Chapter 5

Hybrid FRP Sheet – PP Fiber Rope Strengthening of Concrete Members

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Additional information is available at the end of the chapter

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1. Introduction

Fiber Reinforced Polymer (FRP) reinforcements are extensively used in the strengthening of existing concrete members. FRP sheets consisting of epoxy resins and carbon, glass, aramide etc. fibers can serve reliably as flexural, shear or confinement reinforcement. Adequate external confinement of concrete by elastic materials leads to far higher effectiveness in strength and strain enhancement of concrete under compression than common steel, since the steel yields. However the use of impregnating resin in FRPs results in a composite material that resists relatively low working temperature. It also requires suitable environmental conditions during impregnation

Significant recent research efforts focus on the overcoming of such disadvantages relative to the use of polymers. The substitution of the organic resins by inorganic cement based binders seems a viable option ([1] among else). The inorganic mortar serves as a matrix that interacts with the grid reinforcement that consists of textiles. Textile reinforced mortars (TRM) have been already used as confining or shear reinforcement successfully.

A few investigations deal with rope reinforcements made of aramide or vinylon fibers. Those ropes are used as external strengthening or internal shear reinforcement. They combine easy handling and low sensitivity to local damage of fibers due to bending or small corner radius or scratching or stress concentrations [2]. Furthermore, there is no need for impregnating resins or binders especially in external confinement applications of ropes. Polypropylene is an ultra high deformability material, recognized as an effective mass reinforcement in concrete. Peled [3] uses polypropylene tubes to confine concrete. However the provided lateral confinement was low and the effects on concrete were limited. Numerous researches look into the response of concrete columns wrapped by carbon FRP sheets of high modulus of elasticity [4, 5, 6, 7 & 8 among else]. FRP confined concrete may present a considerable strength and strain enhancement. However the efficiency of the wraps is limited by the low deformability of the FRP. Confinement with materials of different modulus of elasticity and of the same lateral rigidity (E_l) will provide higher axial strain ductility to concrete according to their deformability [9]. Thus, materials of very low elastic modulus which have high strain at failure may provide considerable confinement of concrete.

Considering the advantages of composite ropes for structural applications, an experimental research program is presented that investigates the use of fiber ropes as external confining reinforcement on standard concrete cylinders already confined by glass FRP jackets. The ropes are mechanically anchored through steel collars, avoiding the use of impregnating resins.

2. Resin impregnated fiber sheet and textile reinforced mortar confining techniques

In columns confined by fiber reinforced sheets impregnated by polymers (fiber reinforced polymers, FRP) an abrupt fracture of the confining reinforcement is usually observed after a certain level of imposed lateral deformations. Figure 1 presents the experimental results of a large experimental program involving high elastic modulus carbon FRP sheet confinement of concrete [4], [9]. In figure 1 the ultimate axial strains range among 0.4% and 2.4% for the specific tests. After the FRP fracture an explosive failure and a rather precipitous drop of the bearing load takes place. The higher the elastic modulus of the FRP jacket, the lower its strain at failure and the lower the axial strain at failure of confined concrete for identical confining rigidity. More recent experimental efforts concern large deformability FRP confining materials made of PET that may present a fracture at far higher levels of concrete axial strains up to 8.5% [10].

Textile Reinforced Mortar (TRMs) jackets are a reliable alternative to FRP jackets with comparable strength and ductility enhancement while they present a higher resistance to elevated temperature [1]. The TRM confinement presents a more gradual failure due to progressive fracture of individual fiber bundles that lead to softening stress-strain behaviour.

Both techniques involve the use of reinforcements working inside a matrix. The epoxy resin or mortar matrix have to be cured for a certain period of time and under controlled environmental conditions in order to bear the final redesign loads. The following sections present a novel strengthening technique utilizing the advantages of the fiber rope reinforcements.

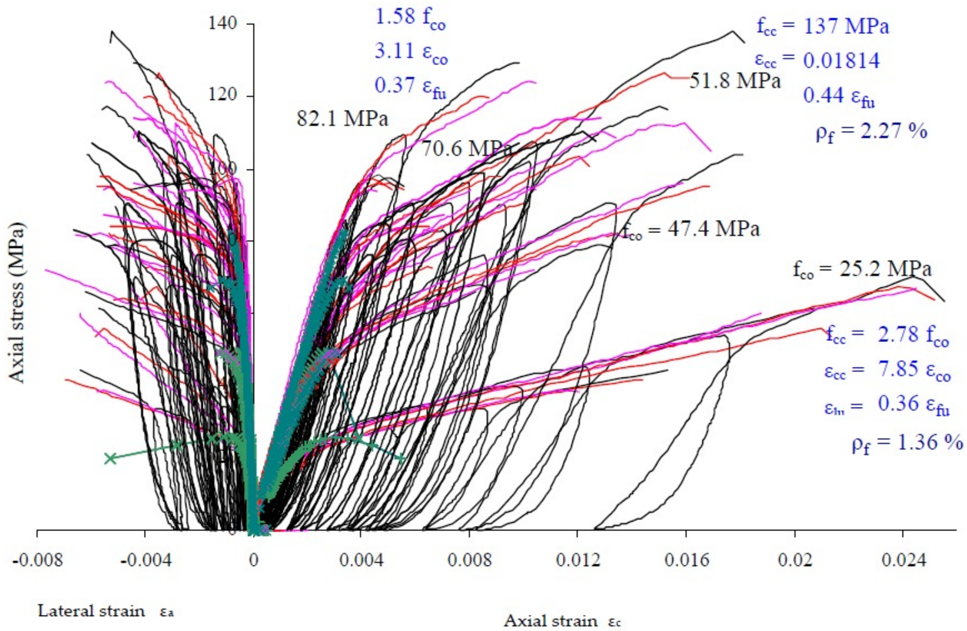

Figure 1. Axial stress versus axial and lateral strain curves of 45 concrete cylinders confined by high-E-modulus carbon FRP sheets under monotonic or cyclic loading. Five concrete strengths and three different volumetric rations are presented.

3. Resin or mortar free PPFR & VFR confinement

In the first part of the experimental program, the vinylon and polypropylene fiber ropes confine standard concrete cylinders (150 mm diameter and 300 mm height) in three different confinement volumetric ratios. The vinylon fiber rope (VFR) is a three-stranded Z-twisted one with 12.66 mm^2 structural area. Its modulus of elasticity is 15.9 GPa and 4.6% tensile failure strain [2]. Two different polypropylene ropes are used in the research (manufactured by Thrace Plastic Co. S.A.). The first rope is braided, having eight strands (bPPFR) and a very low E-modulus of 2250 MPa. The tensile failure strain is 18%. The structural area of the bPPFR is 21.25 mm^2. The second polypropylene fiber rope is a two-stranded Z-twisted one (tPPFR) with a structural area of 12.09 mm^2. Its E-modulus is 1991 MPa and shows 20.35% tensile failure strain. The application is resin-free. Thus, a mechanical anchoring of the rope is applied without the use of impregnating resin. The application of one or multiple rope layers follows a careful wrapping by hand, yet exerting an adequate and continuous tension on the rope. The wrapping process is acceptable only if the confinement is tight enough. Loose wrapping reduces significantly the efficiency of FR wrapping. However thorough wrapping by hand and suitable mechanical anchorage may provide an efficient lateral restriction to concrete. The applications of the two different types of PPFR with different knitting and overall structural diameter reveal no difference in the structural behaviour. The braided multi-strand rope leaves higher percentage of gaps among multiple rope layers than the twisted two-strand rope of half structural area. In addition, the tPPFRs require lower hand force during application in order to achieve an adequate continuous tension. Yet, the braided multi-strand rope provides similar structural effectiveness with the twisted two-strand rope. The concrete strength of the specimens during the tests was 15.56 MPa. Figure 2a presents a concrete column confined by vinylon fiber ropes.

The testing includes monotonic and cyclic axial loading of the columns. The research assesses the effectiveness of rope composite reinforcements considering the whole axial stress versus axial and lateral strain behaviour, as well as the failure values resulting from monotonic or cyclic compressive loading of concrete cylinders. The results are shown in figures 3& 4. Confinement of concrete through fiber ropes leads to substantial upgrade of concrete strain at failure reaching values of 13% strain (around 39 strain ductility). The strength enhancement reached a number of 6.6 times that of plain concrete. Those measured values are recorded from specimen confined by VFR that could not be tested up to failure due to loading machine limitations. Similar is the case with the PPFR confined specimens which reach axial strain ductility of 35.5. All PPFR confined specimens and the heavy VFR confined columns present a failure mode that involves the extensive disintegration of concrete and no fracture of the confining reinforcement occurs. The concrete core disintegrates uniformly up to the point that the transverse restriction by the FR surpasses the transverse rigidity of the concrete. After that point, full unloading of the concrete core does not lead to equilibrium with the external confinement and thus to stable remaining (plastic) axial and lateral strains. On the contrary, the extensively and uniformly cracked core squeezes under the external lateral pressure and the plastic axial and lateral strains of the previous cycle reduce significantly. The specimen lengthens in the axial direction and may become higher than its original height. That unique behaviour of concrete reveals a remarkable efficiency of rope reinforcements to redistribute lateral restriction. That type of concrete response is referred as a "spring-like" behaviour (Figure 2b). Moreover, PPFR show a very low sensitivity to local damage. Both ropes can be easily coupled through simple knots or simple steel chucks. Thus, both ropes can be easily reused even if fractured. More details on the first part of the experiments can be found in [11].

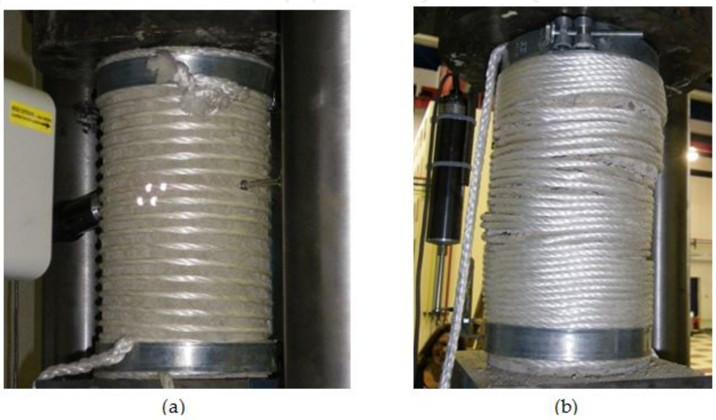

Figure 2. Measurement of lateral deformation on concrete and on FR of specimen VinL1v2 (a). Specimen bPPL1p1 after failure of the concrete core during full decompression (b). Adapted from [11].

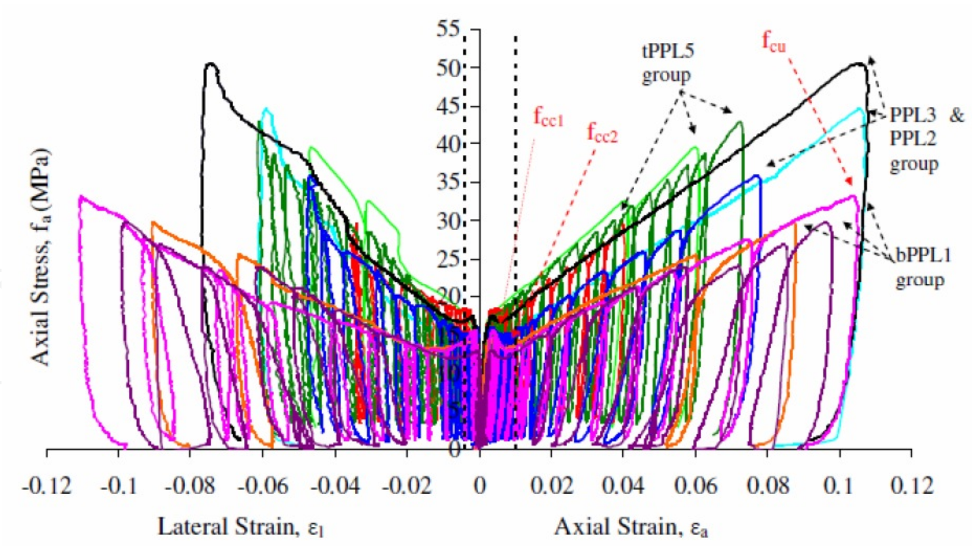

Figure 3. Comparative stress –strain diagrams of PPFR confined concrete. Adapted from [11].

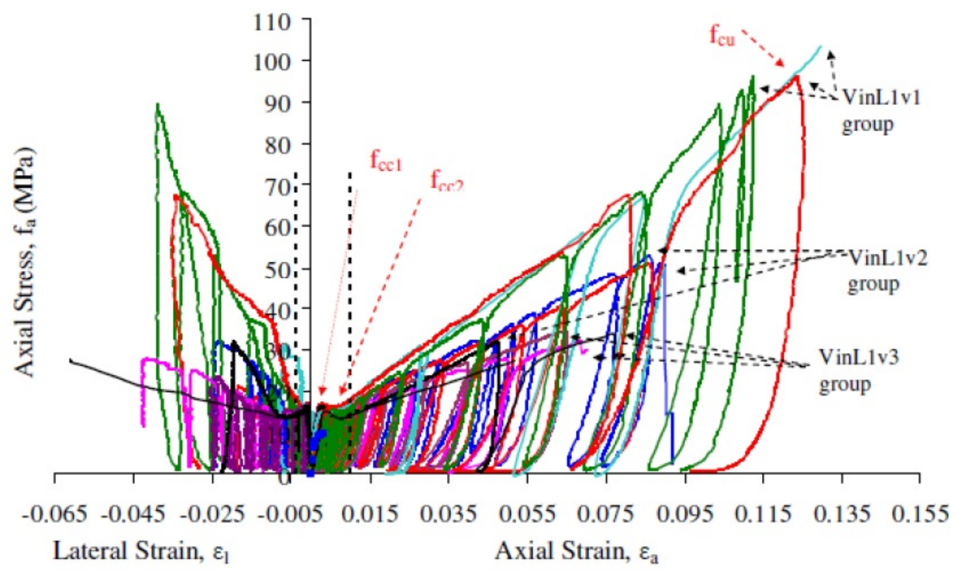

Figure 4. Comparative stress –strain diagrams of VFR confined concrete. Adapted from [11].

Since the majority of specimens could not be tested up to the fracture of the FR, the assessment of the structural behaviour of the columns utilizes the provided lateral rigidity of the confinement $E_l = 0.5\ k_e\ \varrho_{FR}\ E_{FR}$, where E_{FR} is the modulus of elasticity of the FR, ϱ_{FR} is the volumetric ratio and k_e is the effectiveness coefficient due to spiral clear spacing s′ that is $k_e = 1\text{-}s'/2d$ where d is the section diameter. Thus, the confinement aims at achieving a limited load drop (lower than 20%) from f_{cc1} to f_{cc2} (see Figures 3 and 4) upon full activation of the FR (or no drop at all). Then an ever increasing bearing load response up to failure occurs (stress f_{cu}).

The unique "spring – like" behaviour of concrete at ultimate offers experimental evidence that further support the earlier findings on the requirement of further elaboration and development of experimental data on plastic deformations and more sophisticated modeling approaches sensitive to the path-dependent deformation evolution of confined concrete [5, 12, 13, 14 among else]. Finite element analyses may prove necessary in order to model and generate reliably the geometric nonlinearities and material interactions [12, 15 among others]. The response of confined concrete depends on the mode of loading and on the evolution of axial to lateral stresses during loading and unloading as well. The fiber rope confinement application reveals that the redistribution capacity and minimum sensitivity of the rope reinforcement homogenizes the cracks developed inside the concrete core and the response of the member as whole. Thus, the utilization of the concrete deformability under triaxial compression is rather optimized when vinylon or polypropylene FR materials are used. High deformability materials present low modulus of elasticity and thus the required structural thickness is high. Fiber ropes (FR) can provide a solution and at the same time exclude the use of impregnation resins.

4. Hybrid FRP and FR Confinement

This part of the experimental study concerns the utilization of the unique, ductile behaviour of concrete confined by high deformability elastic materials. Such materials may ensure the reserve of the strain ductility of the concrete under compression, often required due to an overloading in the critical region of a member caused by extreme seismic excitations. In columns confined by FRP sheets an abrupt fracture of the confining reinforcement is usually observed after a certain level of imposed lateral deformations (Figure 1). According to the first part of the experimental research, high deformability elastic confining materials can maintain the integrity of low strength concrete to a remarkable strain level even higher than 10% while presenting ever increasing axial load capacity (rather hardening behaviour). Thus, the study further investigates the confining effects of hybrid glass FRP – polypropylene (PP) fiber rope (FR) external confinement. The tests include concrete cylinders in two series with concrete qualities of C16 and C20 under repeated axial compression cycles of increasing displacement similar to the first part of the experimental study. The specimens are confined externally with only one layer of glass FRP sheet and adequate FR confinement in different volumetric ratios. Herein the presentation is limited to the beneficial effects of the dual action of the glass FRP and PPFR.

The whole experimental program includes 21 specimens of two different concrete strengths, C16 batch with average concrete strength of 25.1 MPa and C20 with concrete strength of 33.7 MPa. Three specimens in each batch are confined by 5 layers of tPPFR to examine the efficiency of FR confinement in columns with varying concrete strength. Another two columns in each batch are confined by 1 layer of glass FRP (GFRP). The glass FRP is of S&P G90/10 type (S&P—Sintecno 1999 [16]) with 300 mm width. Details on the application requirements of the sheet FRP on non-circular columns as well can be found in [7]. The glass sheet has structural thickness of 0.154 mm per layer, tensile modulus of elasticity of 73 GPa and strain

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at failure equal to 0.028 (after impregnation and curing). Finally, two columns in each batch are confined by both 1 layer of GFRP sheet and 3 layers of PP fiber ropes. Those four columns are constructed in four phases. At first, the external surface of the cylinders is treated with an epoxy paste (P103, Sintecno) in order to fill the undesirable pores and cavities. The full hardening of the paste may require up to 15 hours. After at least 6 hours a layer of the two-component primer S2W resin (Sintecno) is applied on the external surface of the column. The primer resin is left to harden at least 1 hour. After the curing of the primer resin the application of the glass sheet follows with the use of the two-component impregnating resin S2WV (Sintecno). An overlap of 150 mm of the sheet layer prevents anchorage debonding failure. Full development of the impregnating resin capacity may require up to 7 days. After the hardening of the second resin, the 3 layers of the Z-twisted, two-strand polypropylene fiber rope (tPPFR) are applied by hand. The continuous rope may include several ropes reused or not, connected with simple knots if necessary. The FRs are anchored mechanically through steel collars that simply tighten and thus exert an adequate pressure on the ropes against the concrete surface. Thus the anchorage of the ropes is performed mainly by friction. That set up is necessary given the small size of the standard cylinders. In real size concrete components, the anchorage of the rope may be easily constructed outside the region of the expected damage by simply tighten the rope itself with a simple knot or with a suitable steel collar. In concrete specimens confined exclusively by PPFR no special treatment of the external concrete surface is necessary. Consequently, the application of the FR confinement may be directly applied and operating since it may involve zero materials' curing time. Considering the high performance of the rope against local concrete damage and stress redistribution, the FR may be applied on any concrete surface even after severe cracking of the concrete core. However, in confinement applications, large concave surfaces in the external surface should be avoided since they reduce the effectiveness. The following paragraphs present the experimental results of the columns with the dual action of the glass FRP and PPFR confinement.

The typical test setup is presented in Figure 5. Axial and lateral deformations are measured through four displacement meters (linear variable displacement transducers –LVDTs). An advanced laser meter measures the deformation of the rope on the outer surface. The columns are subjected to multiple close compression – decompression – recompression cycles of increasing deformations.

Figures 6 and 7 present the specimen of C16 concrete quality confined by 1 layer of GFRP and 3 layers of tPPFR after the end of the test. It should be mentioned that no tPPFR fracture occurs. After the first fracture of GFRP the axial load drops gradually as it is bared mainly by the tPPFR confinement while the GFRP jacket merely contributes through the interface friction with the adjacent PPFR. At successive cycles of compression the load stabilizes under the PPFR confining action and rises again. During those cycles multiple fractures of the GFRP sheet may develop. Such multiple FRP fractures may be evidenced after the removal of the FR (Figures 6 and 7). Those multiple fractures are characteristic of hybrid confinement and reveal a further utilization of the GFRP sheet as surface reinforcement. All the tests of specimens with hybrid confinement ended prematurely due to loading machine capacity restrictions or after steel collars dislocation and concrete unstable behaviour.

Figure 5. Test setup of specimens confined by 1 layer of GFRP and 3 layers of tPPFR material.

Figure 6. Specimen of C16 concrete confined by 1 layer of GFRP and 3 layers of tPPFR material after the removal of the fiber rope. The GFRP sheet jacket is fractured in two opposite positions. View of the fracture near the overlap region.

Figure 7. Specimen of C16 concrete confined by 1 layer of GFRP and 3 layers of tPPFR material after the removal of the fiber rope. View of the GFRP fracture far from the overlap region.

Since the PPFR confined column present no rope fracture, the remaining response milestones are discussed. The first milestone involves specimens with hybrid confinement that present axial load regaining after the GFRP fracture. The second milestone concerns the further development of axial load equal to the one during first GFRP fracture. The second milestone clearly reveals the efficiency and the effects of the rope confinement.

Figure 8 shows the typical structural response of axial stress versus strain for the GFRP confined specimen of C16 concrete batch, the respective column with 5 layers of tPPFR and the one with hybrid confinement by 1 layer of GFRP and 3 layers of tPPFR. The confinement with 5 layers of PPFR is designed in order to ensure the controlled temporary load drop upon full activation of the PPFR confinement. The lateral rigidity of the PPFR confinement is around 300 MPa. The confinement by 1 layer of GFRP provides a lateral rigidity of around 150 MPa. Thus, the hybrid confinement is designed in order to provide a combined lateral rigidity almost equivalent to that of 5 layers of tPPFR. The GFRP jacket and 3 layers of PPFR correspond to a lateral rigidity of around 340 MPa.

The experimental evidence show that the 3 layers of PPFR lead to further utilization of the GFRP jacket. The fracture of the GFRP occurs at higher axial load and axial strain in hybrid confinement. After the fracture of the GFRP, the outer PPFR confinement results in a temporary and smooth load drop while the GFRP confined specimen presents an abrupt failure. The PPFR confinement can bear the abrupt energy release after the fracture of the FRP and redistributes the resulting uneven lateral pressure through the friction between the FR and sheet confinement. The removed rope presents no fracture or even limited local individual fibers' damage after the end of the test. The load is stabilized under the restrictive action of the PPFR and a load regaining occurs (see the hybrid glass FRP-PPFR confinement in Figure 8). Proper design of hybrid confinement by FRP sheets and high deformability FR as the outermost reinforcement, utilizes fully the confining effects of the FRP sheet up to its fracture. Then adequate FR ensures further increased strain ductility of concrete which withstands also high axial loads and avoids an abrupt load capacity loss. The axial load capacity loss in FRP or in steel stirrup confinement occurring after the fracture of those materials may be replaced by a smooth softening, followed by a hardening behaviour of no “detected failure” for practical applications in structural concrete members.

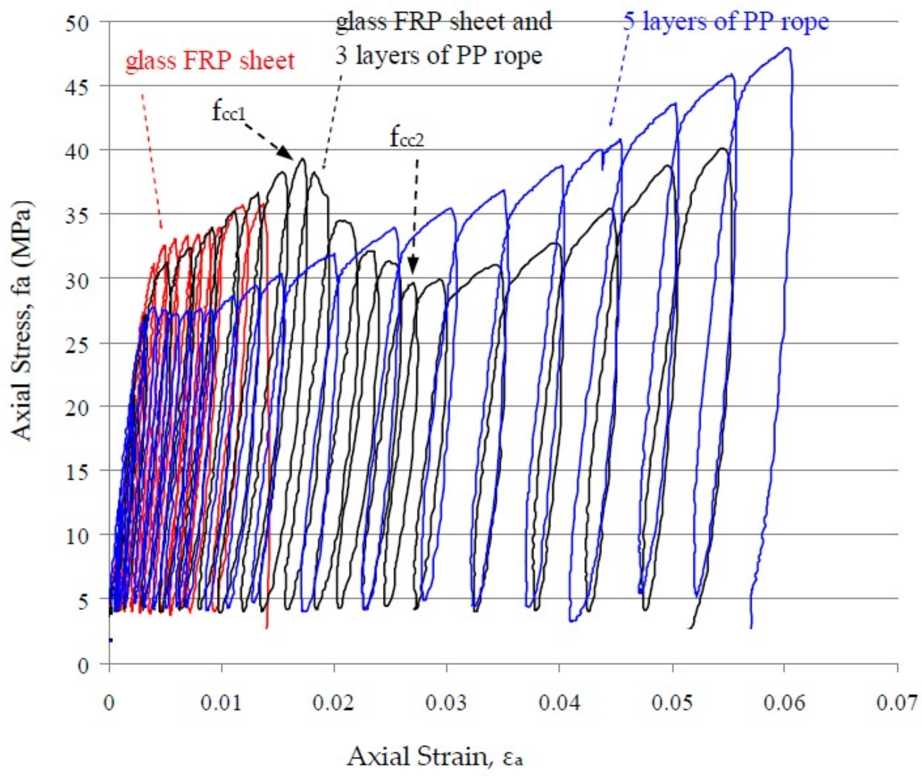

Figure 8. Axial stress versus axial strain curves for concrete specimens confined by 1 layer of glass FRP sheet, by 5 layers of PP rope or by hybrid FRP and 3 layers of PP rope reinforcement.

The temporary load drop can be controlled within desirable levels. As depicted in Figure 8, three layers of PPFR can lead to a minimum axial load before regaining that is higher than the strength of plain concrete.

As mentioned above, the fracture of the GFRP occurs at higher load and strain than the specimen without external PPFR strengthening because of the dual confinement effect and twofold E_l. Figure 8 depicts that the confining effects of GFRP and PPFR confinement are different. The hybrid confinement presents significantly higher load enhancement than the 5 layers of PPFR – with almost equal confinement rigidity – at the same strain levels until the fracture of the GFRP jacket.

Concerning the deformability of concrete, the glass FRP confined column fails at around 1.3% axial strain as the sheet fractures abruptly. On the other hand, an adequate additional quantity of PP fiber rope can provide a hardening stress-strain response of concrete including a temporary load drop with softening behaviour. The deformability goes beyond 5.5%,

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while no abrupt failure occurs as the PPFR does not fracture. The loading is ended early in all tests due to concrete unstable behaviour or steel collars dislocation.

5. Fiber rope confinement modeling and design

The available confinement models predict the stress-strain behaviour or the ultimate stress and strain values of concrete at the fracture of the confining means. Since the case of hybrid GFRP and PPFR confinement does not include the fracture of the PPFR for the recorded tests, this approach need to be reconsidered. In this section two significant recent existing models are used to predict the stress and strain values at the characteristic point of the fracture of the GFRP sheet due to dual hybrid confinement.

In their study, Teng et al. (2009) [17] propose empirical relations for the strength and strain of FRP confined columns that recognize the confinement stiffness and the FRP tensile to concrete compressive strain ratio as significant parameters. The strength is predicted by the relation:

$$\left.\begin{array}{l} \dfrac{f_{cc}}{f_{co}} = 1 + 3.50\cdot(\rho_{\kappa} - 0.01)\cdot\rho_{\varepsilon},\ when\,\rho_{\kappa} \geq 0.01 \\ \dfrac{f_{cc}}{f_{co}} = 1,\ when\,\rho_{\kappa} < 0.01 \end{array}\right],\ \rho_{\kappa} = \frac{2\cdot E_j\cdot t_j}{\dfrac{f_{co}}{\varepsilon_{co}}\cdot d},\ \rho_{\varepsilon} = \frac{\varepsilon_{je}}{\varepsilon_{co}},\ \varepsilon_j = 0.586\cdot\varepsilon_{fu}$$

The strain at failure is given by the relation:

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 1,75 + 6,50\cdot\rho_{\kappa}^{0,80}\cdot\rho_{\varepsilon}^{1,45},\quad \rho_{\kappa} = \frac{2\cdot E_{FRP}\cdot t}{\dfrac{f_{co}}{\varepsilon_{co}}\cdot D},\quad \rho_{\varepsilon} = \frac{\varepsilon_{FRP}}{\varepsilon_{co}}$$

In the research by Rousakis et al. (2012) [18], a strength model is proposed that identifies the normalized axial rigidity of the confining means ($\varrho_f E_f / f_{co}$) as a significant parameter. The lateral strain at failure of concrete is found strongly dependent on the modulus of elasticity of its reinforcing fibers (E_f) and on the confinement effectiveness coefficient (k_1). The model has the following form (see also [9], [5] and [6]):

$$f_{cc}/f_{co} = 1 + k_1(f_{le}/f_{co}) = 1 + k_1(0.5\rho_f E_f \varepsilon_{je}/f_{co}) = 1 + (\rho_f E_f/f_{co})(0.5\,k_1\varepsilon_{je}),$$

that is

$$f_{cc}/f_{co} = 1 + (\rho_f E_f/f_{co})(\alpha E_f 10^{-6}/E_{f\mu} + \beta)$$

with $\varrho_f = 4t_f / d$ and $E_{f\mu} = 10$ MPa (for units' compliance). For FRP sheet wraps $\alpha = -0.336$ and $\beta = 0.0223$. For FRP tube encased concrete $\alpha = -0.2300$ and $\beta = 0.0195$.

The above models are applied to the experimental results of GFRP confined columns and of columns with dual GFRP-PPFR confinement. Figures 9 and 10 present the predictions of strength and strain at failure of the two models. The absolute error of the predictions for both strength and strain is less than 7.1% for the columns with hybrid confinement.

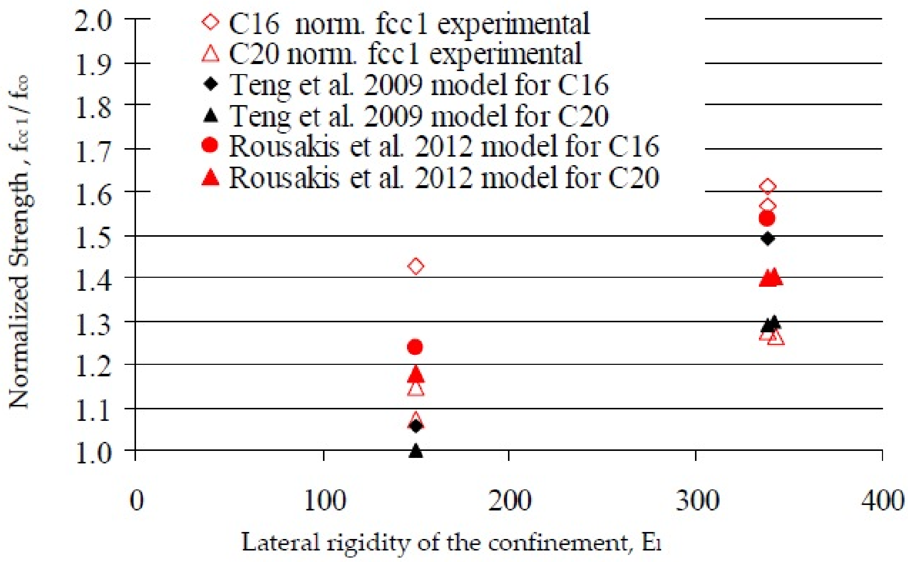

Figure 9. Normalized bearing stress f_{cc1} at first drop of the load to the plain concrete strength versus lateral rigidity of the confinement for 1 layer of glass FRP sheet or by hybrid FRP and 3 layers of PP rope reinforcement for C16 and C20 concrete batches.

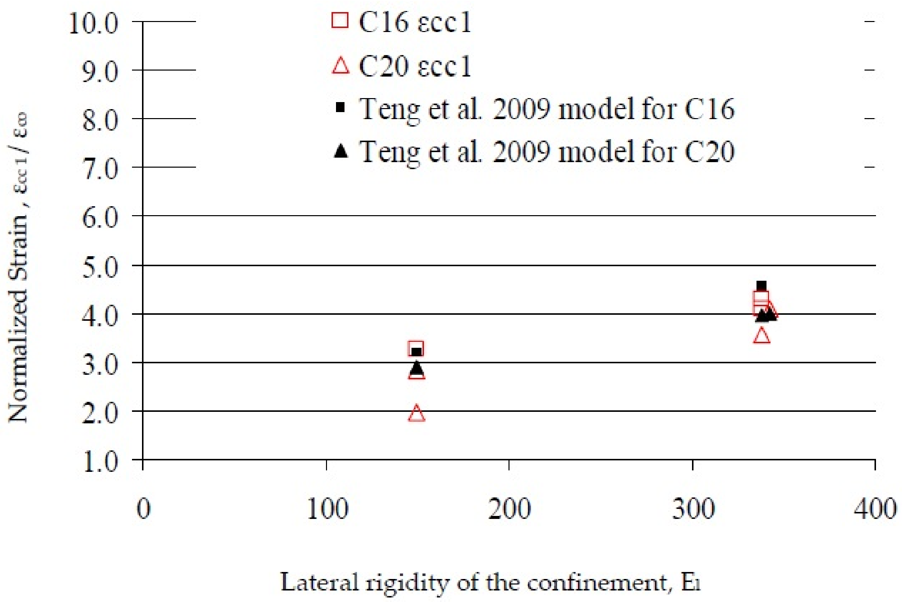

Figure 10. Normalized strain at first drop of the load to the plain concrete strain versus lateral rigidity of the confinement for 1 layer of glass FRP sheet or by hybrid FRP and 3 layers of PP rope reinforcement for C16 and C20 concrete batches.

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6. Conclusions

The research presents a novel hybrid confining technique that involves FRP jacketing and fiber ropes mechanically anchored through steel collars. Fiber rope confinement is a “directly applied and operating” strengthening technique. The additional polypropylene fiber rope confinement may enhance the axial stress and strain of concrete prior to FRP fracture. It also restricts the lateral strain of concrete. After the fracture of the FRP, the PPFR restricts the abrupt load drop and stabilizes the concrete softening response up to load regaining and rehardening. PPFR withstands the abrupt energy release and the multiple fractures of the FRP jacket throughout the loading. No new load drop or PPFR fracture or local PP fiber damage occurs up to axial strains equal to 5.5%. That hybrid technique can enhance remarkably the performance of lightly FRP confined columns that are expected to present abrupt failures during an event of overloading due to seismic excitations.

The redistribution of stress and strain of the rope is feasible because, as mentioned above, the polypropylene fiber rope (PPFR) is not used with resin. The PPFR is applied after the full curing of the common FRP sheets impregnated by resins. Thus the PPFR is bond free when wrapped around the FRP jacket.

In hybrid confining schemes the PPFR is not in conduct with concrete. Thus the concrete is protected by the FRP sheet. The PPFR (if fully wrapped) is expected to provide some protection for the FRP sheet. However no investigations exist on this mater so far. The polypropylene is already used widely as mass fiber reinforcement inside concrete. Thus, even if in direct conduct with concrete, the PPFR exhibits no alkalinity related degradation. On the other hand exposure to UV light or high temperatures should degrade the PPFR. Thus a UV light protecting and fire-resistant finishing mortar is required as in common FRPs applications.

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