Construction and Building Materials 46 (2013) 19–27

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Effect of temperature on mechanical properties of pre-damaged steel reinforcing bars

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HIGHLIGHTS

- This research establishes residual stress–strain behaviour of heated pre-damaged reinforcing bars.
- The outcome shall help in evaluating the residual capacity of concrete structures exposed to post earthquake fire.
- The elevated temperature had more detrimental influence than the mechanical pre-damage level.

ARTICLE INFO

Article history:
Received 20 July 2012
Received in revised form 14 February 2013
Accepted 18 March 2013
Available online 11 May 2013

Keywords:
Pre-damage level
Elevated temperature
Post-earthquake fire
Residual mechanical properties
Fire-following-earthquake scenario

ABSTRACT

The effect of simulated earthquake-induced damage on the residual mechanical properties of steel bars exposed to elevated temperatures are reported towards understanding the behaviour of such bars in a fire-following-earthquake scenario. Earthquake damage was simulated by inducing two levels of tensile strains in the rebars corresponding to the desired levels of pre-damage. Subsequently, the pre-damaged rebars were tested for residual strength in tension after exposure to a single cycle of heating and cooling for different target temperatures ranging from room temperature to 800 °C. The other variables in the investigation were: yield strength, rebar diameter and the rebar manufacturing process (cold-worked or thermo-mechanically treated). It was observed across all the rebars of this study that the selected pre-damage levels had practically no influence on residual mechanical properties and the effect of heating the rebars was significant only for temperatures greater than or equal to 400 °C. The findings of this investigation have implications for prediction of residual capacity of reinforced concrete structures exposed to fire-following-earthquake scenarios.

1. Introduction

Fire remains one of the serious potential hazards to most buildings and structures. Since concrete in combination with steel reinforcement is one of the most widely used construction materials, the behaviour of reinforced concrete structures in fire deserves attention. The response of a reinforced concrete structure to fire is governed by the properties of the constituent materials viz. concrete and steel, at elevated temperature. Although the effect of temperature on residual mechanical properties of steel reinforcement has been extensively investigated in the past [1–12], information is lacking on the effect of temperature on residual mechanical properties of steel reinforcing bars *which may already have experienced some degree of straining (pre-damage) before exposure to elevated temperature.*

Post earthquake fires (PEFs) are a significant threat to modern urban infrastructure and current design codes do not have provisions for designing structures against such events. Unless specially designed, it is very unlikely for a conventionally designed reinforced concrete structure to withstand a fire following an earthquake due to severe damage and deformation which may have been caused by the earthquake in the first place. Further, after a typical fire-following-earthquake event, it is generally required to evaluate the residual capacity of the structure to enable a suitable retrofitting strategy to be proposed. In either of these scenarios, it is imperative to assess the residual properties of the constituent materials of reinforced concrete, particularly of steel bars, for determining the load carrying capacity of the structure.

In a typical fire-earthquake multi-hazard scenario, the behaviour of steel rebars exposed to fire will be significantly affected by the degree of (*pre*) damage sustained by the rebars under earthquake loading. *Although mechanical behaviour in the heated state and the residual behaviour of steel bars has been extensively investigated, the residual behaviour of pre-damaged steel bars has not received the attention it deserves. This investigation has been carried out towards addressing this gap in the literature.* To *simulate* the effect of *sequential* earthquake and fire loading *on steel bars in a typical*

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0950-0618/$ - see front matter
http://dx.doi.org/10.1016/j.conbuildmat.2013.03.051

Nomenclature

f_y	yield strength of steel bars at room temperature
f_{yTd}	residual yield strength of pre-damaged steel bars after exposed temperature
f_u	residual ultimate strength of steel bars at room temperature
f_{uTd}	residual ultimate strength of pre-damaged steel bars after exposed temperature
ε_u	residual ultimate strain of steel bars at room temperature
ε_{u5}	5% tensile strain (termed as usable strain) of steel bars at room temperature
ε_{uTd}	residual ultimate strain of pre-damaged steel bars after exposed temperature
ε_y	yield strain of steel bars at room temperature
E	elastic modulus of steel bars at room temperature
U	toughness of steel bars at room temperature
A	rebar without initial damage
B	rebar with first level initial pre-damage
C	rebar with second level initial pre-damage
T	exposed temperature (°C)

reinforced concrete element, the following methodology was adopted: *In the first phase of the experimentation,* the steel rebar specimens were pre-damaged whereby residual pre-defined strains were intentionally induced in the rebars to simulate the effect of earthquake loading. Subsequently, the pre-damaged rebars were exposed to a single cycle of heating and cooling representing various fire scenarios and then tested to failure in tension so as to determine the residual mechanical properties. The details of the experiments, the test results and their analysis are presented *and discussed* in this investigation.

2. Experimental programme

Amongst the various parameters under consideration, the effect of manufacturing process on the behaviour of the steel bars was investigated by testing rebars rolled using the following two methods: (i) Cold working; (ii) thermo-mechanical treatment (TMT). The cold-worked (CW) bars were of relatively smaller diameters and were commercially produced by a process which involves stretching and unloading steel billets at room temperature. Thermo-mechanical treatment (TMT) of steel is an advanced heat treatment process involving controlled quenching of hot-rolled steel bars. The chemical composition of the CW and TMT bars is given in Table 1. While the CW bars were of one-grade (high strength, with minimum yield strength of 1000 MPa), the TMT bars were of grades Fe 415 and Fe 500 per the Indian standard IS 1786: 2008 [13]. The nominal diameter of the CW bars was 6 mm whereas the TMT bars were of nominal diameters 8 and 10 mm.

The test bars have been identified with a four letter identification system where the letter in the first place holder represents the manufacturing process and the grade of steel with the letter *H* representing cold-worked high strength steel bars, the letter *D* stands for TMT bars of grade Fe 500 and the letter *T* represents TMT bars of grade Fe 415. The numeral (6, 8 or 10) in the second place holder of the rebar identification stands for the nominal rebar diameter and the letter (*A*, *B* or *C*) in the third place holder shows the level of pre-damage. Finally, the numeral in the last place holder stands for the exposure temperature (2 for 200 °C, 4 for 400 °C, 6 for 600 °C and 8 for 800 °C). In the pre-damage classification, '*A*' represents an undamaged state and the damage states '*B*' and '*C*' were defined in terms of strains obtained from the stress–strain relationships of the rebars measured at ambient conditions.

In the pre-damage classification, '*A*' represents undamaged state and the pre-damage states '*B*' and '*C*' were defined in terms of strains derived from the stress–strain relationships of the rebars measured at ambient conditions. A typical stress–strain curve obtained under ambient conditions for a 10 mm diameter TMT reinforcement bar of Fe 415 grade and taken as the average of the measured stress–strain relationships of three nominally identical companion specimens is presented in Fig. 1 wherein the yield strain (ε_y) and 5% strain (ε_{u5}) level, which is the maximum tensile strain or usable strain to be used in structural design per FEMA 356

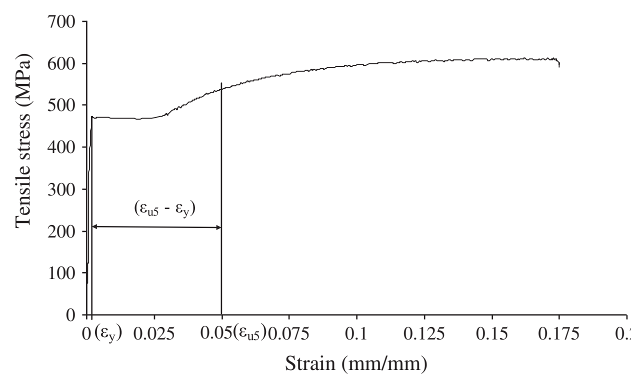

Fig. 1. Measured stress–strain relationship of a 10 mm diameter Fe 415 grade TMT bar.

[13], is identified. The pre-damage levels are explained with reference to Fig. 1. The pre-damage state '*B*' corresponds to a strain value equal to the yield strain (ε_y) plus 25% of the difference between the yield strain (ε_y) and the usable strain (ε_{u5}), see Fig. 1 for typical values of ε_y and ε_{u5}. The strain corresponding to pre-damage state '*C*' was taken equal to the yield strain plus 50% of the difference between the usable and the yield strain. The strain increments of 25% and 50% were arbitrarily selected on the basis of good design practice. It was reasoned that though theoretically a strain increment of 100% was admissible per FEMA 356 [14] the strain values corresponding to such a strain increment would be associated with unduly high levels of distress in the concrete section which would be an impractical scenario. Hence, strain increments of 25% and 50% were considered suitable for defining the pre-damage levels. Therefore, for each type (CW/TMT) and rebar diameter (6/8/10 mm) the pre-damage states were first defined from the measured stress–strain relationship in axial tension obtained under ambient conditions. Subsequently, every rebar was subjected to the defined pre-damage state by straining it under axial tension in an U.T.M. followed by exposure to the desired elevated temperature. Following this, the rebars were allowed to naturally cool to ambient conditions and then again subjected to an axial tensile test to evaluate the residual mechanical properties.

A summary of mechanical properties derived from the measured stress–strain relationship of the undamaged rebars at ambient temperature is presented in Table 2. The parameter '*U*' in column 9 of Table 2 is the modulus of toughness which is a measure of the total energy absorption capacity of the material. This parameter is important in selecting materials for application where high overloads are likely to occur and large amounts of energy must be absorbed. The modulus of toughness was evaluated as the total area under the stress–strain curve expressed as:

Table 1
Chemical composition (%) of the steel reinforcing bars.

Bar type/grade/diameter	C	Si	Mn	P	S	Cr	Ni
Cold work/high strength/6 mm	0.169	0.199	0.642	0.071	0.030	0.043	0.166
TMT/Fe 500/8 mm	0.227	0.150	0.945	0.013	0.014	0.188	0.248
TMT/Fe 500/10 mm	0.236	0.126	0.948	0.018	0.018	0.053	0.248
TMT/Fe 415/8 mm	0.344	0.206	0.609	0.070	0.050	0.025	0.206
TMT/Fe 415/10 mm	0.303	0.180	0.781	0.092	0.036	0.026	0.236