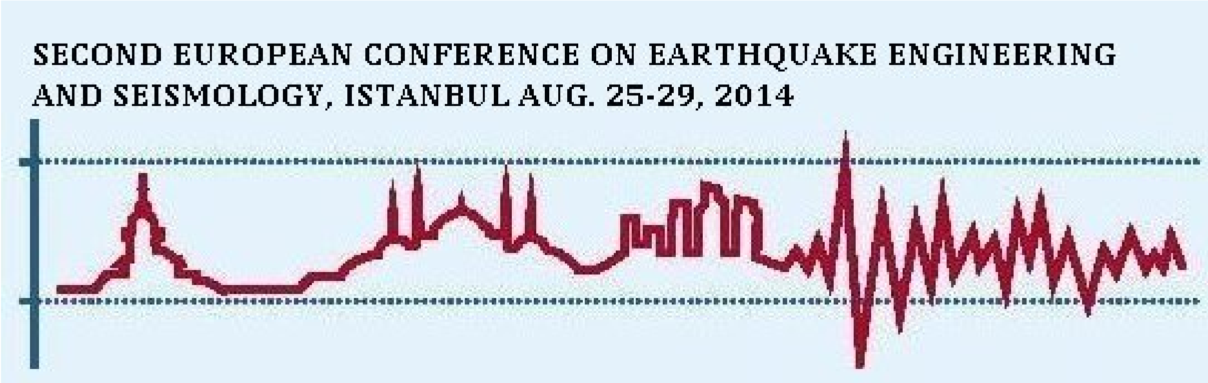

SHEAR CAPACITY OF RC BEAM-COLUMN JOINTS RETROFITTED WITH FRP SYSTEMS

1

Ciro DEL VECCHIO[1], Marco DI LUDOVICO[2], Andrea PROTA[3] and Gaetano MANFREDI[4]

1
2

ABSTRACT

Major seismic events have shown the high vulnerability of existing RC structures, especially for those designed according to obsolete code provisions. Field surveys have identified the brittle failure modes of poorly detailed beam-column joints as one of the main cause of vulnerability. This encouraged the scientific studies to investigate their seismic behaviour and find reliable and cost-effective strengthening solutions. Experimental evidences demonstrated the effectiveness of fiber reinforced polymers (FRP) systems increasing the global seismic capacity of structural systems. However, even if a large number of experimental tests on beam-column subassemblies have been carried out, simple and generalized formulations able to predict the increase of shear strength provided by the FRP system are still lacking. This paper proposes a critical review of the existing capacity models for beam-column joints retrofitted with FRP systems basing on recent experimental findings. The outlined experimental and theoretical considerations may be useful for the development of new capacity models to estimate the contribution of FRP systems to the strength capacity of poorly detailed beam-column joints.

INTRODUCTION

Premature brittle failures of reinforce concrete (RC) members strongly affect the seismic behavior of structural systems. Catastrophic structural collapses, frequently observed in the field surveys of major earthquakes, have encouraged the scientific effort to prevent the brittle failures modes. As a result, current seismic design provisions suggest to adopt an adequate amount of transverse reinforcements to promote a more favorable ductile failure mode.

However, the brittle failures represent a critical issue for existing structural systems designed with obsolete code provisions. The high seismic vulnerability of these buildings is usually related to the premature failure of beam-column joints as recently observed in field surveys and analytical studies (Frascadore et al., 2014).

[1] Ph.D. Student, Department of Structures for Engineering and Architecture, University of Naples “Federico II”, Italy, ciro.delvecchio@unina.it;

[2] Assistant Professor, Department of Structures for Engineering and Architecture, University of Naples “Federico II”, Italy, diludovi@unina.it;

[3] Associate Professor, Department of Structures for Engineering and Architecture, University of Naples “Federico II”, Italy, aprota@unina.it;

[4] Full Professor, Department of Structures for Engineering and Architecture, University of Naples “Federico II”, Italy, gamanfre@unina.it.

Several scientific works were carried out in order to characterize the behavior of RC beam-column joints subjected to seismic loads. They resulted in different theories and simplified capacity models to assess the seismic capacity of existing beam-column joints (Priestley et al., 1996, Priestley, 1997, Pampanin et al., 2002).
Along with the progress in the characterization of the mechanical behavior of RC poorly detailed beam-column joints, several techniques were proposed to improve their seismic capacity.
The effectiveness of classic retrofit techniques, as RC jacket and steel jacket of the joint panel, was largely demonstrated. However, they present several installation difficulties related to the materials weight, durability properties, difficulties in handling, high disruption level of the surrounding elements and high installation costs (Balsamo et al., 2012). This strongly promoted the widespread of composite materials such as the fiber reinforced polymer (FRP) as innovative strengthening solutions.
Several experimental program were carried out to investigate the seismic behavior of poorly detailed beam-column joints strengthened with FRP systems (see Fig. 1). They pointed out that the FRP effectiveness depends on the strengthening layout, amount of fibers, fibers mechanical properties, mechanical anchors and surface preparation (Gergely et al., 2000; Ghobarah and Said, 2002; Antonoupolos and Triantafillou 2003, Prota et al., 2004; Del Vecchio et al. 2014). More recent tests and analytical studies on typical RC existing buildings demonstrated that the adoption of FRP materials as a local strengthening solution is a cost effective solution to improve the seismic capacity of the whole structural system (Di Ludovico et al. 2008, Frascadore et al. 2014). This background strongly promoted the installation of composite materials in the aftermath of major recent earthquakes.

Figure 1. Experimental test on beam-column joints strengthened with FRP systems (Del Vecchio et al. 2014).

A significant effort in the definition and development of a mechanical model to estimate the strength capacity of beam-column joints retrofitted by FRP systems has been made by Antonopoulos and Triantafillou (2002). The model accounts for different failures mode: joint core web crushing, fiber rupture, fiber deboning or longitudinal reinforcement yielding. In spite of the model effectiveness for beam-column joint subassemblies retrofitted with fibers in the direction of the beam and/or column, an iterative quite complex procedure is required to compute the strength capacity. More recently another theoretical model has been proposed by Tsonos (2008). By assuming a mechanical equivalence of FRP fibers oriented in the direction of the beam axis with steel hoops, the maximum strength capacity of the joint panel can be computed by solving a polynomial equation. In the recent years, the model proposed by Antonopoulos and Triantafillou (2002) was improved by Akguzel and Pampanin (2012) on the basis of experimental observation. They also provided a simplified non-iterative procedure, suitable for beam-column joints with plain round bars with end hooks; it has been calibrated on experimental results and allows to calculate the resisting principal stress in the concrete core. Furthermore, the model proposed by Bousselham (2010) needs to be mentioned in the simplified procedures. This model, based on the principal stresses approach proposed by Priestley (1997), provides an expression to calculate the effective strain in the FRP fibers by using an empirical formulation calibrated on experimental results.

RESEARCH MOTIVATION

Although the use of FRP systems is widespread in the seismic strengthening of beam-column joints, simple reliably expressions to predict their benefits are still lacking or based on a limited number of experimental result. Moreover the available models are mainly related to specific joint types and reinforcement layouts. The uncertainty related to the mechanical behavior of the joint panel under seismic action and the number of variables that affect the effectiveness of the FRP strengthening system, make difficult the development of simple and reliable formulations to predict the shear strength increase due to the FRP system.

With the scope to clarify the parameters that affect the mechanical behavior of poorly detailed beam-column joints retrofitted with FRP layouts commonly adopted in field applications, an experimental program was carried out by Del Vecchio et al. (2014).

The present paper deals with the theoretical principles of the available simplified models and compares their predictions with existing experimental results. The critical issues related to the complex mechanical behavior of the FRP strengthening system are identified. With reference to experimental evidence and design requirements, several considerations for the improvement of the simplified capacity models are discussed.

EXPERIMENTAL EVIDENCE

The effectiveness of FRP systems as seismic strengthening of poorly detailed beam-column joints was widely demonstrated by experimental tests. However, the significant number of parameters that affect the mechanical behavior of the composite systems in addition to the complex behavior of beam-column joints open to several interpretations of experimental results.

An overview of experiments on beam-column subassemblies subjected to cyclic loads is herein reported in order to point out the critical aspects in the definition of a simplified theoretical expression to predict and design FRP retrofit systems.

Capacity of unstrengthened joints: experimental tests pointed out that the strength capacity of beam-column joints is strongly affected by reinforcement details (Paulay and Priestley 1992). The internal transverse reinforcements allow the development of a truss resisting mechanism that involves the whole concrete core that exhibit a significant shear strength. Poorly detailed beam-column joints usually resist seismic actions by a diagonal concrete compressive strut. The absence of transverse reinforcements lead to the premature cracking of the concrete core. The post cracking behavior is governed by rigid body mechanisms, crack slips and the compressive strength of cracked concrete. These nonlinearities that strongly affect the ultimate strength of the joint panel.

Furthermore, the joint mechanical behavior changes with the joint type (i.e. external, internal, corner). This is related to the different boundary conditions as the confinement pressure of surrounding members (i.e. transverse beams, columns and slab) and the actions transmitted by the transverse beams and anchorages of longitudinal bars (Beres et al., 1996; Pampanin et al., 2002; Murty et al., 2003). The lack of the confinement pressure on all the faces of the joint panel and the local actions transmitted by the anchorages of longitudinal bars make the corner joints the most vulnerable against seismic actions as demonstrated by Priestley (1997) and Pampanin et al. (2002). The same authors, based on the Mohr's circle approach, proposed a simplified model to predict the average principal tension stress of the joint panel at the first cracking or at the peak strength. In particular, the expected principal tension stress is proportional to the square root of the concrete compression strength, $\sqrt{f_c}$, by means of a numerical coefficient k that is a function of the internal reinforcements and the anchorage type. This coefficient was experimentally calibrated and it accounts for all the nonlinearities and local failures in the joint panel. This model showed a good match with experimental tests on poorly detailed beam-column joints tested by Del Vecchio et al. (2014). These tests have also shown that the failure mechanism is characterized by large deep diagonal cracks and concrete wedge spalling-off.

Subassembly failure mode and capacity: the use of FRP system to strengthen the joint panel may result in a sequence of failures change as experimentally demonstrated by Prota et al. (2004). In this case the subassembly strength is governed by the flexural or shear strength of the surrounding members. In particular, the structural members designed without an adequate amount of transverse reinforcement may fail in shear or in flexure without achieving the hardening of longitudinal reinforcements. Thus, the shear strength or the bending moment at the yielding commonly represents the upper bound limit of the subassembly strength.

Mechanical behavior of FRP strengthening: the FRP strengthening applied on the joint panel showed the similar mechanical behavior of the internal transverse reinforcements. The fibers in the direction of the beam axis resist to the concrete wedge spalling-off with a confinement pressure. Furthermore, they work as shear reinforcements. The inspections after experimental tests on FRP strengthened specimens showed that the concrete core is characterized by a diffused crack pattern with a low depth of cracks (Del Vecchio et al., 2014). This confirms that the mechanical behavior of the joint panel retrofitted by externally bonded FRP systems is similar to the truss behavior of joint panel with smeared transverse reinforcements. However, the presence of transverse beams do not allow the joint core full wrapping and this strongly reduces the confinement effect of FRP sheets. In terms of mechanical behavior, this is an important difference in comparison with internal transverse reinforcements (i.e. stirrups). This aspect is deeply analyzed and discussed in Antonopoulos and Triantafillou (2003).

Substrate properties: as for all the other applications of the FRP systems on RC members, also for beam-column joints the debonding strongly affects the performances of the strengthening system. Several devices or surface treatment can be adopted to improve the bond between the concrete surface and the composite system avoiding the debonding at the interface of the two materials. An interesting discussion on this topic is reported in Gergely et al. (2000). However, for poor concrete mechanical properties as in the case of existing buildings, debonding may interest the concrete substrate reducing the effectiveness of the strengthening system as outlined by Realfonzo et al. (2014) and Del Vecchio et al. (2014).

FRP anchorage solutions: a noteworthy problem in the case of beam-column joints strengthened with externally bonded FRP systems is the limited dimensions of the joint panel and the corresponding poor anchorage length of fibers. Several solutions have been provided to anchor the joint panel fibers. In particular, Ghobarah and Said (2002) suggested the adoption of discrete restrain points with the use of bolted steel plates. Antonopoulos and Triantafillou (2003) pointed out that extending the joint panel FRP fibers on the beam and columns a significant increase in the FRP effectiveness can be achieved. However, the adoption of an improved anchorage in a short distance outside the joint panel led to the full exploitation of fiber tensile capacity as pointed out by Antonopoulos and Triantafillou (2003) and Del Vecchio et al. (2014). This anchorage can be obtained by wrapping uniaxial FRP fabrics around the beams and columns (Di Ludovico et al. 2008).

FRP mechanical properties: several type of fibers can be adopted for the strengthening of beam-column joints. In particular, carbon fibers (CFRP) and glass fibers (GFRP) are the most used. However, these fibers present different mechanical properties. The glass fiber are characterized by a lower elastic modulus of about one third the elastic modulus of the carbon fiber. Antonopoulos and Triantafillou demonstrated (2003) that the same strength increase can be achieved by using an amount of GFRP fibers three times higher than that adopted for CFRP fibers. Thus, the axial rigidity of the strengthening system (i.e. the product of the fiber amount multiplied by the elastic modulus) plays an important role in the design of the strengthening system. Furthermore, a small amount of GFRP fibers can lead to high strain levels in the fibers and to large cracking of the concrete surface that can strongly reduce the bond properties and the concrete core resisting capacity.

FRP layout: a large number of experimental test on beam column joints have been carried in order to investigate the influence of the strengthening layout by changing the amount of fibers on the joint panel, the geometry of the strengthening system and the number of strengthened sides of joint panel. In particular, Antonopoulos and Triantafillou (2003) and Del Vecchio et al. 2014 demonstrated that the FRP effectiveness in terms of strength and dissipated energy increased with the amount of fibers, but not proportionally. This can be related to the substrate mechanical properties that can be not able to carry high stress levels. Furthermore, Antonopoulos and Triantafillou (2003) and Shrestha et al. (2009) pointed out that the effectiveness of fibers bonded in the direction of the column was significantly lower than those applied on the beam direction. This because, as discussed before, the fibers in the direction of the beam axis, work as shear reinforcements but also in confining the concrete core. However, the reduced effectiveness of fibers in the direction of the column is also related to the direction of the principle tension stresses in the concrete core that will be discussed in the next session. Antonopoulos and Triantafillou (2003) also demonstrated that FRP sheets are more effective than the FRP strips with the same amount of fibers. This is related to the difficulties in achieving a good bonding on a reduced contact surface, as in the case strips. Finally the presence of a transvers beam orthogonal to the plane of loading, strongly reduce the effectiveness of the FRP system. This can be related to a lower amount of FRP fibers working as shear reinforcements for the concrete core.

Multiaxial loads: Akguzel and Pampanin (2010) demonstrated that the FRP strengthening is effective also if the beam-column subassembly is subjected to a multiaxial load protocol. A more severe load protocol reduces the effectiveness of the strengthening system and should be accounted in the design of the seismic retrofit. However, in the strengthening of three dimensional specimens with an orthogonal beam that intersect the joint panel, the reduced amount of FRP fibers that can be applied to the joint panel should be accounted.

DISCUSSION ON ANALYTICAL MODELS

The analysis of available experimental tests outlines the high number of parameters which affect the mechanical behavior of RC beam-column joints retrofitted with FRP systems. This make the development of simple mechanical models quite a challenging. Several models, based on mechanical principles, have been developed in the past (Antonopoulos and Triantafillou, 2002; Tsonos, 2008 and Akguzel and Pampanin, 2012). In spite of their effectiveness in predicting the strength improvement related to FRP system, they are quite complex to be applied, and several problems in the application in the design practice may occur.

Two big issues need to be accounted in the developing of simple and reliable prediction models: the nonlinearities related to the behavior of the concrete core and the high variability of the effective strains of the FRP strengthening system. The same points were identified by Triantafillou (1998) and Khalifa et al. (1998) as critical issues in the developing of design models for the shear strengthening of RC beams. They also pointed out that, due to concentration of stresses, the FRP systems may fail for stress levels below than their ultimate capacity. To account of these criticisms, they proposed an experimental calibration of the effective FRP strains back calculated from experimental tests. The data were then statistically fitted to obtain the theoretical formulations.

A similar approach was adopted by Bousselham (2010) to estimate the strength increase of the FRP system in the retrofit of poorly detailed corner joints. A simple capacity models has been proposed to account of the effectiveness of different FRP strengthening layouts. It accounts for the fiber elastic modulus E_f (CFRP or GFRP), the amount of fibers on the joint panel ρ_f and the substrate mechanical properties f_c to calculate the effective FRP strain $\varepsilon_{f,e}$. Once the effective strain of fibers is known, the contribution of the FRP strengthening to the principal tension stress can be computed with a simple formulation that account of the fiber inclinations with respect to the inclination of the diagonal cracks. In the design process, a constant inclination of the diagonal cracks related the geometry of the joint panel can be assumed. The resisting principal tension stress can be calculated by adding to the FRP contribution the capacity of the unstrengthened joint. Bousselham (2010) suggested to compute the capacity of the unstrengthened joint panel with the formulation suggested by Priestley (1997) at the peak strength. Finally, the strength capacity of the joint panel retrofitted with FRP systems in terms of joint shear stress can be computed by using the equilibrium relation proposed by Priestley (1997). The comparisons between the theoretical model proposed by Bousselham (2010) and experimental results with reference to the shear stress of the joint panel and to the effective FRP stain are reported in figure 2 and figure 3, respectively. The database, proposed in origin by Bousselham (2010) was enriched by the more recent experimental tests carried out by Del Vecchio et al. (2014) in order to discuss on the accuracy of the model.

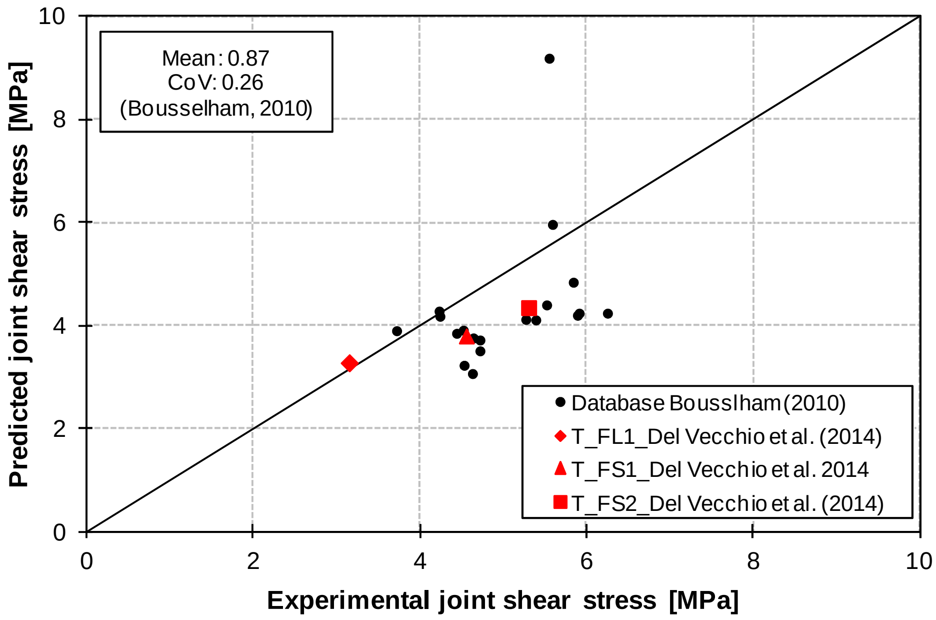

Figure 2. Comparison of experimental results with the theoretical model of Bousselham (2010).

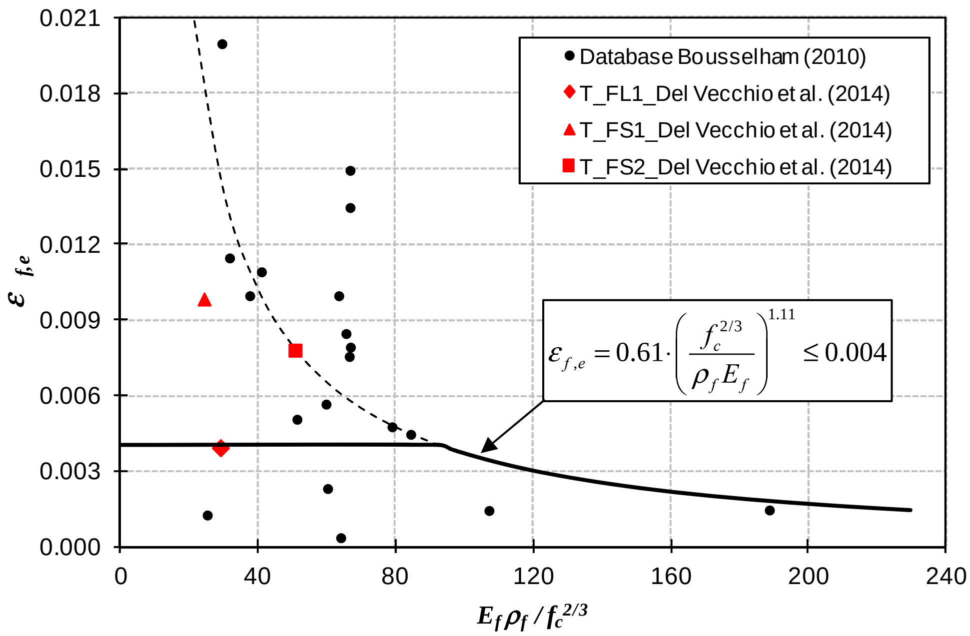

Figure 3. Comparison of experimental results with the formulation for the effective strain proposed by Bousselham (2010).

The comparison between the predicted shear strength and experimental observations, depicted in figure 3, shows the accuracy of the analytical model. In particular, the average value of the ratio between the predicted and experimental data of about 0.87 shows the high safety level related to this model. Figure 2 shows that the safety predictions are related to the FRP effective strain that is limited to 0.4% for design purpose. This limit is commonly adopted to preserve the concrete integrity in the case of RC member confined by externally bonded FRP systems. However, the experimental evidence demonstrated that in the strengthening of beam-column joints, the FRP system works in confining the concrete core and also as shear reinforcement. This led to effective strains in the fibers significantly higher than the proposed limits, as reported in Table 1. In fact, this limitation is commonly not adopted for shear strengthening applications. However, as in the case of RC members strengthened in shear

(Khalifa et al., 1998), an opportune design limit needs to be calibrated in order to reduce crack width. In fact an extensive cracking of the joint panel could led to a premature failure mechanism.

Table 1. Experimental records of joint panel FRP strains

					ε_{max} [%] for specific directions		
Reference	**Specimen**	**Steel**	**FRP reinf.**	**Notes**	**0°**	**45°**	**90°**
Del Vecchio et al. (2014)	T_FL1	Deform.	CFRP fabric	Premature debond.	0.48	0.72	0.09
	T_FS1	Deform.	CFRP fabric	1layer	0.66	1.02	0.1
	T_FS2	Deform.	CFRP fabric	2 layers	0.5	0.64	0.05
Gergely et al. (2000)	all spec.	Deform.	CFRP fabric	FRP bonded on columns (90°)		0.35	
Akguzel and Pampanin (2010)	2DR2	Plain	GFRP fabric		0.7		
	2DR3	Plain	GFRP fabric		0.8		
	2DR4	Plain	GFRP fabric	2 layers in beam direction(0°)	0.4		
Shrestha et al. (2009)	SM1	Deform.	CFRP strips	FRP bonded on columns (90°) monotonic			0.35
	SM2	Deform.	CFRP strips	FRP bonded on beam monotonic	0.8		
	SC1	Deform.	CFRP strips	FRP bonded on columns (90°)			0.3

The strain records on joint panel FRP strengthening systems show that the effectiveness of the fibers depends from their inclinations. The strain records on the fibers in the direction of the column axis (angle of 90°) demonstrate the reduced contribution of these fibers to the joint strength. It is even lower in the case of fibers with a short anchorage length (Del Vecchio et al. 2014) if compared to fibers anchored by mechanical systems (Shrestha et al. 2014). On the other side, the fibers disposed in the direction of the beam axis (angle of 0°) exhibit strain values significantly higher as well as far from the ultimate tensile capacity. These differences can be related to the confinement pressure that the horizontal fibers oppose to concrete core expansion. Furthermore, the vertical fibers are effective as shear reinforcements only when the joint panel is subject to relevant shear stresses that produce significant inclination of the direction of principal tensile stresses respect to the horizontal direction. The comparison between the strain records on these two type of fiber can be useful to quantify the two mechanical contribution that participate to the strength the joint panel. However, the analytical model proposed by Bousselham (2010) do not allow to consider the contribution of the fibers in the direction of the column axis (90°).

Finally, the high number of parameters that affect the mechanical behavior of joint panel strengthened with FRP system suggests the statistical calibration on experimental effective tensile strains. This can be a reliable solution to consider phenomena that can be very difficult to be reproduces as the debondig of fibers. In particular, in this case the concrete substrate of the joint panel strengthening is subjected to a multiaxial stress field transmitted by the FRP fibers placed in different directions. This can sensitively reduce the effective bond carried by the concrete. Further limitation to the fiber effective strain can be related to the reduction of the joint flexibility that represent a parameter that cannot be neglected in the seismic retrofit of existing buildings.

CONCLUSIONS

A literature review of experimental tests on poorly detailed beam-column joint retrofitted with FRP systems is presented. It pointed out that a simple and reliable strength capacity model suitable for all the practical applications is still missing. Focusing on relevant experimental tests, the main parameters that significantly affect the mechanical behavior of the strengthening system are identified and listed below:

- the mechanical behavior and the resisting mechanisms of beam-column joints changes with the joint type (internal, external, corner) and the different boundary conditions should be accounted in developing specific capacity models;
- the mechanical properties of the concrete substrate plays an important role in the effectiveness of the strengthening system and in the case of a strengthening system with fibers in different directions it may be subjected to a multiaxial stress field that can strongly affect the bond properties;
- the analytical models should account of the different layouts and fiber mechanical properties of the strengthening systems that are commonly adopted in field applications;
- the fibers with different inclinations showed a different effectiveness with significant changes in the recorded effective strains;
- the mechanical anchorage significantly increase the FRP effectiveness and could led to the fully exploit of fiber tensile capacity;
- due to concentration of stresses, the FRP systems may fail for stress levels below than their ultimate capacity;
- due to the relevant number of parameters an experimental calibration of the effective tensile strain can be required;
- an upper bound limit to the effective strain should be properly calibrated to account of premature failure mechanisms and high deformations of the joint panel.

AKNOWLEDGMENTS

This study was performed in the framework of PE 2014–2016 joint program DPC Reluis.

REFERENCES

Akguzel U and Pampanin S (2010). "Effects of Variation of Axial Load and Bidirectional Loading on Seismic Performance of GFRP Retrofitted Reinforced Concrete Exterior Beam-Column Joints" *ASCE Journal of Composites for Construction*, ISSN 1090-0268/ 2010/1-94–104, Vol. 14 n°1, 94-104.

Akguzel U and Pampanin S (2012). "Analysis Assessment and Design Procedure for the Seismic Retrofit of Reinforced Concrete Beam-Column Joints using FRP Composite Materials" *ASCE Journal of Composites for Construction*, ISSN 1090-0268/2012/1-21– 34 Vol. 16 n°1, 21–34.

Antonopoulos CP and Triantafillou TC (2002). "Analysis of FRP-Strengthened RC Beam-Column Joints." *ASCE Journal of Composites for Construction*, ISSN 1090-0268/2002/1-41–51/, Vol. 6 n°1, 41–51.

Antonopoulos CP and Triantafillou TC (2003). "Experimental investigation of FRP-strengthened RC beam-column joints." *ASCE Journal of Composites for Construction*, 10.1061/(ASCE)10900268 (2003)7:1(39), 39–50.

Balsamo A, Di Ludovico M, Lignola GP, Prota A, Manfredi G and Cosenza E (2012). "Composites for structural strengthening". *Wiley Encyclopedia of Composites, Second Edition*. Luigi Nicolais and Assunta Borzacchiello eds. John Wiley & Sons, Inc.

Beres A, Pessiki SP, White RN and Gergely P (1996). "Implications of experiments on the seismic behavior of gravity load designed RC beam-to-column connections." *Earthquake Spectra*, 12(2), 185–198.

Bousselham A (2010). "State of research on seismic retrofit of RC beam-column joints with externally bonded FRP." *ASCE Journal of Composites for Construction*, 10.1061/(ASCE)CC.1943-5614.0000049, 49–61.

Del Vecchio C, Di Ludovico M, Balsamo A, Prota A, Manfredi G and Dolce M (2014) "Experimental investigation of exterior RC beam-column joints retrofitted with FRP systems", *ASCE Journal of Composites for Construction*, DOI: 10.1061/(ASCE)CC.1943-5614.0000459, (published online on January 20, 2014).

Di Ludovico M, Manfredi G, Mola E, Negro P and Prota A. (2008). "Seismic behavior of a full-scale RC structure retrofitted using GFRP laminates." *ASCE Journal of Structural Engineering*, 10.1061/(ASCE)0733 9445(2008)134: 5(810), 810–821.

Frascadore R, Di Ludovico M, Prota A, Verderame GM, Manfredi G, Dolce M and Cosenza E (2014). "Local strengthening of RC structures as a strategy for seismic risk mitigation at regional scale". Earthquake Spectra In-Press. doi: http://dx.doi.org/10.1193/122912EQS361M

Gergely J, Pantelides CP and Reaveley LD (2000). "Shear strengthening of RC T-joints using CFRP composites." *Journal of Composites for Construct.*, 10.1061/(ASCE)1090-0268(2000)4:2(56), 56–64.

Ghobarah A and Said A, (2002). "Shear strengthening of beam-column joints" *Engineering Structures*. Vol. 24, 881–888

Khalifa A, Gold WJ, Nanni A and Aziz A (1998). "Contribution of externally bonded FRP to shear capacity of RC flexural members". *ASCE Journal of Composites for Construction*, ISSN 1090-0268/98/0004-0195-0202, Vol. 2, N° 4, 195-202.

Murty CVR, Rai DC, Bajpai KK and Jain SK (2003). "Effectiveness of Reinforcement Details in Exterior Reinforced Concrete Beam-Column Joints for Earthquake Resistance". *ACI Strucutral Journal*, V. 100, No. 2, 142-156.

Pampanin S, Calvi GM, Moratti M (2002). "Seismic behaviour of R.C. beam-column joints designed for gravity loads". *12th European Conference on Earthquake Engineering*. Paper Reference 726. Published by Elsevier Science Ltd.

Paulay T and Priestley MJN (1992). "Seismic design of reinforced concrete and masonry buildings". John Wiley & Sons, Inc.

Priestley MJN, Seible F and Calvi GM (1996). Seismic design and retrofit of bridges, Wiley, New York.

Priestley MJN (1997). "Displacement-based seismic assessment of reinforced concrete buildings." *Journal of Earthquake Engineering*, DOI: 10.1080/13632469708962365, 1(1), 157–192.

Prota A, Di Ludovico M, Balsamo A, Moroni C, Dolce M and Manfredi G (2014). "FRP local retrofit of non-conforming RC beam-column joints. Seismic evaluation and rehabilitation of structures." *Geotechnical, geological and earthquake engineering*, A. Ilki and M. N. Fardis, eds., 26, Springer International Publishing, Switzerland

Prota A, Nanni A, Manfredi G and Cosenza E (2004). "Selective upgrade of under-designed reinforced concrete beam-column joints using carbon fiber-reinforced polymers." *ACI Structural Journal*, 101(S69), 699–707.

Realfonzo R, Napoli A, Ruiz Pinilla JG (2014). "Cyclic behavior of RC beam-column joints strengthened with FRP systems". *Construction and Building Materials*. Vol. 54, 282–297.

Shrestha R, Smith ST and Samali B (2009). "Strengthening RC beam–column connections with FRP strips". *Structures and Buildings*. Vol. 162, Issue SB5.

Triantafillou TC (1998). "Shear Strengthening of Reinforced Concrete Beams Using Epoxy-Bonded FRP Composites" . *ACI Strucutral Journal*, V. 95, No. 2, 107-115.

Tsonos A (2008). "Effectiveness of CFRP-jackets and RC-jackets in post-earthquake and pre-earthquake retrofitting of beam–column subassemblages." *Engineering Structures*, Vol. 30, 777-793.