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Influence of service temperature and strain rate on the bond performance of CFRP reinforcement in concrete

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ABSTRACT

Bond of FRP reinforcement is expected to be more sensitive to temperature and rate of loading than conventional steel reinforcement. Present paper introduces experimental results on Carbon Fiber Reinforced Polymer (CFRP) wires of sand coated surface tested by pull-out tests in a multi-parameter laboratory test programme. In the experimental programme low, normal and high strength concretes, −25 °C, +20 °C and +65 °C testing temperatures, and static to impact loads were applied for the pull-out tests (with an order of 1000 in the increase of the rate of loading). Results indicate that the bond strength of the tested CFRP wires follows the change of temperature in a more pronounced manner than the concrete compressive strength does. A viscous-elastic, load rate dependent behavior can be realized in the bond response of the CFRP wires studied. Failure of bond is different for different concrete strengths, testing temperatures and loading rates. Results also indicate that the mathematical functions that are used for the modeling of bond of conventional steel reinforcements are not optimal for the CFRP wires studied.

1. Introduction

Structural behavior of reinforced concrete considerably depends on the bond between concrete and reinforcement [1–5]. Bond (or special anchoring) can provide the load carrying action of the components as composite material (i.e., reinforced concrete). Bond influences the flexural, shear and torsion capacity of concrete members and has principal influence on serviceability performance (cracking and deformations) [6–9]. Tension stiffening can be directly derived from bond analysis, i.e., from the solution of the differential equation of bond–slip [10–12]. Anchorage lengths and transfer lengths of reinforced and prestressed concrete members can be determined by bond analysis as well.

Bond of reinforcement in concrete is usually represented with the bond stress vs. slip (τ_b–s) response (Fig. 1) that is the result of the pull-out tests [13–17]. Bond is a combination of multiple mechanisms that are activated at different load/deformation levels of concrete: (1) resistance given by adhesion at zero slip, (2) resistance given by mechanical interlock at increasing slip, (3) resistance given by friction during pull-out failure (conditions when slip exceeds that of corresponds to the bond strength) [18]. Failure of bond for steel reinforcement is always pull-out failure if splitting is prevented (with sufficient concrete cover or stirrups). During pull-out, shearing of the concrete occurs between the ribs of the reinforcement and failure of the steel surface is never formed [19].

Fiber Reinforced Polymer (FRP) reinforcements can be applied to avoid corrosion of reinforcement in concrete [20–24]. Bond behavior and failure of bond can be different from that of steel reinforcement due to the different surface configurations of FRP reinforcements [13,19]. During pull-out failure of FRP reinforcements, the outer layers (periodic ribs, helical wrapping, indentations, etc.) may be damaged. The bond strength of FRP reinforcements is, therefore, governed not only by the mechanical properties of concrete but the mechanical properties of the FRP reinforcements as well. Deformation capacity of the surface texture of FRP reinforcements influences slips both at bond strength and during pull-out failure. One special surface texture of FRP reinforcements is *sand coated surface* that results considerably increased adhesion resistance, but also, bond strength is provided at limited slip. For FRP reinforcements with sand coated surface, residual bond strength is utilized mainly by friction that is expected to be less pronounced than that of conventional steel reinforcement, due to the differences between the surface roughness of the peeled-off sand coating of FRP reinforcement and the sheared-off concrete between the ribs of the steel reinforcement.

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Notations

a_i	empirical parameter
b_i	empirical parameter
c_{min}	minimum concrete cover
D_{max}	maximum size of aggregate
$f_{ci,imp}$	individual compressive strength of concrete under dynamic loading
$f_{ci,stat}$	individual compressive strength of concrete under static loading
f_{cm}	mean compressive strength of concrete
$f_{cm,imp}$	mean compressive strength of concrete under dynamic loading
$f_{cm,stat}$	mean compressive strength of concrete under static loading
s	slip
T_g	glass transition temperature
$\dot{\varepsilon}$	strain rate
$\dot{\varepsilon}_{imp}$	strain rate of dynamic loading
$\dot{\varepsilon}_{stat}$	strain rate of static loading
τ_b	bond stress
τ_b^*	characterizing parameters of the τ_b–s diagrams
$\tau_{b,max}$	bond strength
τ_{br}	residual bond strength
$d\tau_b/ds$	bond stiffness (initial slope of the τ_b–s diagram)

2. Research significance

Typical service temperature of concrete structures is in the range of −25 °C to +65 °C. Compressive and tensile strength of concrete is influenced by this temperature range [25–27]. FRP reinforcements are rich in polymer resin at their surface layers. Glass transition temperature (T_g) of polymer resins is in the range of +60 °C to +180 °C. Polymer resins are brittle under T_g temperatures and losing strength and stiffness rapidly over T_g temperatures. Influence of service temperature on bond of FRP reinforcements is more considerable than that of conventional steel reinforcements.

Concrete, but especially polymer resins, are viscous-elastic materials [28–34]. Their structural response is more viscous at low strain rates and more elastic (brittle) at high strain rates. Long term loading generates considerable creep of both materials. The viscous-elastic behavior is remarkable during pull-out bond testing at different strain rates.

Service loads of different strain rates and load intensities act on structural concrete elements at different temperatures (additionally to the long term dead loads). Test results obtained at room temperature and under static loading can be used, therefore, with limited accuracy to model the real performance of FRP reinforced structures. The analysis of the influence of combined experimental parameters may provide better estimate of the real behavior. Aim of present tests is to study the bond performance of sand coated CFRP wires under the combined influence of strain rate and service temperature.

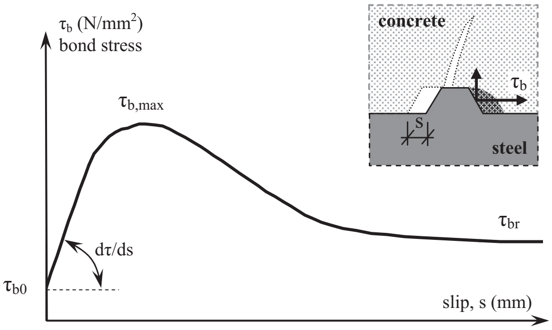

Fig. 1. Schematic bond stress (τ_b) vs. slip (s) diagrams for deformed steel reinforcements.

3. Materials and methods

The experimental programme was completed in the testing laboratory of Budapest University of Technology and Economics (BME), Dept. of Construction Materials and Engineering Geology. Nominal diameter Ø5 mm sand coated CFRP wires (CarbonStress® AS, manufactured by Nedri Spanstaal BV) were used for the laboratory tests. Material properties according to the manufacturer (not tested during the experimental programme at BME) are [35]:

Tensile strength:	2700 N/mm^2
Tensile modulus:	155–165 kN/mm^2 (depends on fiber content)
Ultimate strain:	1.7%
Poisson's ratio:	0.3
CTE:	Longitudinal: +0.2 × 10^{-6} 1/°C Transverse: +23 × 10^{-6} 1/°C

Glass transition temperature (T_g) of the resin of the CFRP wires used was found to be T_g = 121–125 °C [36]. Fig. 2 indicates the results of own differential thermal analyses that confirm the literature findings.

Normal weight concretes were mixed from Danube sand and gravel (MSA, D_{max} = 16 mm) with CEM II/A-S 42.5 (EN 197-1) with targeted mean cube strength of 30, 50 and 70 MPa, respectively. Consistency of each mix was set by water reducing admixture to reach 500 ± 20 mm flow. Design air content of the compacted fresh concretes was 1.0 V%. The specimens were cast into steel

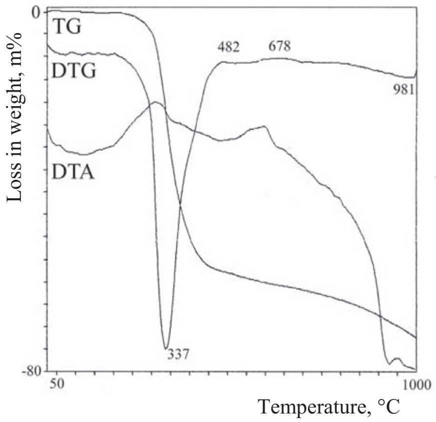

Fig. 2. Results of differential thermal analysis of the CFRP wires used.