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CONSIDERATIONS ABOUT NON LINEAR STATIC ANALYSIS OF A REINFORCED CONCRETE FRAME RETROFITTED WITH FRP

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Abstract. In seismic areas there are a lot of buildings that need to be retrofitted. In some cases it is possible to apply fibre-reinforcement polymer/plastic (FRP) as rehabilitation method. Several researches have been developed with this technology in the last years. Also there are guides for the design of FRB systems for strengthening existing structures. But it is necessary to count with reliable methodologies for structural analysis of these structures retrofitted. In some cases the codes require non linear analysis for the verification of design proposed as retrofit. And in this area it is necessary to do new researches. Considering this topic, the object of this paper is to evaluate the possibility of the non linear static analysis for simulate the response of reinforced concrete (RC) frame retrofitted with FRP. We designed RC frames with an old Argentinian code. These 2 dimensions frames had one floor and one span. These frames were built and then subject to a pseudo static test. One of the frames was retrofit with FRB, and then it was again subject to a pseudo static test. With two finite element programs we created a numerical simulation of the frame with/without a retrofit with FRP, and emphasized the possibility of both programs. We evaluated and compared the responses obtained. In the conclusions we made consideration about the simulation of reinforcement concrete frame with FRP.

1 INTRODUCTION

In recent years, nonlinear static analyses have received a great deal of research attention within the earthquake engineering community. Their main goal is to describe the nonlinear capacity of a structure when subject to horizontal loading with a reduced computational effort with respect to nonlinear dynamic analysis. Pushover methods are particularly indicated for assessing existing structures (Ferracuti *et al.*, 2009).

When existing structures need a retrofitting we can apply different methodology. One of them is the use of FRP (Ferracuti and Savoia, 2005 and 2007, Ferracuti et al., 2006). But it is necessary to have software where the analysis of these structures can be made. Research in this area is necessary to develop and to check the accuracy of these programs.

The object of this paper is to evaluate the possibility of two commercial programs for simulate the response of RC frame retrofitted with FRP through the non linear static analysis.

For reach this object we divided the research in two phases. The first was an experimental phases, where we could get experimental values for RC frames with and without FRP. These frames were designed with an old Argentinian code. It is described in section 2 of this paper. In the second phase we selected two commercial programs to simulate the RC frames with/without FRP. We described the characteristic of these programs in section 3, and the result obtained in the section 4. Finally we present the conclusion in section 5.

2 FRAMES TESTED

We considered the pseudo static tests of two RC frames, called Frame1 and Frame2. They are shown in Figure 1.

a) Frame1 b) Frame2

Figure 1: Frame tested

The Frame1 was tested until collapse, whereas Frame2 was tested in two phases. In the first part we applied a load until to get a story drift of 1%, and then we unload the frame. As a second phase, we applied FRP at the ends of the columns, and then we applied a load until collapse.

The Figure 2 shows a detail of the FRP in the Frame2, and the Figure 3 and 4 show the Frame1 and Frame2 after the test.

In Frame1 we observed a lot of important cracks at the ends of the columns and beam (Figure 3). After the test in the Frame2 without FRP we observed little cracks at the ends of the columns (Figure 4-a). The Frame2 with FRP had a behavior very ductile (Figure 4-b). In this test only appeared cracks in the section where the FRP was not effective (joint column/beam and column/base).

Figure 2: Frame2 with FRP

Figure 3: Frame1 after the test

a) First phase (without FRP) b) Second phase (with FRP)

Figure 4: Frame2 after the test

The parameters of these frames are given in Table 1.

Parameter		**Frame1**	**Frame2**
Type of frame		2D	2D
Number of bays		1	1
Number of story		1	1
Bay length [m]		2	2
Storey height		1.64	2.64
Structural material		Reinforced concrete	Reinforced concrete without and with FRP
Concrete	Compressive strength [MPa] (1)	13	13
Reinforc.	Modulus of elasticity supposed [MPa]	200000	200000
	Yield strength fy [MPa] (1)	535	535
FRP	Type	-	Composite material sheets SikaWrap Hex-100g and Sikadur41 as adhesive
	Jacket elastic modulus supposed[GPa] (2)	-	70
	Jacket ultimate strain supposed (2)	-	0.030
	Number of layer over the ends of the columns	-	1
	Length of the FRP at columns [mm]	-	700
Column	Section height [mm]	150	150
	Section width [mm]	125	125
	Reinforcement	4Ø6 + 1Ø4.2 c/15 cm	6Ø6 +1Ø4.2 c/15 cm
Beam	Section height [mm]	200	200
	Section width [mm]	125	125
	Reinforcement	4Ø6 + 1Ø4.2 + 1Ø4.2 c/15 cm	4Ø8 +1Ø4.2 c/15 cm
Highest applied load [kN]		14.71	Frame without FRP: 7.65 Frame with FRP: 13.53

(1) According to tests
(2) According to SeismoStruct (2001)

Table 1: Parameters of the frames tested.

With these tests we obtained the pushover curves (base shear vs. displacement). These curves are shown in Figure 5 and 6 for the Frame1 and Frame2. For the highest displacement in the Frame2 without FRP, the base shear is 15% lower that in the Frame2 with FRP.

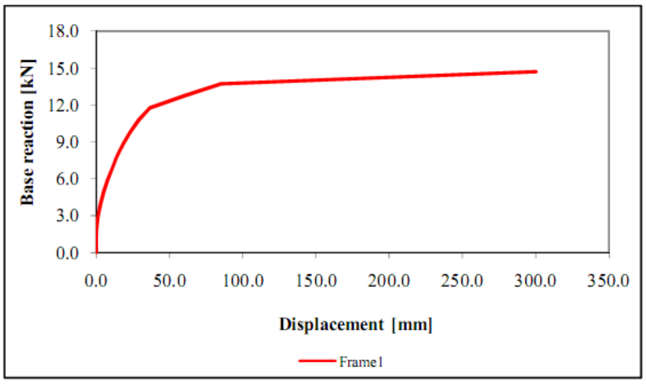


Figure 5: Base shear vs. displacement in Frame1 according to the test

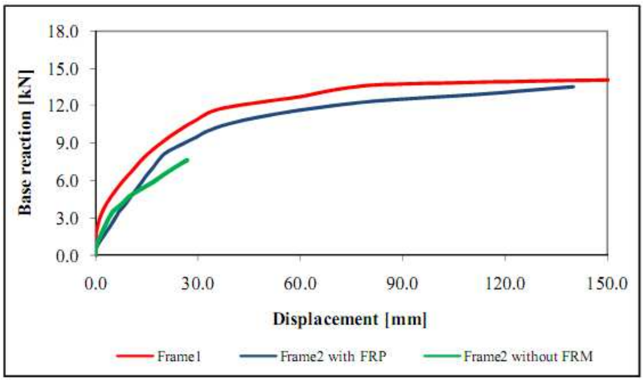


Figure 6: Base shear vs. displacement in Frame1 and Frame2 according to the tests

3 SOFTWARE USED IN THE PUSHOVER ANALYSIS

The pushover analyses were executed with two finite element programs: SAP2000 (SAP2000, 2009), and SeismoStruct (SeismoStruct, 2010). SAP2000 is an integrated software for structural analysis & design, who was introduced 30 year ago. SeismoStruct has been developed for the accurate analytical assessment of different classes of structures, such as buildings, bridges or industrial plants, subjected to earthquake strong motion. In the next sections we describe the main characteristics of these programs for pushover analysis.

3.1 SAP2000 (SAP2000, 2009) for pushover analysis

For pushover analysis is necessary consider the material nonlinearity. In SAP2000 yielding and post yielding behavior can be modeled using discrete user-defined plastic hinges in frame elements (or default hinge properties). Outside of the hinges, the material is considered linear and elastic.

For each degree of freedom, you may define a force-displacement or moment-rotation curve that gives the yield value and plastic deformation following yield. This is done in terms of a curve with values at five points: A (the origin), B (represent the yielding), C (represent the ultimate capacity for pushover analysis), D (represent a residual strength for pushover analysis), and E (represent total failure). One of these moment-curvature curves used in SAP2000 for this paper is shown in Figure 7.

Point	Moment/SF	Curvature/SF
E-	-0.23	-0.8
D-	-0.23	-0.48
C-	-5.12	-0.44
B-	-3.65	0
A	0	0
B	3.65	0.
C	5.12	0.44
D	0.23	0.48
E	0.23	0.8

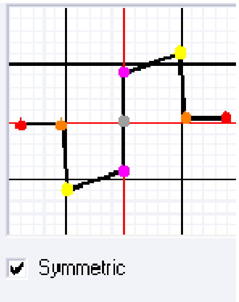


Figure 7: Frame hinge properties in SAP2000

In SAP2000 is possible to consider different numbers of hinges in each column. We compared (see section 4.1) result of pushover analysis with ten and with two hinges for column.

The values of moment and curvature for the point A to D (before mentioned) were obtained through sectional analysis using the software Response-2000 (2001). This was made only in the Frame1 and in the Frame2 without FRP. We do not have experimental values or program to get moment vs. curvature curve in a reinforced concrete element with FRP.

One of the moment vs. curvature curve obtained with Response-2000 (2001)is shown in Figure 8. For the concrete this curve is based in: Popovic/Thorenfeldt/Collins for the base curve, Vecchio-Collins 1986 for compression softening, and Bentz 1999 for tension stiffening. For the reinforcement we consider the parameters mentioned in Table 1 and: 7.0 mm/m as e-strain hardening, 100 mm/m as rupture strain, 802 MPa as ultimate strength.

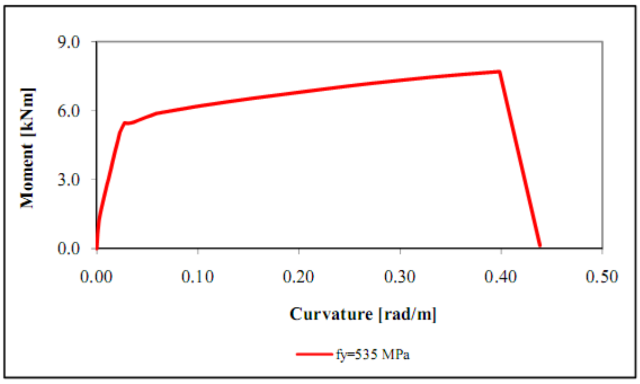
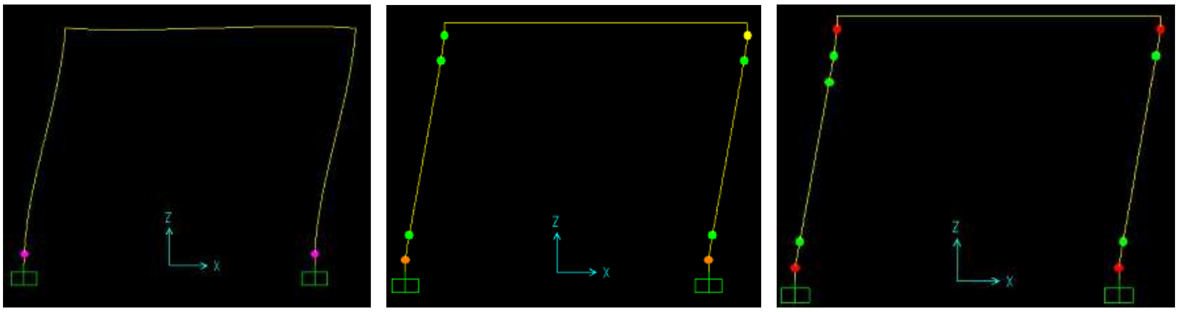


Figure 8: Moment vs. curvature of one column in Frame2 according to Response-2000

As load case we consider a lateral load as load pattern. Also it is possible to use an acceleration load or a modal load. We applied a displacement control, using a monitored displacement (with a magnitude of 1.00 m).

The pushover results in SAP2000 are: pushover curve (base shear vs. displacement), capacity spectrum, moment vs. plastic rotation in each hinge, and the deflected shape showing the hinge state. So, in Figure 9 the state of the hinges at different step of one pushover analysis is presented (the hinge is pink when she get yielding, yellow when she get the ultimate capacity, and red when she get the total failure.



a) Step 1 b) Step 5 c) Step 24

Figure 9: Hinges in different steps of Frame1 according to SAP2000

3.2 SeismoStruct (SeismoStruct, 2010) for pushover analysis

In SeismoStruct, use is made of the so-called fibre approach to represent the cross-section behaviour, where each fibre is associated with a uniaxial stress-strain relationship; the sectional stress-strain state of beam-column elements is then obtained through the integration of the nonlinear uniaxial stress-strain response of the individual fibres (typically 300-400) in which the section has been subdivided. Such models feature additional assets, which can be summarized as: no requirement of a prior moment-curvature analysis of members; no need to introduce any element hysteretic response (as it is implicitly defined by the material constitutive models); direct modelling of axial load-bending moment interaction (both on strength and stiffness); straightforward representation of biaxial loading, and interaction between flexural strength in orthogonal directions.

As constitutive laws we use: a uniaxial bilinear stress-strain model with kinematic strain hardening for reinforcement, a uniaxial nonlinear constant confinement model for the concrete (the confinement effects provided by the lateral transverse reinforcement are incorporated as a confinement factor), and an uniaxial nonlinear variable confinement model developed and programmed by Ferracuti and Savoia (2005) for the reinforced concrete with FRP (the effects of the confinement introduced by the FRP wrapping are modelled through the employment of the rules proposed by Spoelstra and Monti (1999).

We use different values of confinement factor for concrete cover and the concrete in the section core.

The values to include in the reinforced concrete with FRP model (FRP jacket elastic modulus and FRP jacket ultimate strain) were selected according to the recommendation given in SeismoStruct (2010). More details about the nonlinear variable confinement model for the reinforced concrete with FRP can be found in Ferracutti *et al.* 2006 and Ferracuti and Savoia (2007).

In columns and beam we consider inelasticity displacement-based frame elements.

Distributed inelasticity frame elements can be implemented with two different finite elements (FE) formulations: the classical displacement-based (DB) ones, and the more recent force-based (FB) formulations.

The applied load was an incremental load in one of the node of the beam, and the manner in which the load factor is incremented throughout the analysis (loading strategy adopted in the pushover analysis) was a response control with a specific target displacement. The more advanced adaptive pushover analysis of the SeismoStruct (2010) was not used because the structures studied have one bays and one story.

As results in this software we obtained displacement and load factor to plot pushover curve (base shear vs. displacement).

4 PUSHOVER CURVES AS RESULT OF THE PUSHOVER ANALYSIS

In this section we present the pushover curves obtained with SAP2000 (2009) and SeismoStruct (2010), and compare with the values measured in the test. We present the results for Frame1 and Frame2 (with and without FRP).

4.1 Pushover curves for the frames without FRP

The pushover curve for the Frame1 is shown in Figure 10. The curve obtained in SeismoStruct (2010) has the same shape that the experimental curve. But the highest load in this software is 13,6 % lower that the corresponding experimental load. The pushover curve in SAP2000 (2009) is also similar to the experimental curve until a displacement of 130 mm. Then, some hinges of the model exceed the ultimate capacity, and the load decrease.

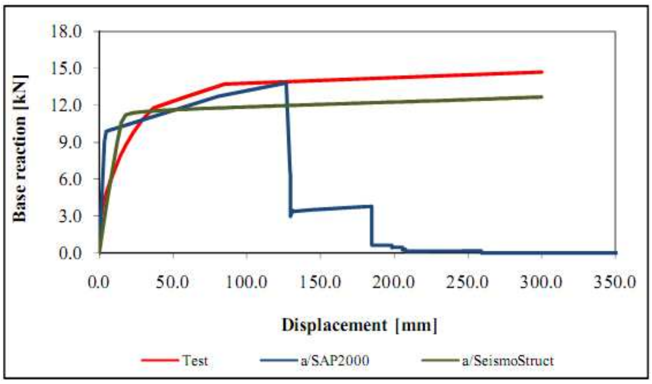


Figure 10: Base shear vs. displacement in Frame1

In Figure 11 we can see the pushover curve for the Frame2 without FRP. The experimental curve reached only a displacement of 27 mm, because this was the displacement fixed in the first phase of the test. The shape of the pushover curves in SAP2000 (2009) and SeismoStruct (2010) have the same characteristic that in the case of Frame1.

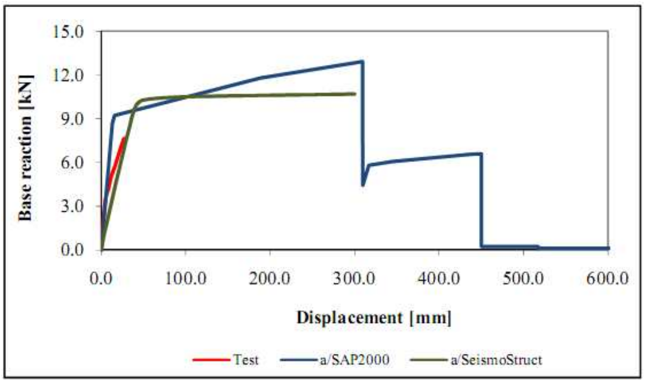


Figure 11: Base shear vs. displacement in Frame2 without FRP

We compared in SAP2000 (2009) the pushover curves obtained in models with one and with ten hinges in each column. Also we considered a model with fy = 420 MPa and fy = 535

MPa (the difference is about 21%). These curves are presented in Figure 12. Of course, the pushover curve for the model with lower fy present a lower base reaction (the difference for the highest load is about 21%). In the model with two hinges for columns the load drops first. In the model with ten hinges for columns, the hinges reach the ultimate capacity in different steps, the load drop in different steps, and the displacement for the collapse is highest.

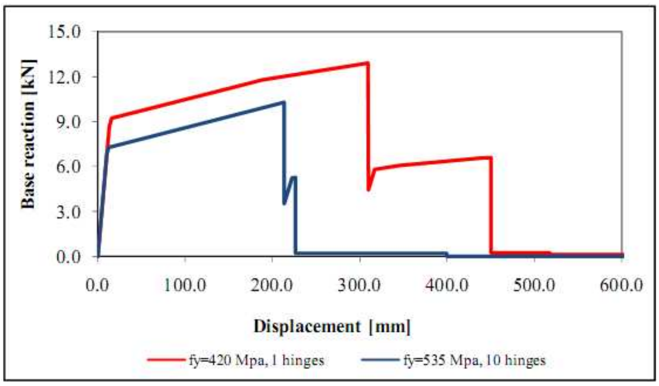


Figure 12: Base shear vs. displacement in Frame2 without FRP according to different numbers of hinges in SAP2000

4.2 Pushover curves for the frames with FRP

In Figure 13 it is possible to see the pushover curves (experimental and according to SeismoStruct, 2010) for the Frame2 with FRP. For the highest displacement in the test, the base shear is 11% lower in the software used.

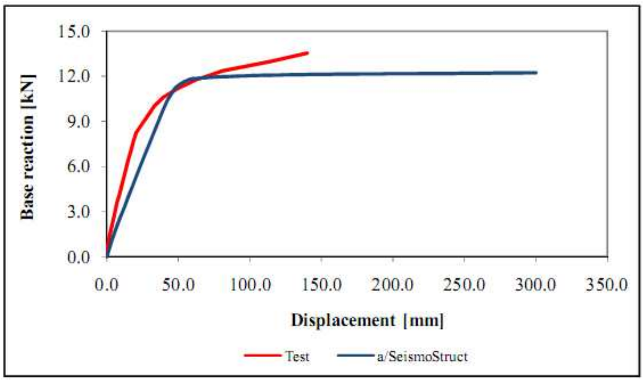


Figure 13: Base shear vs. displacement in Frame2 with FRP

5 CONCLUSION

It is possible to get a good accuracy of the highest load that a RC frame can reach through the pushover analysis in SAP2000 (2009) or in SeismoStruct (2010). But in our research with SAP2000, the ultimate displacements were different respect to tests.

The pushover analysis in SeismoStruct (2010) has a lower computational effort, because it is not necessary to make sectional analyses.

It would be possible to make pushover analysis in SAP2000 (2009) for RC frames with FRP if we get sectional analyses of this type of element (through test or other software).

It is necessary new researches to improve the accuracy of SeismoStruct (2010) to simulate RC frames with FRP.

REFERENCES

Ferracuti, B. and Savoia, M., Cyclic behaviour of FRP-wrapped columns under axial and flexural loadings. *Proceedings of the International Conference on Fracture*, Turin, Italy, 2005.

Ferracuti, B., Savoia, M., Pinho, R. and Francia, R., Pushover analysis of FRP retrofitted RC frame. *Proceedings of the First European Conference on Earthquake Engineering and Seismology*, Geneva, Switzerland, 2006.

Ferracuti, B. and Savoia, M, Columns retrofitted by FRP subjected to cyclic action. *Proceedings of the Materiali* ed Approcci Innovativi per Progetto in Zona Sismica e la Mittigazione della Vulnerabilità delle Strutture, Università degli studi di Salerno – Consorzio ReLUIS, 2007.

Ferracuti, B., Pinho, R., Savoia, M. and Francia, R., Verification of displacement-based adaptative pushover through multi-ground motion incremental dynamic analyses. *Engineering Structures*, Vol. 31, pp. 1789-1799, 2009.

Response-2000, Reinforced Concrete Sectional Analysis using the Modified Compression Field Theory. *Evan Bentz at Department of Civil Engineering, University of Toronto*, Canada, V.0.8.5, 2001

SAP2000, Integrated Software for Structural Analysis & Design. *Computers & Structures, Inc.*, Berkeley, California, USA, V. 14.0.0, 2009.

SeismoStruct, Software applications for analysis of structures subjected to seismic actions. *SeismoSoft Ltd*., Pavia, Italy, V. 4.1.0.

Spoelstra M., Monti, G., FRP-confined concrete model. *Journal of Composites for Construction*, ASCE, Vol. 3, pp. 143-150, 1999