Construction and Building Materials 148 (2017) 344–358

Contents lists available at ScienceDirect

Construction and Building Materials

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

Bond properties for deformed steel bar in frost-damaged concrete under monotonic and reversed cyclic loading

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HIGHLIGHTS

- Bond properties for deformed steel bar in frost-damaged concrete were tested.
- Effect of freezing-and-thawing cycles on the bond response indications were analyzed.
- The new bond stress-slip models for deformed steel bar in frost-damaged concrete were presented.

ARTICLE INFO

Article history:
Received 8 February 2017
Received in revised form 4 May 2017
Accepted 8 May 2017
Available online 13 May 2017

Keywords:
Bond properties
Deformed steel bar
Concrete
Freezing-and-thawing
Monotonic and reversed cyclic loading

ABSTRACT

This study presented a systemic research to investigate the bond properties for deformed steel bar in frost-damaged concrete under monotonic and reversed cyclic loading. Specimens of three kinds of concrete strength grade and four kinds of frost damage level were tested and the primary bond response indications were analyzed. Results showed that accompanied by the increasing number of freezing-and-thawing cycles, the initial bond stiffness, the maximum bond resistance and the remaining bond strength decreased whereas the slip at peak bond stress increased, moreover, the progressive acceleration of bond stiffness degeneration as well as the more obvious bond strength decay and the worse energy dissipation capacity were also observed for the specimens of the same concrete strength grade. Results also indicated that with regard to the specimens exposed to the same freezing-and-thawing cycles, the initial bond stiffness, the slip at peak bond stress, the maximum bond resistance and the remaining bond strength increased with the increasing concrete strength grade. Thereafter, the analytical local bond stress-slip models for deformed steel bar in frost-damaged concrete under monotonic and reversed cyclic loading were presented to reproduce the bond degradation caused by loading and freezing-and-thawing.

1. Introduction

Concrete structures in service are subjected to not only mechanical loads but also physical and chemical environmental actions. Frost damage, which resulted from the volume expansion of frozen water in the interior pore structure [1], is one of the typically physical and chemical environmental actions for the concrete structures in the north China [2]. Freezing and thawing induced variation which consists of the deterioration of mechanical properties of concrete and bond performance of concrete-rebar interface caused the degradation of load carrying capacity [3–8] and seismic performance [9] for the reinforced concrete structures. The seismic performance indexes for the reinforced concrete columns with different levels of frost damage were compared together within the experimental investigation undertook by Xu et al. [9]. It showed that although the inner frost damage of the concrete was approximately negligible for the specimens which merely subjected to 100 freeze-thaw cycles, the bond property was seriously deteriorated and hence the seismic performance of the specimens was significantly deteriorated. Frost-damage occurs or not mainly depends on the saturation ratio of the internal porosity of concrete and it appeared only when the saturation ratio of the internal porosity reached to a critical value [3]. Considering that the saturation ratio increased from the superficies to the interior parts of structural component and that the thicknesses of concrete cover is always negligible in comparison with the structures' sectional dimension, the freezing and thawing induced degradation of reinforced concrete structures primarily presented as bond loss at the beginning of freeing-and-thawing.

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http://dx.doi.org/10.1016/j.conbuildmat.2017.05.090

Notation

The symbols adopted in this paper are as follows:

FTC	freezing and thawing cycles
RTT	relative transmission time
RDME	relative dynamic modulus of elasticity
RCS	relative compressive strength
δ	bond strength ratio
RBS	ratio of bond strength for the specimens with and without frost damage
RSPBS	ratio of slip at peak bond stress for the specimens with and without frost damage
t_n	transmission time for the specimens subjected to n freezing-and-thawing cycles
t_0	transmission time for the specimens without freezing-and-thawing exposure
τ_u,τ_{rM}	maximum bond resistance and remaining bond strength of specimens under monotonic loading, respectively
S_u	slip at peak bond stress
S_r	transverse rib spacing of the rebar
S_n, S_0	arbitrary unloading slip and first unloading slip, respectively
τ_u^+, τ_u^-	maximum bond resistance in tension and compression direction, respectively
τ_{rR}^+, τ_{rR}^-	remaining bond resistance in tension and compression direction, respectively
τ_{rR}	average value of remaining bond resistance in tension and compression direction
τ_{f0}, τ_{fr}	initial reversal bond resistance and remaining reversal bond resistance, respectively
τ_{fn}	reversal bond resistance corresponding to the arbitrary unloading slip S_n
τ_n, τ_0	bond resistance at slips of S_n and S_0, respectively
E_c, E_{ci}	cumulative energy dissipation and energy dissipated in a single loading cycle, respectively
K_0^d	unloading stiffness
β	bond degradation factor
γ	reversal bond degradation factor
τ_u^d, τ_{rM}^d	maximum bond resistance, and remaining bond strength under monotonic loading for the frost-damaged specimens, respectively
S_u^d	slip at peak bond stress under monotonic loading for the frost-damaged specimens
τ_0^d, τ_{rR}^d	bond resistance at slips of S_0 and remaining bond resistance for the frost-damaged specimens, respectively
τ_{f0}^d, τ_{fr}^d	initial reversal bond resistance and remaining reversal bond resistance for the frost-damaged specimens, respectively

To repair the frost-damaged concrete structures, the performance assessment is becoming more and more urgent and important, and finite element analysis can yet be regarded as a good technique in assessing the effect of frost damage on the load carrying capacity and the seismic performance of reinforced concrete structures [10]. However, the accurate prediction of the nonlinear response for the frost-damaged reinforced concrete structures to static, dynamic and reversing loads using finite element technique is dependent on the knowledge of several complex phenomena such as the mechanical properties of the frost-damaged concrete and the bond properties between steel bars and frost-damaged concrete under monotonic and reversed cyclic loading, etc. [11]. Several researches have been carried out on the mechanical properties of frost-damaged concrete and the mainly conclusions are as follows: accompanied by the increasing number of freezing and thawing cycles (*FTC*), the fracture energy of the frost-damaged concrete increased at first and decreased afterwards [12–14]; the elastic modulus, the compressive strength, the tensile strength and the peak tensile strain under monotonic loading decreased whereas the peak compressive strain and the ultimate compressive strain increased [15–22]; the hysteresis of strain recovery for frost-damaged concrete under reversed cyclic loading is more obvious than that for the undamaged concrete [23]. While only a limited amount of researches have been carried out with the effect of freezing-and-thawing on the bond properties [3,13,18,24–27]. It is generally agreed that the bond resistance of concrete-rebar interface primarily consisted of three components, that is, the cementing force of cement gel, the frictional resistance of concrete-rebar interface and the mechanical interaction between intercostal concrete and transverse rib of steel bar. As for the deformed steel bar, the mechanical interaction which depends on the surface topography of steel bars and the mechanical property of intercostal concrete, is the conclusive constituent of the aforementioned three components [28–30]. Hence, the deterioration of the mechanical properties for the intercostal concrete which caused by freezing-and-thawing is bound to cause the degradation of bond performance. Shih et al. [24] reported that cyclic temperature changes definitely changed the bond strength and the shape of the bond stress-slip curves, the average value of bond factors and the maximum bond resistance decreased with the increasing number of *FTC*. The continuously increase of the slip at peak bond stress, which accompany with the increase of frost damage level quantified by number of *FTC* and(or) relative dynamic modulus of elasticity, has been found within the experiments of Ji [26] and Hanjari et al. [13], by contrast, some slight decrease for the slip at peak bond stress has been experimented by Petersen et al. [3] during the initial freeze-thaw expose of which the internal frost damage was only located in superficial coat of specimen and the area of the reinforcing bar is not reached. Several types of bond stress-slip relationships for the frost-damaged concrete under monotonic loading relating to different damage indicators, such as "relative dynamic modulus of elasticity" [3,13,25] and "number of freeze-thaw cycles" [26], etc., have been proposed. However, to the authors' knowledge, due to the inconformity of surface morphology for the deformed steel bar in different countries and the difference of loading scheme which include monotonic and reversed cyclic loading, et al., the local bond properties, especially for the analytical local bond stress-slip models for the deformed steel bar in frost-damaged concrete under reversed cyclic loading, have not been systematically investigated.

The main purpose of this study is to investigate the bond properties for deformed steel bar in frost-damaged concrete under monotonic and reversed cyclic loading. Specimens of three kinds of concrete strength grade and four kinds of frost damage level were tested. The primary bond response indications which consist of the characteristic value of bond property, feature of bond stress-slip hysteretic, (reversal) bond degradation ratio, and cumulative energy dissipation were analyzed, moreover, the concrete strength grades and the number of *FTC* were the main factors to be considered. In addition, the analytical local bond stress-slip models of deformed steel bar in frost-damaged concrete under monotonic and reversed cyclic loading were also proposed.