PAPER REF: 3880

BUILDING FAÇADE PERFORMANCE IN THE LORCA EARTHQUAKE AND RETROFIT SOLUTIONS

Julio C. López-González[1(*)], Jaime Fernández-Gómez[2], Ramón Álvarez-Cabal[3]

[1]Dpt. of Building and Precasting, School of Civil Engineering, Technical University of Madrid, Madrid, Spain
[2]Dpt. of Building and Precasting, School of Civil Engineering, Technical University of Madrid, Madrid, Spain
[3]Dpt. of Structures, E.T.S.I.I, Technical University of Madrid, Madrid, Spain
[(*)]*Email:* julio.lopez@caminos.upm.es

ABSTRACT

This work studies the earthquake damage of building façades in the recent Lorca earthquake (Spain). The deficient performance of building façades, which resulted in either partially detachment or total collapse, caused that a number of people were injured as well as significant economic losses since it has led to building being unoccupied. The causes of failure of these elements are analyzed and a study of retrofit techniques is carried out in order to select the most effective solution.

Keywords: façades, seismic retrofit, rehabilitation, masonry.

INTRODUCTION

The poor seismic behavior of building façades (out-of-plane stability and structural integrity) is a problem which is very significant for seismic performance and one which is often ignored. The earthquake damage of some building façades, which are consider as non-structural elements, reflects improper construction solutions for seismic zones, which have been found to be the most common causes of failure.

These construction solutions consists of improper anchorage of masonry panel to the frame, weak plane due to waterproofing membrane, partially supported masonry elements, among others. More striking yet is the fact that detailing of waterproofing membrane is contained in Spanish standard (Álvarez-Cabal, 2011) and the regulatory stress on the parapets, a 1.6 kN/m live load on the upper edge, is greater than the earthquake demand (Dávila, 2011).

Even though the seismic performance depends strongly on the type of masonry and frame, it is widely known that a key to achieve out-of-plane performance is a good connection to the frame. It is noted that in confined masonry this comes naturally and for infill panels special ties are required (Totoev Y, personal communication September 21, 2012). However, for out-of-plane strengthening of existing masonry panels, special aspects should be taken into account such as the influence of strengthening on overall response of the structure, functionality and aesthetics.

This paper presents the damage assessment of the façade system of reinforced concrete buildings in Lorca, Spain, and a study of retrofit solutions is carried out to improve its out-of-plane performance.

EARTHQUAKE DAMAGE OF BUILDING FAÇADES IN LORCA

In the Spanish construction practice of apartment buildings, the exterior wall overhangs the frame, one third of the wall thickness at most (Fig. 1). These masonry façades are, in the main, designed to resist wind loads; however, the recent earthquake in Lorca, which exceeded the stipulated seismic demand in the current Spanish standard, caused the collapse of façades and parapets, arousing interest for increased research.

It is worth mentioning that after post-earthquake inspection of damaged buildings, the excessive wall overhang, the lack or deficient anchorage to the frame and the weak plane formed by the presence of waterproofing membrane (Fig. 2), were considered as the most common causes of failure of masonry façades.

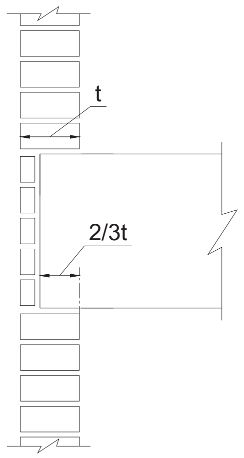

Fig.1 External wall configuration in Spanish construction practice

Fig.2 Waterproofing membrane placed on horizontal joint

In light of the foregoing, this paper compares the seismic action obtained according to the current Spanish code with the Lorca earthquake demand on a masonry infill belonging to the top story of a common reinforced concrete (RC) building. On the basis of the out-of-plane strength assessment of the masonry wall, the retrofit systems are studied to enhance its performance, including an economic evaluation.

OUT-OF-PLANE ANALYSIS OF MASONRY INFILL

The object of this section is the seismic assessment of masonry infill belonging to an idealized eight-story regular building. The wall has a thickness of 115mm, 4.6m of clear length and 2.7m of clear height. The solid brick used for façades in Spanish construction practice has nominal dimensions of 240×115×50mm, a compressive strength of 5MPa and Young's modulus of 5GPa. The weight of the masonry is 15kN/m³.

Seismic demand on the masonry infill

On the basis of a masonry infill can be analyzed as non-structural element, the out-of-plane seismic demand has been determined by the equivalent static load according to EC-8 (Eq. 1), using the basic acceleration a_b corresponding to the town of Lorca which is equal to 0.12g according to the Spanish Seismic Building Code NCSE-02.

$$F_a = \rho a_b S \left(\frac{3\left(1+z/H\right)}{1+\left(1-T_a/T_1\right)^2} - 0.5 \right) W_a \, \gamma_a / q_a \qquad (1)$$

Since the masonry wall belongs to a building with normal importance, thus $\rho = 1$. Moreover, for a masonry infill, $\gamma_a = q_a = 1$. Considering level z at the mid-height of the wall, thus $z/H = 0.94$ and, assuming no rocking of the wall, $T_a/T_1 = 0$. Therefore, the amplification factor (term in brackets) of the design ground acceleration is equal to 2.41. The Table 1 provides, for each type of soil, the amplified acceleration S_a, the equivalent static load F_a and the corresponding pressure q_a.

Table 1. Seismic demand on masonry infill pursuant to EC-8 and NCSE-02

Type of soil	S_a (g)	F_a (kN)	q_a (kPa)
I	0.235	5.04	0.41
II	0.300	6.43	0.52
III	0.365	7.82	0.63
IV	0.451	9.67	0.78

It is widely known that earthquake in Lorca exceeded the seismic demand stipulated in the current Spanish standard. Fig. 3 shows the acceleration time history of the N-S component and Fig. 4 the response spectrum as well as those calculated according to NCSE-02 for soil types I and II.

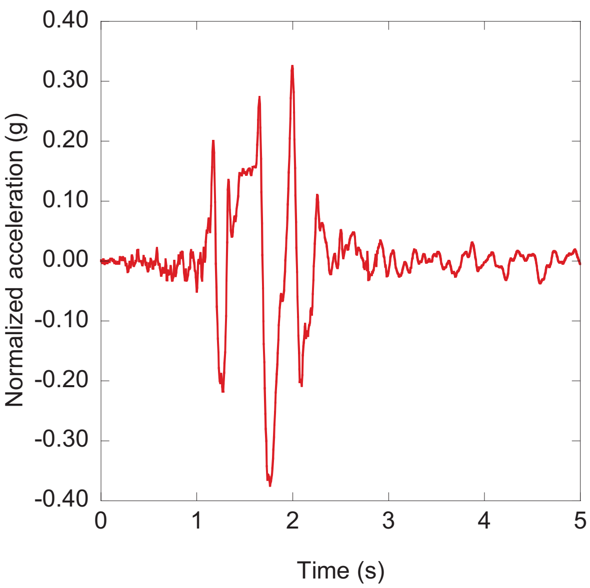

Fig. 3 Acceleration time history of N-S component of Lorca earthquake

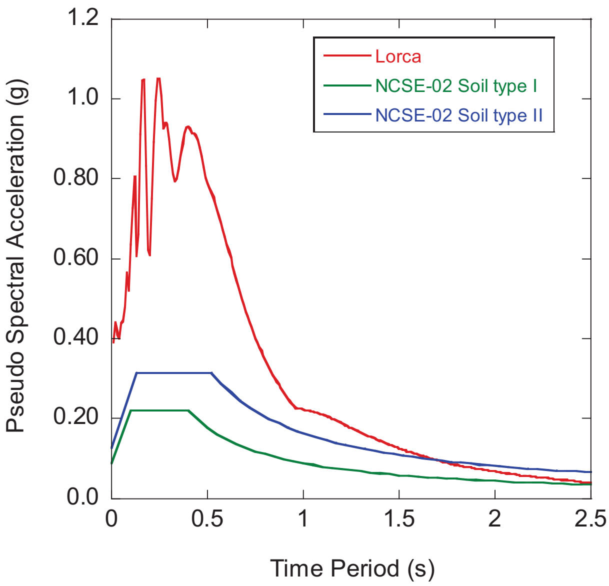

Fig. 4 Response spectrum

Using the spectral acceleration corresponding to $T = 0$ as the basic acceleration $a_b = 0.4$ g, and substituting this value in Equation (1), the seismic acceleration demand on masonry infill for soil type I is equal to 0.96 g and the static equivalent force is equal to 20.6 kN, which is significantly greater than those contained in Table 1. This value is used hereafter as the design seismic demand.

Out-of-plane strength of the masonry infill

Out-of-plane strength of the masonry infill has been evaluated considering arching action. Three basic requirements are needed to consider an arching mechanism. Firstly, the masonry infill should be in full contact with the surrounding frame; secondly, the frame elements should be capable of resisting the arch thrust and finally, the ratio height-to-thickness should not be greater than a limit value ranging from 20 (EC-6) to 25 (ASCE/SEI 41-06). Due to the last requirement, the EC-6 is not applicable to the present case. In addition to this, the EC-6 calls a minimum vertical design stress of 0.1 MPa.

On the other hand, according to CTE-2009 a partial coefficient for compressive strength between 1.7 and 3.0 should be applied depending upon the fabrication category and the execution control. In this analysis, a coefficient of 2.2 has been applied, thus the design compressive strength of masonry is equal to $5/2.2 = 2.27$ MPa.

The out-of-plane strength of the masonry infill has been estimated for different fractions of the total thickness t to simulate the wall overhang. The ratio capacity-to-demand obtained according to each code is provided in Table 2.

Table 2. Out-of-plane strength of the masonry wall obtained by arch effect analysis.

Wall thickness	F_R/F_a	
	CTE-09	ASCE 41
t	3.53	1.44
2/3t	0.95	NA
0.5t	NA	NA

The results contained in Table 2 demonstrate the out-of-plane vulnerability of masonry infills that overhang the frame without proper anchorage.

Finally, considering that the arch mechanism can be developed through the entire thickness by inertial force acting towards the interior of the building, only retrofit in the opposite direction is studied.

OUT-OF-PLANE RETROFITTING TECHNIQUES

It is worth noting that the out-of-plane strength of masonry wall retrofitted by any system described below is estimated assuming to behave under simply supported conditions. (i.e. arching effect is not considered). This behavior does not reflect the real boundary conditions in a masonry infill. Lunn, D (2009) reported a premature failure at the boundary (transverse shear sliding) that can occur before those described in simply supported test methods (e.g. compression masonry, debonding or rupture of the external reinforcement). Hence, the collapse of the entire wall should be prevented through proper connection to the surrounding frame. The same author (Lunn, D 2011, 2012) reported the largest strength by using steel restraints.

FRP laminates. In this method, GFRP laminates are bonding to one side of the masonry wall. In the present paper, the out-of-plane strength of the masonry wall has been obtained applying the usual flexural theory. Since GFRP debonding often controls the flexural capacity of the wall, the force limit proposed by Kashyap, 2012 has been applied. The reader is referred to the aforementioned paper and to Willis CR 2009, 2010 for details of the procedure.

The GFRP material needed to increase the flexural capacity of the masonry wall in order to withstand the seismic demand consists of 200mm-with and 2mm-thickness GFRP laminates spaced 800mm (Fig. 5). The GFRP laminate has an ultimate strain of 2.5% and Young's modulus of 37GPa.

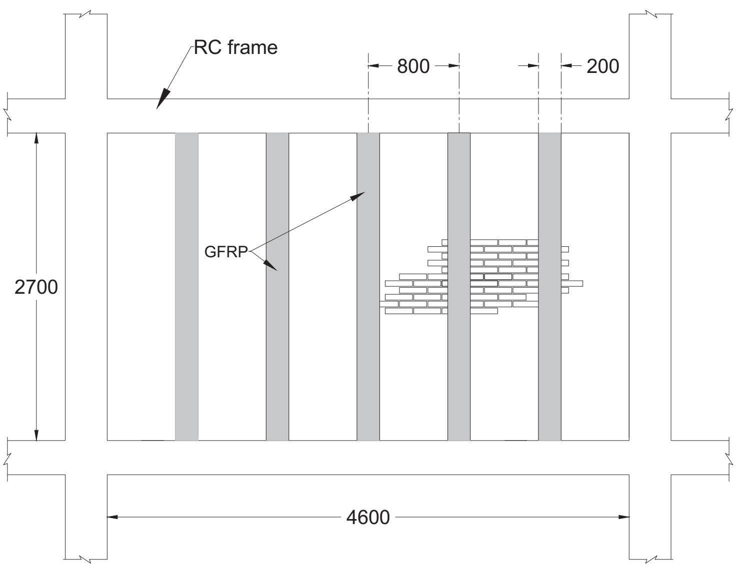

Fig. 5 GFRP laminates

Since the out-of-plane strength has been estimated assuming that the masonry wall behaves as simply supported element, a proper anchorage should be provided. Steel angles are proposed for that purpose, as illustrated in Fig. 6.

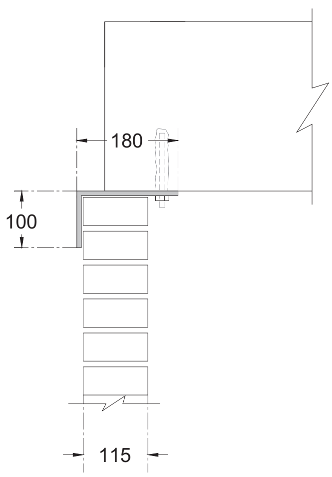

Fig. 6 Anchorage system

A total of ten angles (one at each end of the laminates) of 100mm×180mm×6mm can be disposed to transfer the reaction force. Each steel angle has a length of 200mm (the same as the width of the GFRP laminate). The turned-down length of the steel element would tend to straighten out and the bending stresses set up would require calculation, as noted by Curtin WG, 1984.

FRP strips. In this method, FRP strips/bars are inserted into grooves made in the masonry surface (Willis CR 2009; Dizhur D, 2010; Griffith MC, 2012). The out-of-plane strength of the masonry wall has been obtained using the formulation of Dizhur D, 2010. The reader is referred to that paper for details. The retrofit solution consists of three 15×1mm CFRP strips spaced 1.5m, as shown in Figs. 7, 8 and 9. The CFRP strip, as reported by the manufacturer, has Young's modulus of 165GPa and ultimate strain of 1.5%.

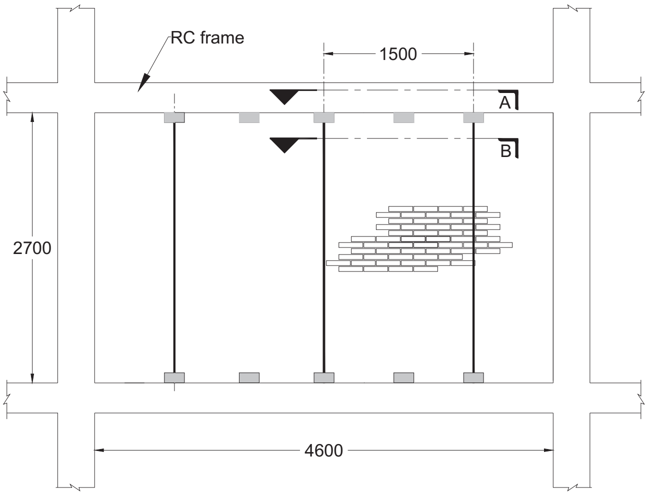

Fig. 7 NSM Retrofit. ELEVATION

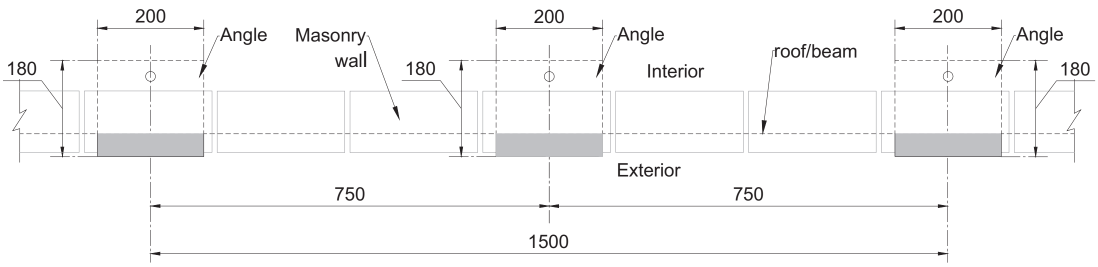

Fig. 8 NSM Retrofit. VIEW A.

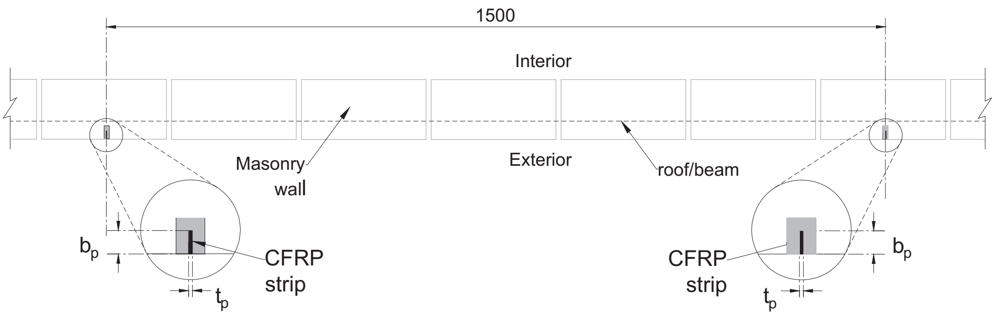

Fig. 9 NSM Retrofit. VIEW B

GFRP grid and mortar overlay. The more recent researchers use fiber-reinforced cement based materials (Kyriakides, 2011), which are commonly referred as engineered cementitious composites, and elastomeric polyureas (Hrynyk, T 2007). This technique improves significantly the flexural strength and deformation capacity. Kyriakides, 2011 reported an increase of load carrying capacity by 35 times. Though this system is an ongoing research topic and there is no established design procedure, it has been included in this paper for economic comparison purpose.

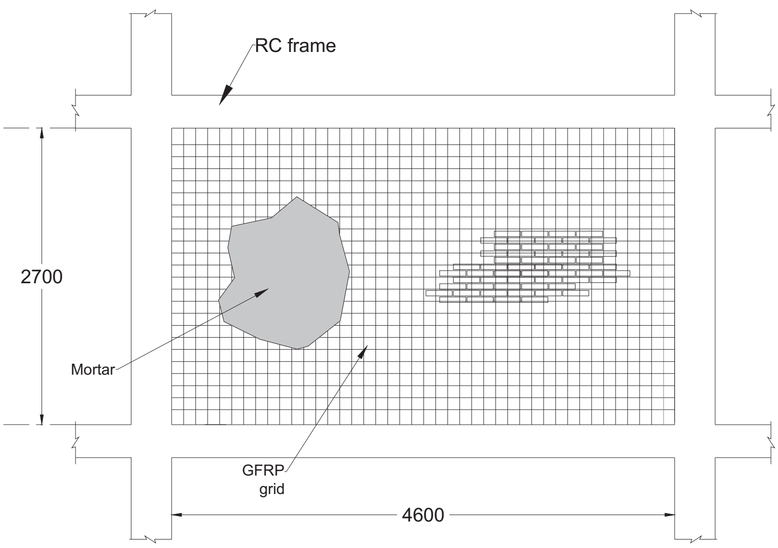

Fig. 10 GFRP Grid Retrofit. ELEVATION.

Economic evaluation

An economic comparison of the three retrofit systems has been carried out. The cost of each technique CR_i has been compared to the sum of demolition and reconstruction cost of the masonry infill CDC as follows

$$\mathrm{C} = \frac{\mathrm{CDC} - \mathrm{CR}_i}{\mathrm{CDC}} \times 100 \qquad (2)$$

The new infill would include horizontal reinforcement and ties. The cost of demolition and reconstruction of the infill have been taken from of CYPE Ingenieros S.A. price bank, and from suppliers for the retrofit systems. Fig. 11 illustrates the C-factor of each retrofit system.

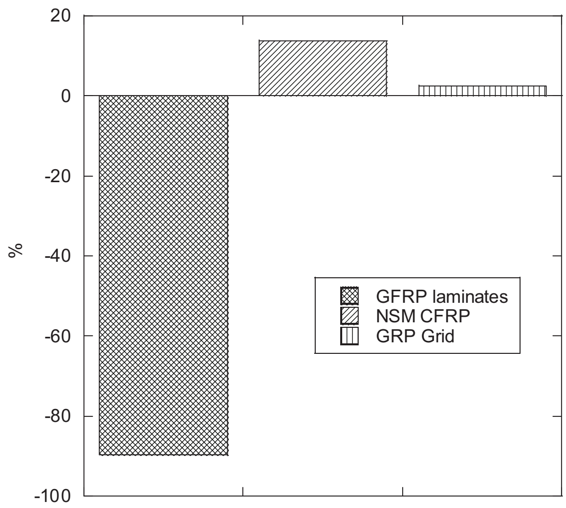

Fig. 11 Economic comparison

It is noteworthy that demolition and reconstruction of the masonry infill imply more time consuming and the need of unoccupied area, which involves an additional cost not included in this study.

Special considerations in seismic rehabilitation of masonry infills

Masonry infills that are not connected to the surrounding frame are considered, primarily, as nonstructural elements (EC-8) and they are not taken into account in global response of the structure. However, if retrofit solution involves an increase of in-plane strength and an interaction with the surrounding frame is expected, the following verifications are desirable:

a) Global response. Diagonal strut is a typical method for represent the masonry infill in the model. However, the load-displacement response of the strut should be in agreement with the properties of the strengthened wall.

b) Local effects. The stress concentration generated by the diagonal strut should not exceed the shear strength of the frame elements. According to EC-8 and ASCE standard, the shear strength of the columns should be higher than either, the shear strength of the masonry infill or the shear force obtained by a capacity design of a column with reduced length given by the vertical dimension of the diagonal strut.

Retrofit systems described in this paper involve an increase in shear strength of the masonry infill, thus, a case-specific study should be carried out in order to check the above verifications.

CONCLUSIONS

From comparison of seismic demand calculated according to the current Spanish Seismic Building Code NCSE-02 with the corresponding to the acceleration time history of the N-S component of Lorca earthquake, a masonry infill belonging to the top floor of an eight-story RC building has been found vulnerable to collapse. The more recent retrofit techniques have been studied to increase the out-of-plane strength of the masonry wall.

The following conclusions can be drawn from the findings:

- Retrofitting masonry infills via NSM system bears the new seismic demand, affecting minimally the aesthetics of the wall. Furthermore, this technique is the least-cost alternative. Since the out-of-plane strength has been evaluated as isolated component in flexure, an anchorage system should be installed (e.g. steel angles).
- The use of waterproofing is a common practice in Spanish construction, thus there is a need to investigate the capability of transmitting horizontal force. Furthermore, in the view of the authors, the arching action in both directions in a masonry infill overhanging the frame is another area that needs investigation. Similarly, experimental tests are needed to evaluate the effectiveness of the anchorage system suggested in this paper.
- From author's perspective, this study shows that there is an imperative need to unify seismic recommendations and construction practices of masonry infills. In light of the findings, further research should be carried out in order to update standard of façades, parapets and partitions, and develop guidelines for rehabilitation of non-structural elements.

ACKNOWLEDGMENTS

Special thanks are due to Sika® and to the Instituto Técnico de Materiales y Construcciones (INTEMAC) for their funding support. The authors would also like to acknowledge the comments and observations done by Suyapa Dávila, Tiago Teixeira and Borja Jimenez, Civil Engineers at Dpt. of Structures, INTEMAC.

REFERENCES

ASCE/SEI 41-06. Seismic rehabilitation of existing buildings. American Society of Civil Engineers.

Álvarez-Cabal R, Dávila S, Diáz-Pavón, E. Comportamiento de los cerramientos y particiones durante el terremoto de Lorca. Zuncho, 2011, 30, p. 29-43. (In Spanish).

Curtin WG, Shaw G, Beck JK, Parkinson GI. Structural masonry detailing. 1984. Granada Publishing.

Dávila S, Hoogendoorn P, Álvarez-Cabal R. Actions on façades. Intemac quaterly, 2011, 83, 3rd quarter '11.

Dizhur D, Derakhshan H, Lumantarna R, Griffith M, Ingham I. Out-of plane strengthening of unreinforced masonry walls using near surfaced mounted fibre reinforced polymers strips. SESOC Journal, 2010, Vol. 3 No. 2.

Erdem I, Akyuz U. Analytical investigation of lateral strength of masonry infilled RC frames retrofitted with CFRP. Journal of Performance of Constructed Facilities. 2010, 24-4.

Eurocode 6. Design of masonry structures. Part 1-1 General rules for reinforced and unreinforced masonry structures. UNE-EN 1996-1-1.

Eurocode 8. Design of structures for earthquake resistant. Part 1. General rules, seismic action and rules for buildings UNE-EN 1998-1.

Griffith MC, Kashyap J, Mohamed Ali MS. Flexural displacement response of NSM FRP retrofitted masonry walls. Construction and Building Materials. 2012. In press.

Hrynyk, T. Static Evaluation of the out-of-plane behavior of URM infill walls utilizing modern blast retrofit systems.MsS Thesis, 2007, University of Missouri-Rolla.

Kashyap J, Willis CR, Griffith MC, Ingham JM, Masia MJ. Debonding resistance of FRP-to-clay brick masonry joints. Engineering Structures, 2012, Vol. 41, 186-198.

Kyriakides, M. Seismic retrofit of unreinforced masonry infills in non-ductile reinforced concrete frames using engineered cementitious composites. PhD Thesis, 2011, Stanford University.

Lunn D, Rizkalla S. Strengthening of Infill Masonry Walls with FRP Materials. Journal of Composites for Construction. 2011, 15, 2, 206-214. ASCE.

Lunn D, Rizkalla S, Maeda S, Ueda T. FRP Anchorage Systems for Infill Masonry Structures. Proceedings of the 3rd Asia-Pacific Conference on FRP in Structures (APFIS 2012).

NCSE-02 Norma de construcción sismoresistente. BOE no. 244. Viernes 11 Octubre 2002.

Ozcebe G, Binici B. Seismic evaluation of infilled reinforced concrete frames strengthened with frps. Proceedings of the 8th U.S. National Conference on Earthquake Engineering. San Francisco, California, USA.

Paulay T, Prestley MJN. Seismic design of reinforced concrete and masonry buildings. John Wiley & Sons. 1992.

Willis CR, Seracino R, Griffith MC. Out-of-plane strength brick masonry retrifitted with horizontal NSM CFRP strips. Engineering Structures. 2010, 32, 547-555.

Willis CR, Griffith MC, Ingham JM. Design of FRP retrofitted masonry under out-of-plane bending. Asia-Pacific Conference on FRP in Structures. Seoul, Korea 2009.