-bars elastic modulus which has been calculated as the ratio of modulus at high and room temperatures. The reduction of modulus from 500°C to 650°C is more rapid for sample 2 and 3 than sample 1.

3.6 Rebar ductility

Ductility is often represented with percentage of elongation. From Figure 2 (c) the relationship between temperature and percentage of elongation can be observed. It has increased with increasing temperature for sample 1, 2 and 3 which characterises ductile behaviour of these bars at high temperatures. However, percentage of elongation had decreased for sample 1 when temperature was increased from 600°C to 650°C. The maximum ductility for sample 3 increased much higher than normal ductility at 650°C which was about 38%.

4. Conclusion

In this study we observed that the Yield strength, Tensile strength, Young’s modulus of the re-bars decreased as the heating temperature increased (up-to 650°C). The weakening of the mechanical properties is very stiff after 500°C. The ductility or percentage of elongation for all 3 samples has increased profoundly with temperature and up to 38%. So the samples have become highly ductile at around fire temperatures. It has been clearly observed that the samples lost ~62% yield strength and ~57% UTS at 500°C, whereas, at 650°C they lost almost all of their load bearing capability (~87% of UTS). So, it is clear that these local brands of 500W can hardly bear any load at temperature above 600°C. So, if these rods are used in concrete structures, they will be very vulnerable when exposed to extreme fire condition.

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6. Reference

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