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ScienceDirect

Cement & Concrete Composites 28 (2006) 928–937

Cement & Concrete Composites

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FRP confined concrete columns: Behaviour under extreme conditions

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Abstract

The behaviour of concrete columns wrapped with fibre reinforced polymer (FRP) materials when exposed to several extreme conditions is evaluated. Cold regions environments, FRP repair of corroding reinforced concrete columns, and fire resistance are all considered. For the cold regions exposure, FRP wrapped cylinders (152 × 305 mm) are exposed to temperatures as low as −40 °C or to up to 300 cycles of freeze-thaw (−18 °C to +15 °C). The combination of freeze-thaw exposure with sustained loading is also examined. For FRP wrapping of corroding reinforced concrete columns, the results of tests on cylinders and larger-scale circular columns (300 × 1200 mm) are presented. The specimens are corroded and then wrapped with FRP sheets. The rate of corrosion is monitored both before and after wrapping. The final extreme condition that is considered is fire exposure. Tests on full-scale reinforced concrete columns (400 × 3800 mm) exposed to a standard fire are described and discussed. Overall, the results demonstrate that FRP confined concrete columns tested in concentric axial compression have adequate performance under several extreme conditions such as low temperature, freeze-thaw action, corrosion of internal reinforcement, and fire exposure.

Keywords: Fibre reinforced polymers; Concrete; Cold regions; Freeze-thaw; Low temperature; Corrosion; Columns; Fire endurance; Repair; Rehabilitation; Strengthening

1. Introduction

Fibre reinforced polymer (FRP) materials are increasingly being applied for the rehabilitation and strengthening of reinforced concrete structures. The potential market for such applications is huge since the estimated annual cost of repairing bridges in the United States alone is 9.4 billion dollars [1]. One popular technique of FRP strengthening is the wrapping of reinforced concrete columns to increase their axial strength, shear strength, and seismic resistance. In this application, the FRP sheets are generally wrapped around the columns with fibres oriented mainly in the circumferential direction. The fibres confine the concrete and increase the axial strength by creating a triaxial stress condition. The FRP wraps also increase the shear resistance of columns and prevent premature spalling failures when columns are subjected to lateral loadings typical of those observed during earthquakes. In the current paper, the focus is on applications where FRP wraps are used to increase the axial strength of the columns.

Such FRP wrapped columns may be subject to harsh conditions during their service life. In cold regions, column repairs for bridges and exterior parking structures will be exposed to temperature extremes, freeze-thaw cycles, and potential corrosion due to de-icing salts. In interior building applications, FRP wrapped columns may be subjected to fire and thus wrapped columns must be able to maintain strength and integrity for a reasonable period during the fire to prevent collapse of the structure. This paper will discuss the effects of these extreme conditions on FRP wrapped concrete columns.

This paper considers three main extreme conditions in three separate sections: cold regions, wrapping of corroded reinforced concrete columns, and fire exposure. In each section, short literature surveys are provided and the results of investigations conducted by the authors are discussed. The paper concludes with a section discussing these extreme

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doi:10.1016/j.cemconcomp.2006.07.008

effects and potential interactions if these effects are combined.

2. Cold regions

Two basic effects occur when FRP materials are exposed to cold regions conditions: thermal incompatibility and polymer embrittlement. The first effect is related to the thermal expansion of the constituent materials of FRPs which consist of fibres embedded in a polymer matrix. The coefficients of thermal expansion (CTEs) for fibres typically differ considerably from those of matrices. These thermal incompatibilities can cause internal stresses to develop in the FRP at the fibre–matrix interface. Further, CTE differences can also cause bond issues when the FRP is applied to concrete structures. For column wrapping applications, bond is not a critical issue and thus will not be investigated in this paper.

The other major effect is polymer embrittlement whereby the strength and stiffness of the polymer increases at the lower temperature but the failure mode becomes more brittle. The increased stiffness may also reduce the effectiveness of the matrix to transfer stresses between fibres, or between the composite and the substrate concrete.

To examine these effects, some limited research has been conducted by other researchers. Karbhari and Eckel [2] tested FRP wrapped cylinders at low temperature (−18 °C) and found increased brittleness of FRP fibres at low temperature. Further work by Karbhari [3] showed strength reductions at low temperature after exposure to freeze-thaw in a saturated condition. Toutanji and Balaguru [4] exposed FRP wrapped concrete cylinders to 300 freeze-thaw cycles. They found some deterioration due to freeze-thaw with carbon FRP (CFRP) performing better than glass FRP (GFRP). Teng et al. [5] compared field evaluation of wrapped FRP columns to laboratory tests of freeze-thaw resistance. They found little deterioration in the field over a period of 2 years but some loss of ductility in wrapped cylinders subjected to large thermal cycles in the laboratory.

2.1. Low temperature

Two separate sets of tests [6,7] investigated the low temperature behaviour of CFRP and GFRP wrapped cylinders (152 × 305 mm). Table 1 presents the manufacturers' specified properties for the sheets used in these tests. In the first set of tests, six cylinders (two plain cylinders, four wrapped with CFRP-A) were kept at −18 °C for 200 days and subsequently tested for strength in axial compression at room temperature. Additionally, nine cylinders (three plain, six wrapped) were kept at room temperature as control specimens. In the second set of tests, 16 cylinders were wrapped with either a single layer of CFRP-B or two layers of GFRP-A. Half of these specimens were exposed to −40 °C for 16 days while the other half were kept at room temperature. In this second set of tests, the cylinders were tested in a frozen state immediately after being removed from the cold room. Table 2 summarizes the results of the tests on the cylinders.

For the first set of tests, the low temperature exposure did not affect the strength of the cylinders wrapped with one layer of CFRP-A. A slight reduction in strength (4 MPa loss) was noted for the specimens with two layers of wrap but this reduction was likely due to experimental scatter rather than to any actual strength loss. For the second set of tests, the wrapped cylinders increased in strength at low temperature by an average of 14%. This strength gain was attributed to freezing of porewater inside the concrete when the cylinders were tested in the frozen state. This effect was not observed in the first set of tests since the cylinders were tested at room temperature.

Table 2
Results from low temperature tests on cylinders [6,7]

Type of wrap	Temperature (°C)	Duration (days)	Average failure stress (MPa)	
			Room temperature	Low temperature
None	−18	200	46	46
One layer Carbon-A	−18	200	53	52
Two layers Carbon-A	−18	200	59	55
None	−40	16	59	
One layer Carbon-B	−40	16	70	80
Two layers Glass-A	−40	16	73	83

Table 1
Properties of FRP products as specified by the manufacturers

Designation	Manufacturer	Modulus per unit width (kN/mm/ply)	Ultimate strength per unit width (kN/mm/ply)	Ultimate strain	Type of matrix
Carbon-A[b]	Mitsubishi	22.4	0.237	0.015	Epoxy
Carbon-B[b]	Fyfe	70.3	0.881	0.013	Epoxy
Carbon-C[a]	Forca-Tonen	25.3	0.383	0.015	Epoxy
Carbon-D[a]	Wabo MBrace	38.0	0.625	0.017	Epoxy
Glass-A[b]	Fyfe	33.8	0.748	0.022	Epoxy
Glass-B[a]	Forca-Tonen	8.8	0.182	0.021	Epoxy

[a] Material properties calculated using fibre area only.

[b] Material properties calculated using total composite area.