Composites Part B 103 (2016) 15–22

Contents lists available at ScienceDirect

Composites Part B

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

Reusable and recyclable nonbonded composite tapes and ropes for concrete columns confinement

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ARTICLE INFO

Article history:
Received 24 May 2016
Received in revised form
15 July 2016
Accepted 4 August 2016
Available online 5 August 2016

Keywords:
Fibres
Recycling
Buckling
Mechanical testing
Seismic strengthening

ABSTRACT

This paper investigates the use and efficiency of structural continuous tapes (laminates), fibre tapes and fibre ropes made of different materials (natural or not) in enhancing the axial strain ductility and stress of confined concrete. All used confining materials are non-impregnated, unbonded to concrete and thus easy to reuse and recycle. Concrete cylinders confined with polypropylene rope reached axial strain as high as 0.15 with no rope fracture. Wrapping of cylinders with ultra-high molecular weight polyethylene (UHMWPE) tape or aramid fibre tapes or basalt fibre tapes may provide concrete significantly enhanced mechanical properties under monotonic or cyclic load. Cylinders wrapped with basalt fiber tape presented gradual fibre fracture and ductile load drop after maximum bearing load. Vinylon fibre ropes and UHMWPE or basalt or aramid fibre tapes show interesting resilience features as they can reach high portion of their confining efficiency even after their fracture initiation. In addition, the study presents the test results of severely damaged reinforced concrete (RC) column, repaired with high strength mortar and externally wrapped with hybrid basalt – polypropylene confinement. The retrofitted column fully restored the original ever-increasing σ-ε behavior, revealing remarkable energy dissipation under cyclic loading. It reached 0.052 axial strain and then it was early terminated for safety reasons, despite having already sustained 0.058 strain during initial loading.

1. Introduction

Epoxy resin impregnated and externally bonded fibre sheets or fibre reinforced polymers (FRP) are widely used in strengthening of concrete beams and columns [1–16]. FRPs have the following advantages over conventional seismic retrofits [17–19]:

a High strength-to-weight ratio. This leads to structural jacket with a negligible added thickness to the original section. It does not add significant additional dead load to the structure and thus does not increase load bearing demands. It enables for selective local (or global) interventions without adding uncertainties or altering the distribution of internal forces in the structure. It maximizes the net floor plan area when applied to vertical members.
b Continuous and flexible structural fibres impregnated and bonded with polymers in situ. In combination with (a) it provides an easy to handle reinforcement that can follow the form and shape of the existing members. It can be used in multiple layers, in different directions to satisfy design needs and form a composite reinforcement after resin curing. Polymer-bonded jacket allows for direct and full strain compatibility all over the jacket surface and increases the effectiveness in bond-critical applications. It allows for easy laps and self-anchoring. Continuous fibres lead to the minimum material waste during installation.
c Compatibility with other retrofitting techniques in cases of combined intervention.
d FRP is a low-maintenance material and can be used to halt corrosion in existing members.
e Immunity to corrosion of the FRP itself.
f All above advantages may lead to minimized disruption of use during installation, minimized labor, and other costs.

Transverse wrapping of columns with FRP jackets enables concrete to sustain higher shear forces and develop higher axial stress and more importantly axial strain. Enhanced axial strain ductility of concrete through confinement is the basic mechanism to provide

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http://dx.doi.org/10.1016/j.compositesb.2016.08.003
1359-8368/

columns with adequate reserve in order to survive potential seismic overloads or over-displacements through extensive energy dissipation. This aspect may increase significantly robustness and resilience of critical concrete members and structures [20] and contribute to built environment and community resilience [21,22].

Numerous experimental and analytical investigations confirmed the high efficiency of FRPs as confining means [23–33]. In the study by Ref. [34] low stiffness, high extension capacity PEN and PET FRPs enhanced remarkably the displacement ductility of RC columns under seismic loading. Dai et al. [35] used PEN and PET FRPs and assessed their efficiency in enhancing the axial strain of confined concrete. Karantzikis et al. [36] and [37,38], applied unbonded, non-impregnated carbon fibre strips or textiles as confinement reinforcement of concrete specimens and found comparable efficiency with resin impregnated ones. Choi et al. [39] wrapped unbonded glass FRP wire as confining reinforcement for concrete and found efficiency comparable to that of FRP jackets.

In another study, Shimomura and Phong [40] used vinylon and aramide ropes as internal shear reinforcement of beams or external confinement of columns. Rousakis [41] investigated the experimental behavior of concrete columns confined with vinylon or polypropylene fibre ropes. Concrete reached axial strain up to 0.13 and showed a unique spring-like behavior for very high axial strain levels when imposed to monotonic or cyclic compression. Hybrid FRP and fibre rope extended remarkably the bearing capacity of concrete beyond FRP fracture in Rousakis [42] and in Rousakis et al. [43]. There, carbon nanotubes were also used to enhance the deformability and other properties of impregnation resin. RC columns with slender bars and sparse stirrups, wrapped with polypropylene rope (applied by hand or pretensioned) showed remarkable energy dissipation in Ref. [44].

Kwon et al. [45], utilized (among others) the findings by Refs. [40–44] and used composite tape wrapping made of Velcro to enhance seismic performance of substandard RC frames. The columns had dimensions 200 × 300 mm and zero corner curvature radius which is prohibitive for the use of FRP jackets or fragile fibres and steel in general. Even one layer of Velcro tape of 0.3 mm thickness, made of nylon with self-anchoring detailing, raised the energy dissipation capacity of the frame by a factor of 3.7 (VARC columns).

This paper extends the research on non-impregnated, unbonded composite ropes to address unidentified gaps concerning potential for ultrahigh concrete strain. It also explores resilience features of reused ropes. It investigates use and efficiency of laminated tapes made of Ultra High Molecular Weight Polyethylene material and of fibre tapes made of aramid or basalt. Unique confining characteristics, because of different types of wraps and of recyclable materials involved, are discussed. Finally, the paper looks into highly energy dissipative retrofit of damaged RC column with repair mortar and hybrid basalt – polypropylene confinement, under cyclic loading.

2. Experimental testing

The experiments included in this study concern 19 axial compression tests on standard plain concrete cylinders with 150 mm diameter and 300 mm (or 440 mm) height. They are constructed by three different ready-mixed concrete of low compressive strength (labeled CPC1M, CPC2M, CPC3R). Eleven specimens are confined by different advanced materials in different levels of confinement. Furthermore, an already severely damaged reinforced concrete (RC) column of square section with 150 mm side, sharp corners and 750 mm height is repaired and retested under axial load.

2.1. Materials

Standard plain concrete cylinders CPC1M with 150 mm diameter and 300 mm height have an average compressive strength of 24.3 MPa. Similarly, cylinders CPC2M have compressive strength of 15.6 MPa. Concrete cylinders CPC3R with 150 mm diameter and 440 mm height have an average compressive strength of 20.2 MPa when imposed to load-unload cycles.

The tests include confining materials in the form of fibre ropes made of vinylon (labeled Vin) or polypropylene (labeled tPP) in order to extend the findings of the [41] study. They also investigate the efficiency of laminate tapes made of Ultra High Molecular Weight Polyethylene (UHMWPE) material (labeled UPE) and fibre tapes made of aramid (labeled AFT) or basalt (labeled BFT). The mechanical properties of all materials are cited in Table 1.

The elastic fibre rope made of vinylon (vinylon fibre rope, VFR) comprises three Z-twisted fibre strands (product of Kurasoku Kensetsu Consultant Co. Ltd., Japan). The rope presents a low tensile modulus of elasticity of 15.9 GPa and a high tensile elongation at failure of 4.6% [40]. The elastic polypropylene fibre rope (PPFR) is product of Thrace Plastic Co. S.A (Greece) and possesses ultrahigh deformability. PPFR is a Z-twisted two-strand rope with an ultimate stress of 405.3 MPa, a tensile modulus of elasticity of 2.0 GPa and 20.36% elongation at failure. More details on their stress-strain response and applications can be found in Refs. [41–44]. Both vinylon and polypropylene composite ropes are eco-friendly, easy to reuse and recycle as raw materials.

The Ultra High Molecular Weight Polyethylene (UHMWPE) material is in the form of laminate tape (UPE) of different thickness and width (product of TEIJIN, Endumax Tape TA23). Label UPE2 is used for a 2 mm wide tape with 0.055 mm thickness. Label UPE19 concerns a 19 mm wide tape with 0.11 mm thickness, ideal for external confinement. Endumax tape has a bilinear tensile stress – strain behavior with 185 GPa modulus of elasticity, valid up to 0.2% axial strain. Then the tensile modulus decreases smoothly to 120 GPa (valid from 1% to 1.8% axial strain). The tensile strength is 2330 MPa. UHMWPE is eco-friendly, easy to reuse and recycle as raw material, as no solvents are used for its production and very low energy is required compared with other raw materials with similar advanced mechanical properties.

The aramid fibre tape (AFT) is unidirectional fabric (product of Eurocarbon, 301 Aramid UD Tape), made of Twaron HM 1055, with structural thickness of tape 0.28 mm and width of 12.5 mm. The modulus of elasticity of the fibre is 105 GPa and the elongation at failure 2.8%. The aramid material is easy to reuse and recycle to produce pulp products.

The basalt fibre tape (BFT) is 30 mm wide and 0.065 mm thick (structural thickness in axial direction of the tape) and has the same quantity of basalt fibres in warp and weft (product of Juan Gili S.L.). Basalt tape reveals modulus of elasticity of 69 GPa and axial strain at failure of 1.85%, inferior to the properties of the fibres, due to the weaving of the filaments. The tensile strength of BFT is around 1270 MPa. Basalt is an inorganic natural material that reveals superior corrosion resistance and similar mechanical properties to glass fibres [46,47]. The mechanical properties of basalt fibres range between 89 GPa and 95 GPa for the modulus of elasticity, between 2800 and 4900 MPa for the tensile strength and between 3.00% and 5.00% for the ultimate strain [48]. They are derived from volcanic rocks in a single melt process and offer better thermal stability, heat and sound insulation properties, vibration resistance as well as durability than glass fibres [49]. They are inert, non-toxic, non-reactive and biodegradable [47,50]. Advanced basalt fibre reinforcements present better eco-footprint than alternative materials of similar structural performance [48]. They have been widely used in several demanding construction-related applications