Volume 1, Number 4 (December, 2008) p. 393 - 420 • ISSN 1983-4195

IBRACON

REVISTA IBRACON DE ESTRUTURAS E MATERIAIS

IBRACON STRUCTURES AND MATERIALS JOURNAL

Application of Heat-Activated Films as a new generation of adhesives used for bonding Fiber Reinforced Polymers to concrete

Utilização de Filmes Termo-Ativados como adesivos de nova geração para colagem de Polímeros Reforçados com Fibras ao concreto

M. R. GARCEZ [a]
mrgarcez@hotmail.com

U. C. M. QUININO [b]
uziel_quinino@yahoo.com.br

L. C. P. SILVA FILHO [c]
lcarlos@ppgec.ufrgs.br

U. MEIER [d]
urs.meier@empa.ch

Abstract

The application of FRP for post-strengthening of concrete structures induces the use of elevated temperatures to minimize the curing time of the adhesive. The replacement of traditional adhesives by Heat-Activated Films (HAF), with higher glass transition temperatures (Tg), is an interesting prospect, and has been motivating studies regarding the viability of applying termo-activated adhesives. For this study, notched beams post-strengthened with CFRP bonded with two types of heat-activated films (epoxy and phenolic based) and one classical adhesive were tested in bending at EMPA (Swiss Federal Laboratories for Material Testing and Research). To verify the stress redistribution on the notched beams, a computational model, which divides the structure in solid elements, was implemented. The analysis of the behavior of the concrete-laminate interface demonstrates that numerical models are an efficient tool to supplement and explain experimental data.

Keywords: CFRP, heat-activated films, epoxy resin, phenolic resin, concrete.

Resumo

A aplicação de PRF no reforço de estruturas de concreto pode requerer a utilização de elevadas temperaturas para minimizar o tempo de cura dos adesivos. A possibilidade de substituição dos adesivos tradicionais utilizados na colagem de laminados de PRF por Filmes Termo-Ativados (FTA), que apresentam temperaturas de transição vítrea (Tg) mais elevadas que a dos adesivos tradicionais, vêm estimulando o desenvolvimento de estudos acerca da sua viabilidade de aplicação. Para o presente estudo, testes em vigas de concreto entalhadas, reforçadas com laminados de PRFC, foram realizados no EMPA (Swiss Federal Laboratories for Material Testing and Research), analisando o comportamento de dois FTA, baseados em resinas termofixas fenólica e epoxídica. Visando verificar a redistribuição de tensões nos elementos estudados, um modelo computacional foi implementado. Os resultados da análise do comportamento da interface concreto-laminado demonstram que os modelos numéricos são ferramentas eficazes para complementar e explicar os dados obtidos experimentalmente.

Palavras-chave: PRFC, filmes termo-ativados, resina epóxi, resina fenólica, concreto.

---

[a] *Professor Dr., Federal University of Pampa, Researcher at LEME (Portuguese acronym of the Laboratory of Testing and Structural Modeling), Federal University of Rio Grande do Sul, mrgarcez@hotmail.com, Brazil*

[b] *Professor MSc., University of Vale dos Rio dos Sinos, Researcher at LEME, Federal University of Rio Grande do Sul, uziel_quinino@yahoo.com.br*

[c] *Professor PhD., Federal University of Rio Grande do Sul and Researcher at LEME, lcarlos66@gmail.com, Brazil*

[d] *Professor Dr. Honoris Causa, Swiss Federal Laboratories for Materials Testing and Research – EMPA, urs.meier@empa.ch, Überlandstrasse 129, CH-8600, Dübendorf - Switzerland*

1. Introduction

With the advancement of the fields of materials science and engineering, new and more advanced materials have been developed and are gradually being incorporated in several industrial fields. Following this trend, the construction industry, in recent years, seems to be abandoning its more conservative stance, typical of previous times, and adopting several new materials. Polymeric materials, in particular, are being widely used in fields as diverse as aerospace engineering and prosthetics, due to their lightweight, flexible and very resistant nature. The use of polymeric matrices structured with fibers has given rise to the development of Fiber Reinforced Polymers (FRP), a lightweight composite with great chemical stability and tensile resistance, adequate for structural use.

Some pioneering work done by European researchers in the middle 80´s has proved that FRP could be used successfully to strengthen damaged or obsolete reinforced structures, allowing them to support higher loads or extending their service life. In light of these good results, a gradual shift from the use of steel bonded plates to FRP was initiated. Initial studies have focused on carbon fibers to compose the FRP composites used for structural ends, given the non-corrosive nature, the low specific mass, the high elasticity modulus and the very high tensile strength of this type of fiber. Carbon Fiber Reinforced Polymers (CFRP) have, since then, attracted a lot of attention from practitioners, with several applications being recorded in Europe, Canada, Japan and the United States. Today the method is increasingly gaining acceptance in many other countries, including Brazil.

In general, the strengthening with FRP is done by bonding fiber sheets or FRP laminates in the tensile face of a structural element. When fibers sheets are used, the epoxy adhesive formulation is used both to unite the elements and to create the polymeric matrix that surrounds the fiber. The application of the adhesive is normally done at room temperature. The complete cure of the resin, in natural conditions, is obtained in around 7 days. In some applications, however, a quicker cure is desired. It is the case, for example, of the gradual post-stressing method developed by Meier et al. [1] for CFRP laminates. To allow the reduction of stresses along the bonding length, in order to avoid the need for anchorage ties, it is necessary to speed the hardening of the epoxy adhesive used for bonding. The most common way to do this is by heating the laminate, because in higher temperatures the polymerization reactions will occur faster. In some cases, it might be necessary to increase the temperature to around 100ºC, in order to obtain curing times relatively small, such as 2-3 hours. Care must be taken, however, to avoid reaching the Glass Transition Temperature (Tg) threshold of the epoxy resins, which might be as low as 60ºC.

Normally, the heating is generated using electric resistors or it is induced by the application of electric currents to the CFRP laminate. Another solution that is being investigated consists in the use of Heat-Activated Films (HAF), that have a more elevated Tg value compared to traditional adhesives. To check the efficiency of these HAF, 3-point bending tests were performed in notched concrete beams post-strengthened with CFRP bonded with these materials. The tests were carried out at EMPA (Dübendorf -Switzerland), one of the most advanced research centers in the field of CFRP post-Strengthening.

Two types of Heat-Activated Films (HAF), based in phenolic and epoxy thermosetting resins, were used to perform the experimental tests. Additionally, a thermosetting epoxy adhesive was applied in some post-strengthened notched concrete beams, aiming to allow the comparison between the performances of the HAFs and the classical epoxy adhesive.

Aiming to verify the stress redistribution on the notched beams, a computational model, which divides the structure in solid elements, was implemented. The numerical analysis, using ANSYS, allows the investigation of the bond behavior at the concrete-laminate interface.

2. Post-Strengthening of Concrete Structures with Prestressed CFRP Laminates and the Application of HAF

Applications of Carbon Fiber Reinforced Polymers (CFRP) laminates in civil structures started to be investigated in the mid-1980s and today this technique is recognized as an attractive way to post-

Figure 1 – Presstressing device developed by Meier et al. (1): (a) Placement of the device under the beam; (b) Sequence of prestressing procedure

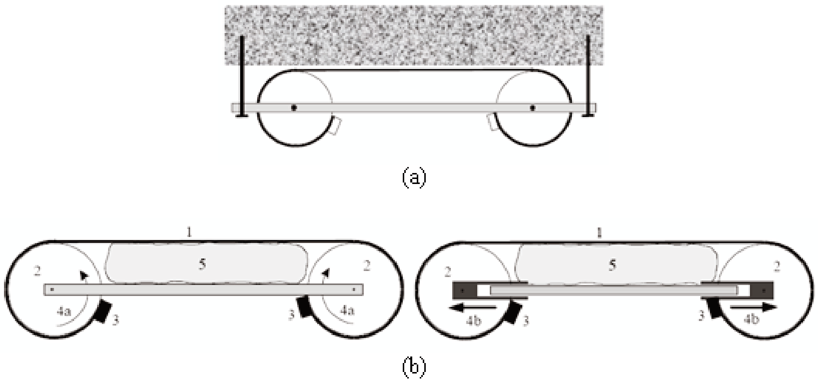
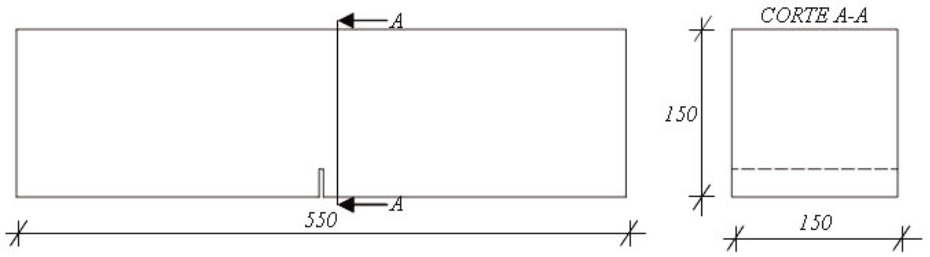


Figure 2 – Geometry of the notched concrete beams



strengthen concrete elements. Despite the considerable evolution and the positive developments regarding the use of CFRP in civil structures, there is still room to explore new possibilities to provide a more efficient, safe and rational use of FRP systems, which could lead to cost reductions and put to better use the high mechanical strength of these materials.

Bonding prestressed CFRP laminates to concrete structures can be considered as one of the main on-going developments of the post-strengthening researches in the last decades, since prestressing leads to a stiffer structural behavior and delays crack openings. According to Meier et al. [1], higher post-strengthening levels may be reached with thicker laminates if they are prestressed, due to the better use of the laminate's tensile strength.

Meier et al. [1] outlined a new concept for prestressing FRP strips against an external element, developed at Swiss Federal Laboratories for Testing Materials and Research (EMPA) in Switzerland. In this method, the FRP is prestressed against an external framework attached to the concrete beam, the adhesive is applied in the inner face of the laminate, before it was brought into contact with the beam. A gradual bonding strategy is used so the prestressing tensions vary up to zero at the laminate´s end

The external framework is specifically designed to adequately grab and pull the FRP strips, as seen in Figure [1]. The device consists of two wheels connected by a beam of the required length. The CFRP strip (1) is wrapped around the wheels (2) and clamped at its ends (3) as showed in the figure. The strip can then be prestressed by rotating one or both wheels (4a) or by displacing the wheels (4b).

As one can see in Figure [1], the prestressing device with the prestressed CFRP strip is temporarily mounted to the structure and can be pressed against the structure with a constant pressure by means of an air-cushion (5) created between the strip and the external beam.

When prestressed laminates are used, temperatures much higher than the ambient one need to be applied during the curing period to speed up the adhesive polymerization. With the reduction of the adhesive curing time, the use of the prestressing device is optimized and the post-strengthened structure becomes able to support loads more quickly, allowing an earlier release of vehicle traffic. The shortening of the time consumed during the curing process significantly reduces the cost of the post-strengthening operation.

Nonetheless, the application of elevated temperatures during curing process is limited by the Glass Transition Temperature (Tg) of the adhesives used to bond the FRP laminates to concrete. According to Callister [2], the epoxy adhesives normally used in post-strengthening applications must be cured at temperatures lower than 60ºC, a condition that restricts the use of elevated temperatures during the curing process. To overcome this obstacle, researches have begun to investigate the possibility of applying adhesives with a higher Tg, which are supplied in the form of Heat-Activated Films HAF.

Aiming to contribute to the development of the prestressed FRP post-strengthening technique, this paper investigates the behavior of notched concrete beams post-strengthened with CFRP laminates, bonded to concrete with two different HAF. The results showed in this paper were obtained in tests performed at EMPA, as part of a preliminary study aimed at reducing curing time and improving the prestressing device developed by Meier et al. [1].

3. Materials and Experimental Program

3.1 Concrete Beams

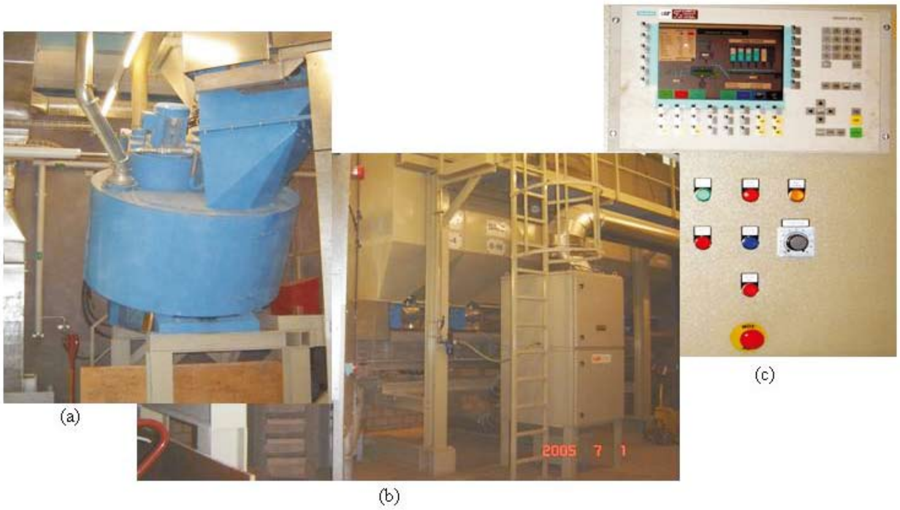
The notched concrete beams used in this work were produced, post-strengthened and tested at the EMPA laboratory, in Switzerland. Geometry details for the notched concrete beams are shown in Figure [1] and follow the recommendations of the document RILEM TC 162-TDF [3]. The notched concrete beams had a square cross-serction (150mm x 150mm) and a 550mm span. The notching was 25mm deep and 5mm ± 1mm thick, as showed in Figure [2].

The notch aims to simulate an opening crack in the concrete, located at mid-span, which induces the rupture at that point. During loading, other cracks appeared along the concrete beam but did not open enough to have any considerable influence on the rupture of the beam.

3.2 Concrete

The aggregates used to produce the concrete were the ones locally available in the Switzerland region and the cement was the Portland CEM I 42,5 (composed of 95% of clinquer and 5% of other components) equivalent to the Brazilian CPI. The concrete was designed according to the mix proportions showed in Table [1], using a w/c ratio of 0.44, aiming to obtain a concrete fulfilling the requirements of the B 35/45 class (MPa). Concrete was produced in the automatic mixer showed in Figure [3].

Figure 3 – Set-up used to produce the concrete at the EMPA laboratory: (a) Concrete Mixer; (b) cement and aggregates garners; (c) Computer controlled command panel



The concrete beams were cast using steel adjustable moulds, showed in Figure [4]. Concrete compaction was carried out with the aid of a mechanical vibration device.

The concrete beams were demoulded 24 hours after casting and stored at 20ºC and RH 95% for 28 days. To determinate the compressive strength, cubic specimens 150mmx 150mmx150mm) were also cast and stored in the same environment for 28 days. The average compressive stress measured in these specimens after 28 days was 33MPa.

After 289 days the beams were notched, using the device shown in Figure [5]. The RILEM TC 162-TDF [3] recommends that, following the notching, the previous cure conditions should be continued for 3 days. However, in this case the RH of the environment were the beams were stored was decreased to 3,5% during the last 3 days. This shift was made to reduce the humidity content of the concrete, in order to avoid bonding problems at the interface concrete-HAF during the strengthening, due to the release of water vapor when the concrete was exposed to the elevated applied to rapidly cure the HAF.

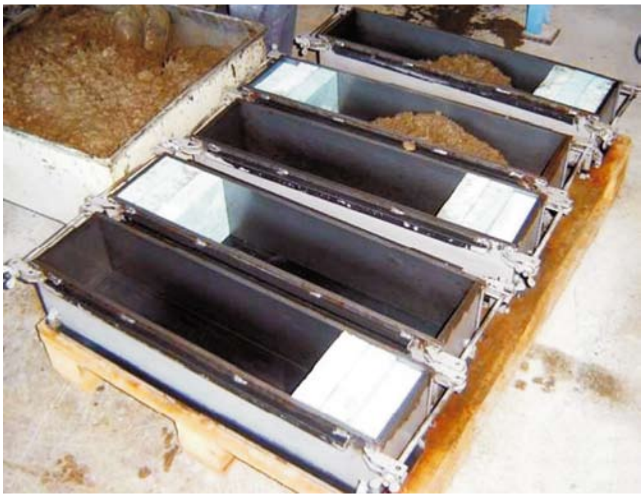
Table 1 – Mixing Proportions

Materials		Mixing-Ratio	Content (kg/m^3)
Cement		1	325
Aggregates	0...4 mm	1.870	610
	4...8 mm	0.940	305
	8...16 mm	0.990	324
	16...32 mm	2.050	667
Water		0.440	145
Additive 1		0.6%	1.950
Additive 2		0.1%	0.325

3.3 Heated-Activated Films

According to Callister [2], one of the main characteristics of polymeric materials is their sensitivity to the strain ratio, the chemical nature of the ambient and the curing temperature. It is known that the mechanical properties of most polymeric materials are temperature-dependent, and that the thermal properties of a polymer are

Figure 4 – Steel moulds used in the casting procedure



often specified in terms of its glass transition temperature (Tg). The Tg value is one of the most important characteristics of polymeric materials, because amorphous polymers can suffer drastic changes in their structure when the Tg is reached. Various polymer properties, such as hardness, volume, mechanical strength, percent elongation-to-break and modulus of elasticity undergo a drastic change in the vicinity of the glass transition temperature.

Figure 5 – Device used to notch the concrete beams

According to the FIB [4], it is important to consider that the Tg may vary in time due to several environmental parameters, such as temperature and moisture. A hot environment may increase the value of the Tg, because it may act induce a post-cure of the material. On the other hand, the absorption of moisture by the resin will lower the Tg. When working with FRP, the glass transition temperature of the system should not be reached, otherwise it can put at risk the safety of the whole system. The Tg of the classical epoxy adhesives used in FRP post-strengthening procedures ranges about 60ºC. However the Tg can reach 100ºC if special, long pot-life adhesives are used. An alternative to the use of classical adhesives is the application of Heat-Activated Films (HAF), which present a higher Tg (120ºC to 250ºC) compared to the traditional adhesives, allowing the use of higher temperatures during the curing process and speeding the strengthening operation.

Two types of HAF, shown in Figure [6], were tested in the present work: the HAF 8400, produced by TESA AG [5] and the ACG VTA^{TM} 260, produced by the Advanced Composites Group [6]. Both are made of thermosetting resins, but the HAF 8400 is based on a phenolic adhesive while the ACG VTA^{TM} 260 is based on an epoxy adhesive. Table [2] shows the characteristics of each HAF.

3.4 Carbon Fiber Reinforced Polymer

The notched concrete beams were post-strengthened with the Sika® Carbodur [7] system, which is composed of a carbon fiber laminate, named Carbodur S 512, and the adhesive formulation Sikadur®-30. As seen in the table, the Carbodur S 512 laminates used was 500mm long and had a cross section of 1.2mm x 50mm. The characteristics of the post-strengthening system, as provided by its manufacturer, are shown in Table [3].

3.5 Experimental Program

For this study eight notched concrete beams were tested: Two of them did not receive any post-strengthening and the other six were post-strengthened with the CFRP Sika® Carbodur system. The ad-

Figure 6 – HAF: (a) HAF 8400; (b) ACG VTA^{TM} 260

(a)
(b)

Table 2 – HAF properties, provided by the manufacturers

Characteristics	HAF 8400	ACG VTA™260
Type of Resin	Phenolic	Epoxy
Tensile Strength (MPa)	> 12	-
Thickness	0.25mm	0.36mm
Width	38mm	1100mm
Storage Temperature	Ambient	-18°C
Curing time	120°C - 250°C 4 sec – 30 min	65°C a 85°C – 16 hours 80°C a 90°C – 5 hours 100°C a 110°C – 2 hours 120°C – 1 hour

hesive Sikadur®-30 was used in two of these beams, which acted as control or reference beams. Other two notched concrete beams were post-strengthened with the Carbodur S 512 laminate, bonded to the concrete beam with two layers of ACG VTA™ 260 film, cured at 100ºC for two hours. The remaining two notched concrete beams were post-strengthened with the Carbodur S 512 laminate, bonded to the concrete beam with three layers of HAF 8400 film, cured at 120ºC for 30 minutes. The experimental program is summarized in Table [4].

3.6 Post-Strengthening Application

The application of the Sika® Carbodur system demands a preliminary preparation of the concrete surface, as well as the dry fabric systems. The concrete surface must be sound, clean from grease and oil and dry.

Table 3 – Properties of the FRP systems, provided by the manufacturer

	Laminate Carbodur S 512
Thickness (mm)	1.2
Width (mm)	50
Tensile Strength (MPa)	2,800
Ultimate Strain (%)	17
Young´s Modulus (MPa)	165,000
Maximum Temperature (°C)	500
	Resin Sikadur®-30
Components	3 Part A : 1 Part B
Pot life a 35°C (min)	40
Open Time 35°C (min)	30
Tg (°C)	62
Young´s Modulus (MPa)	12,800

After the preparation of the concrete surface and the cleaning of the laminate, the Sikadur®-30 adhesive is applied across the width of the concrete surface and on the Carbodur S 512 laminate, ensuring total coverage. The adhesive layer used should be at last 1 mm thick at the laminate end and 2mm thick at the centre. At the concrete surface, the adhesive layer applied should be around 1mm thick.

Within the open time of the adhesive, the laminate is placed and pressed against the concrete surface, until the excess of adhesive is squeezed out from below the laminate. After placing the laminate, a rubber roller is pressed against the laminate to eliminate air bubbles and help force out the adhesive excess. Steel plates are then placed against the laminate to keep the system under pressure until the cure of the adhesive.

The notched concrete beams were post-strengthened with one layer 50mm wide of Carbodur S 512 laminate, placed at the notched face of the concrete beam, as shown in Figure [7].

For the application of the Carbodur S 512 with HAF, the same concrete and laminate preparation used for the traditional adhesive was used. After the surface preparation, the specified number of layers of HAF was applied across the width of the Carbodur S 512 laminate, ensuring total coverage. The HAF was also applied to the laminate as an adhesive tape. Since the curing process of the HAF is done at high temperature, the post-strengthened notched concrete beams tested were placed inside a heating device, as shown in Figure [8].

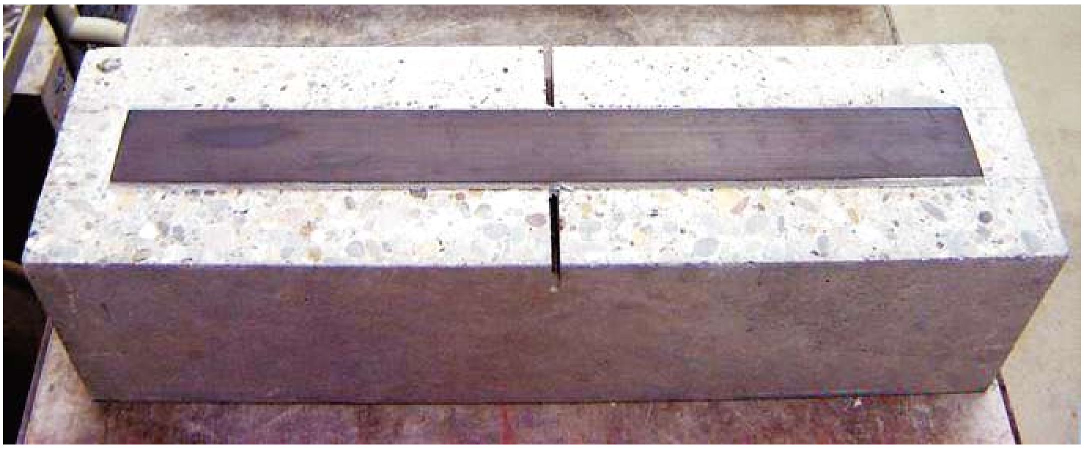
3.7 Test Procedure

As explained before, all the notched concrete beams were produced, post-strengthened and tested at EMPA, in Switzerland. They were subjected to a three point bending test. The test set-up was arranged so the beams were simply supported and received a vertical load at mid-span, as shown in Figure [9]. To monitor the deflections at mid-span, the LVDT (Linear Voltage Displacement Transducer) sensor of the 160kN servo-controlled universal loading machine used in the tests was placed under the beams, as shown in the figure.

Table 4 – Experimental program

Beams	Type of HAF	Number of layers	Curing Temperature (°C)	Curing Time (h)
VT_01 VT_02	-	-	-	-
VSIKA_01 VSIKA_02	-	-	35	168
VACG_01 VACG_02	ACG VTA™260	2	100	2
VTESA_01 VTESA_02	HAF 8400	3	120	0.5

Figure 7 – Notched concrete beam post-strengthened with the Sika® Carbodur system



Data from the LVDT (deflection at mid-span) and from the load cell (applied load) was continuously recorded during the tests, and used to generate load-displacement curves for all tested beams. This data was useful, together with the data obtained from the numerical analysis, to understand the concrete-HAF-laminate behavior, as well as verifying the possibility of applying HAF in real post-strengthening situations.

4. Numerical Analysis

Aiming to verify the stress redistribution on the beams, a numerical investigation, based on a finite element method (FEM) analysis, was carried out. Due to the simple geometry and well-defined boundary conditions of the notched concrete specimens, a discretization of the whole solid was made, according to the specifications of the experimental procedures.

The finite element analysis was implemented using the software ANSYS, that allows the simulation of notched concrete beams under specified boundary conditions. There are several possible

Figure 8 – Heating device use to cure the HAF adhesives

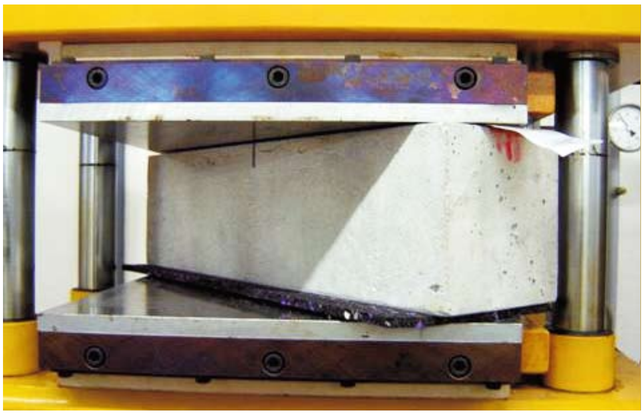
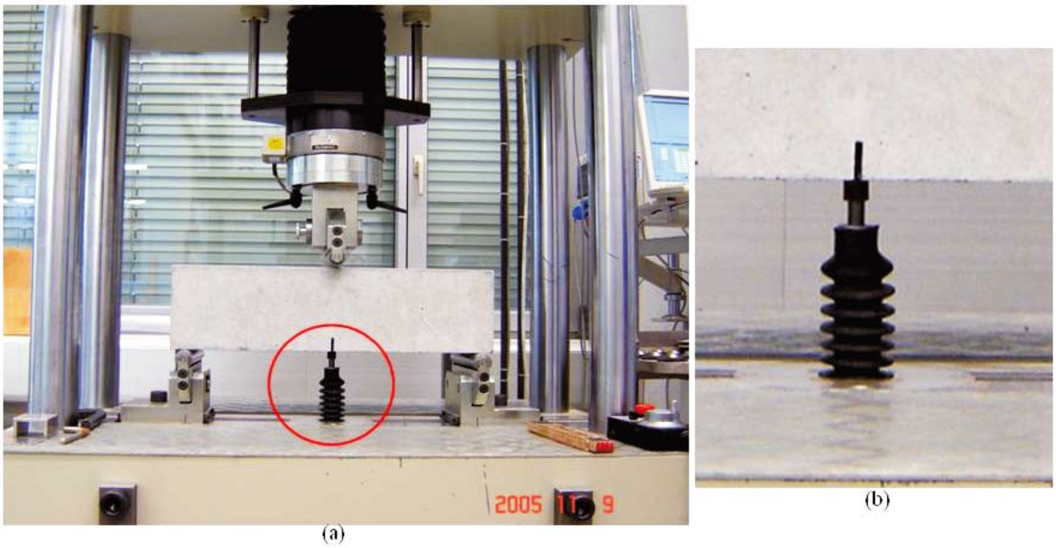


Figure 9 – Test setup: (a) Three point bending test; (b) LVDT



(a)

(b)

ways to implement a numerical simulation in ANSYS, including the Graphical User Interface (GUI), used to simulate the beams tested in this paper.

Some parameters are needed to implement a numerical analysis using the Finite Element Method (FEM), such as the geometry of the structure, the loading scheme, the nature of the connections at the end of the beams, as well as the number of nodes and the type and number of elements used. Finally, the behavior of each material used and its mechanical properties and characteristics must be similar to the ones obtained through experimental testing.

Figure [2] shows the geometry of the simulated beams. The notched concrete beams had a square cross-section (150mm x 150mm) and was 550mm long. The notch was 25mm deep and 5mm thick. The notched beams were post-strengthened with laminates that had a rectangular cross section (1.2mm x 50mm) and were 500mm long. The thickness of the adhesive layer used to glue the laminate to the concrete was about 2mm when the Sikadur®-30 adhesive was used, 0.75mm when the HAF 8400 (3 layers) was used and 0.72mm when the ACG VTA□ 260 (2 layers) was used.

4.1 Elements Type

The SOLID65 element was chosen to model the concrete. This element has eight nodes with three degrees of freedom at each node – allowing translations in the nodal x, y, and z directions. The SOLID65 element is capable of representing plastic deformation, cracking in three orthogonal directions, and crushing. Figure [10] shows the SOLID65 element.

A Solid45 element was used to model the FRP laminates. This element has eight nodes with three degrees of freedom at each node

Figure 10 – Element Solid 65

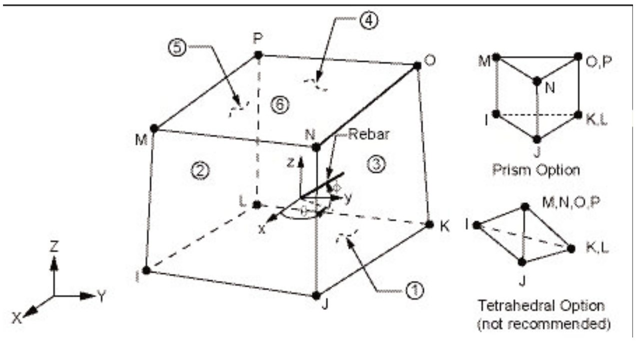
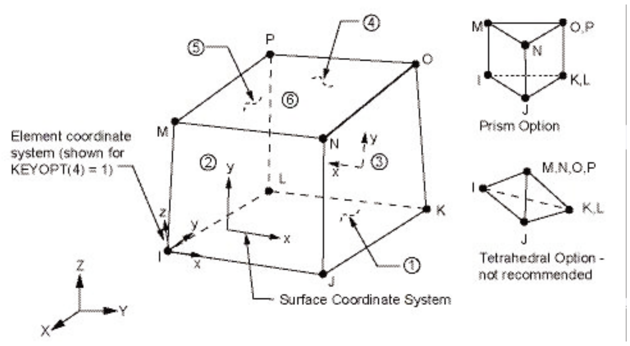


Figure 11 – Element Solid 45



– translations in the nodal x, y, and z directions. The geometry and node locations for this element are shown in Figure [11].

4.2 Material Properties

The parameters needed to define the material models can be found in Table [5]. As seen in the table, multiple materials were used to model the beam element.

The material model number 1 refers to the Solid65 element. The Solid65 element requires linear isotropic and multilinear isotropic material properties to properly model concrete. The multilinear isotropic material uses the von Mises failure criterion to define the failure of the concrete. It is also necessary to define the stress-strain relationship for the concrete, considering Hooke's law at the first point. The value Ex refers to the elasticity or Young´s modulus of the concrete. The material models numbers 2 and 3 refer to the Solid45 element. The Solid45 element was used to represent the CFRP laminate and the adhesive layer. Therefore, this element was assumed as a linear isotropic element with the modulus of elasticity and Poisson's ratio of theses materials.

4.3 Modeling and Mesh

Beams, adhesive layer and laminates were modeled through the creation of volumes with the same dimensions of the experimental prototypes. To obtain good results, a rectangular mesh was adopted. The overall mesh used to represent the concrete, adhesive and FRP laminate is shown in Figure [12]. The finite element mesh includes 4,400 elements and 5,422 nodes. The perspective view, seen in Figure [12], shows the details of the mesh used for the laminate and the adhesive layer, placed over the longitudinal axis of the notched concrete beam.

4.4 Boundary conditions

Displacement boundary conditions are needed to constrain the model to get a unique solution. In the numerical analysis performed in this paper, the boundary conditions were applied where supports and loads exists. Simulations of the three point bending test for the notched concrete beams were performed considering simple supported beams (using a pin and a roller support) submitted to a vertical load, applied at mid-span.

4.5 Analysis

For the purposes of this model, a static non-linear analysis of the notched concrete beams was made, considering the limit displacement as the convergence criterion.

The numerical analysis was based on the simulation of the deformation evolution of the notched beams until the experimental load that caused the failure of the specimen was reached. The results obtained were P = 29.4 kN for the beam that received the adhesive Sikadur®-30, P = 8.8 kN for the beam that received the adhesive ACG VTA™ 260 and P = 26.82 kN for the one that received the adhesive HAF 8400.

A nonlinear Newton-Raphson approach was used to trace the equilibrium path during the tracing of the curve for the load-deformation response. This means that the application of the load up to failure

Table 5 – Constitutive models of the material used to calibrate the model

Material N°	Element Type	Material Properties						
		Isotropic Linear		Isotropic Multilinear			Constants	
1	**Solid65 concrete**	Ex (N/mm^2)	35,000	Point	σ (N/mm^2)	ε	ShrCf-Op^1	0.30
		Poisson	0.35	01	12.25	0.00035	ShrCf-Cl^2	1.00
				02	21.00	0.00060	Un TensSt$_3$	3.50
				03	52.50	0.00150		
				04	70.00	0.00200		
				05	87.00	0.00250		
2	**Solid45 carbon fiber laminate**	Isotropic Linear						
		Ex (N/mm^2)	16,5000					
		Poisson	0.25					
3	**Solid45 HAF**	Isotropic Linear ACG VTA™ 260		Isotropic Linear HAF 8400			Isotropic Linear Sikadur®-30	
		Ex (N/mm^2)	2,800		Ex (N/mm^2)	300	Ex (N/mm^2)	12,800
		Poisson	0.30		Poisson	0.475	Poisson	0.250

1 Shear transfer coefficient for an opened crack; 2 Shear transfer coefficients for a closed crack; 3 Uniaxial tensile cracking stress.

Figure 12 – Finite elements Mesh

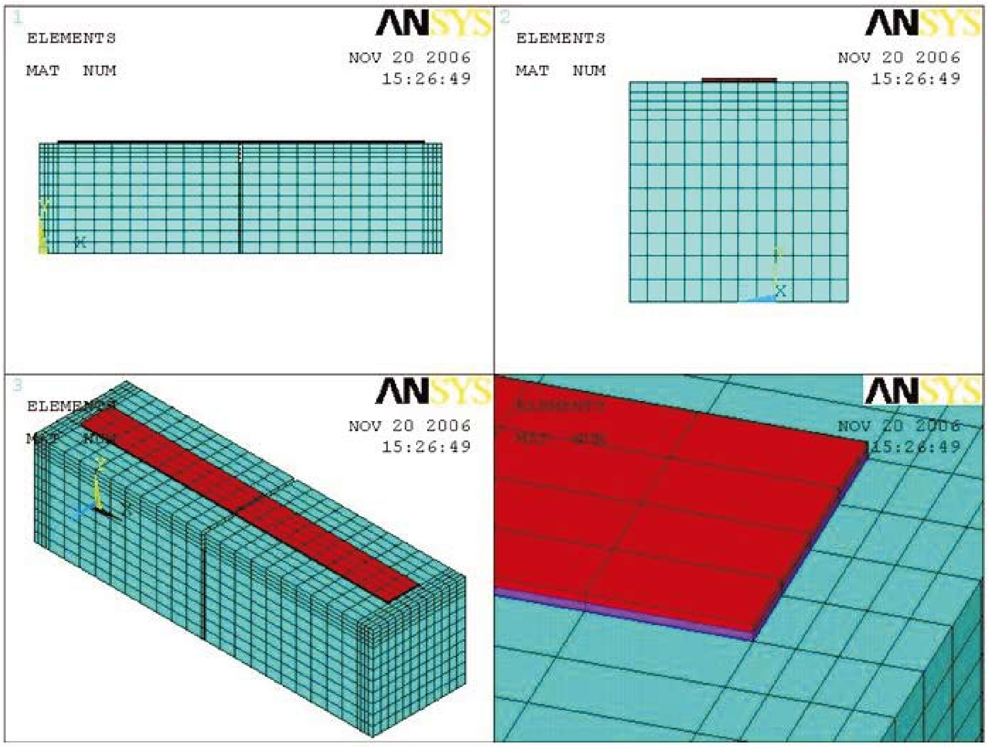
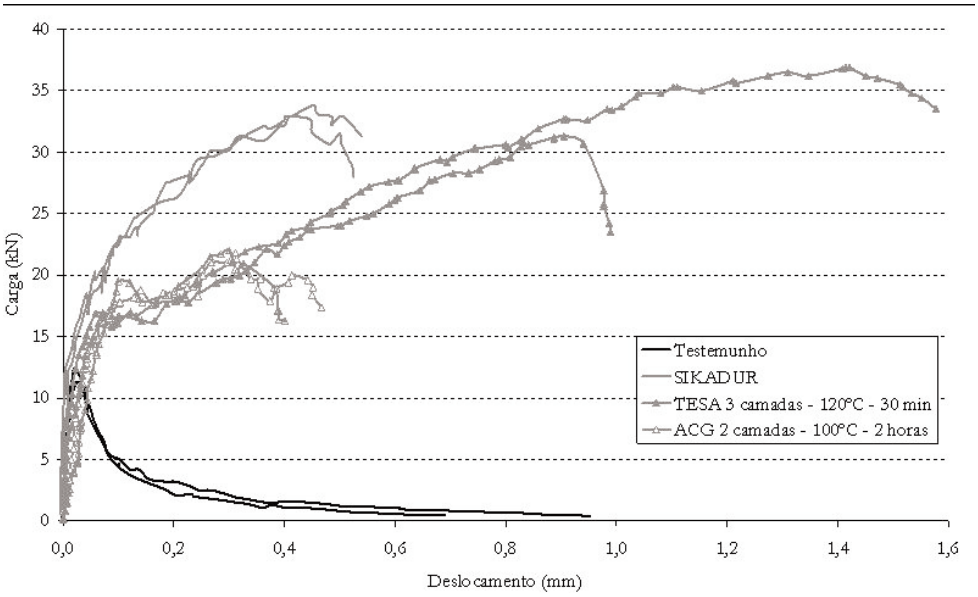


Figure 13 – Experimental results in terms of mid-span vertical displacements



was done incrementally, as required by the Newton-Raphson procedure. After each load increment, the convergence criterion was verified. This procedure allowed the numerical tool to adequately simulate the behavior of the materials (HAF, concrete and FRP) and perform the analysis of the stresses on the notched beam at the load range that caused the experimental failure.

5. Discussion of Results

Figure [13] shows the experimental results in terms of vertical displacements at mid-span, obtained from the three point bending tests that were carried out on the eight notched concrete beams.

The results from the reference beams, which did not receive any post-strengthening, clearly represent the behavior of concrete beams without internal reinforcement. Their curves are marked by a peak load, which represents the tensile strength capacity of the concrete beam, followed by a large displacement at mid-span until rupture.

Analyzing Figure [13] it is possible to notice that the behavior of the post-strengthened beams, in terms of load x vertical displacement at mid-span, is quite different from the behavior of the reference beams. On the post-strengthened beams one can observe a higher peak load and a different and more ductile behavior after the peak until the rupture of the beams.

The maximum load reached by the reference beam was 12kN. The post-strengthened beams that received the classical Sikadur®-30 adhesive reached quite higher loads, nearing 33kN, for a corresponding vertical displacement at mid-span of about 0,4mm, failed soon after the peak load was reached.

The post-strengthened beams that received both types of HAF adhesives also reached higher peak loads than the reference beams but exhibit distinct behaviors. The maximum load reached by the beam that received the ACG VTA™ 260 adhesive was about 22kN, corresponding to a displacement at mid-span of about 0,3mm. The load peaks of the beams that received the HAF 8400 adhesive reached up to 37 kN, but the displacement at mid-span was greater than 1 mm, indicating a very ductile behavior.

The maximum load reached by the beams post-strengthened with the Sikadur®-30 adhesive (at 0.44mm of vertical displacement at mid-span) was reached by the ones that received the HAF 8400 adhesive when they reached around 1mm of vertical displacement at mid-span.

All post-strengthened beams that received the HAF failed due to debonding of the laminate as well as the beams post-strengthened with the Sika® Carbodur system (Sikadur®-30 adhesive).

In general, the beams that received the Sikadur®-30 adhesive showed stiffer behaviors, when compared to the ones that received the HAF. However, they failed suddenly and showed smaller verti-

Figure 14 – ANSYS results of Sikadur®-30 adhesive: (a)σ1; (b)σ2; (c)σ3; (d)τxz

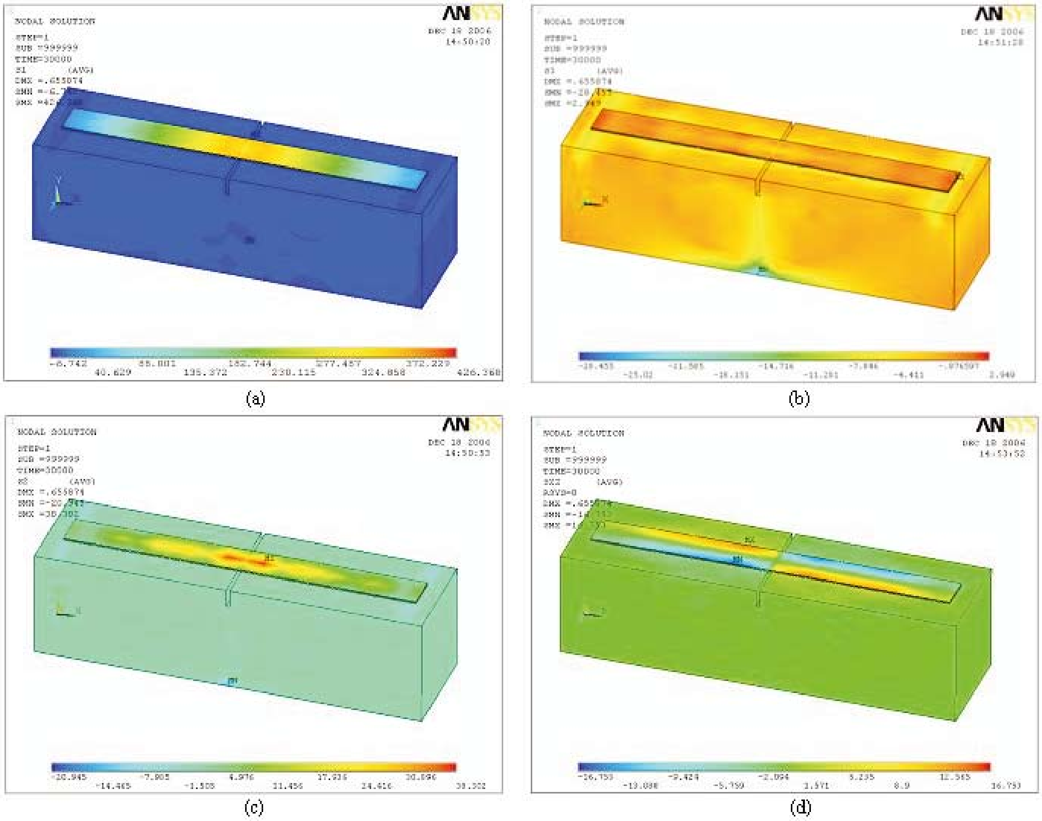
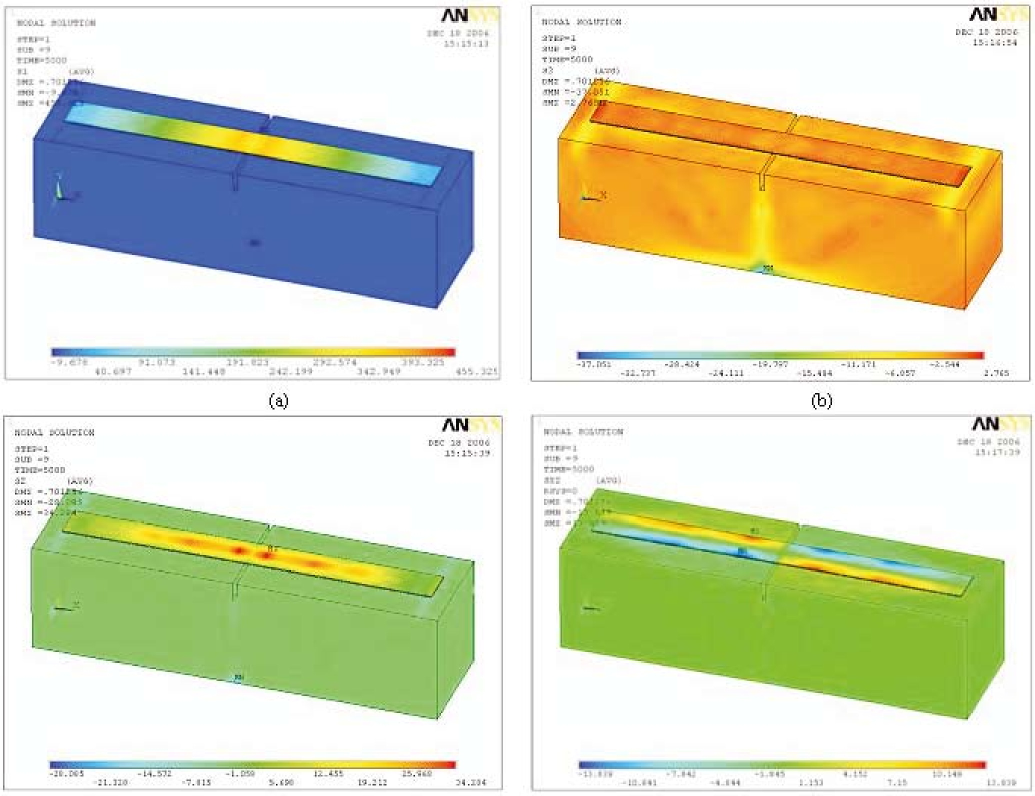


Figure 15 – ANSYS results of ACG VTA™ 260 adhesive: (a)σ1; (b)σ2; (c)σ3; (d)τxz



(a) (b) (c) (d)

cal displacements at mid-span, when compared to the ones that received the HAF.

Due to the lower Young's Modulus of the HAF 8400 adhesive, the experimental results show that beams post-strengthened with this adhesive are more ductile than the ones that received the ACG VTA™ 260 or the Sikadur®-30 adhesives.

Figures [14], [15] e [16] show the principal stresses, σ_1, σ_2 e σ_3 and the shear stress τ_{xz}, respectively expected on the beams that received the Sikadur®-30, under P = 29.4 kN, ACG VTA™ 260, under P = 28.8 kN e HAF 8400, under P = 26.82 kN.

The analysis of the principal stresses on the direction 2 shows that there is a stress concentration at the central part of the beam when the higher Young's Modulus adhesive is used (Sikadur®-30). However, when the HAF are used, these stresses are more distributed along the beam and theirs values are not so high.

When the shear stresses on the XZ plane (where the concrete-adhesive and the adhesive-laminate interfaces are located) are considered, it was observed that the adhesives with higher Young's Modulus promote a more efficient stress re-distribution on the post-strengthened elements. It is important to highlight that the typical failure that happens due to the concentration of shear stresses at the concrete-adhesive and adhesive-laminate interfaces, at the ends of the post-strengthened beams, is one of the weak points of the post-strengthening techniques that use externally bonded elements to concrete structures.

Figure 17 shows the results obtained from the simulation of the beams with the adhesives Sikadur®-30, ACG VTA□ 260 e HAF 8400, in terms of main and shear stresses on the laminate, at the central part of the beams.

It can be concluded that the numerical analysis results do not show any significant difference on the general behavior of the post-strengthened notched concrete beams with distinct bonding systems. The most important differences were associated with the varying stiffness of the adhesives, which is not a particular characteristic of any technique.

6. Conclusions

Promising results were obtained during the test series carried out in this work. They indicate that the use of HAFs as adhesives for bonding FRP and concrete is a viable technical alternative for post-strengthening systems that need rapid curing and strength development.

In general, the experimental results showed that the notched concrete beams post-strengthened with the classical Sikadur®-30 adhesive tend to be stiffer than the ones post-strengthened with the HAF systems. The more ductile behavior, nonetheless, might become an interesting characteristic of the HAF systems in certain applications.

To confirm the results recorded additional tests are necessary, to evaluate the long term behavior of the HAF systems as well as

Figure 16 – ANSYS Results of HAF 8400 adhesive (a)σ1; (b)σ2; (c)σ3; (d)τxz

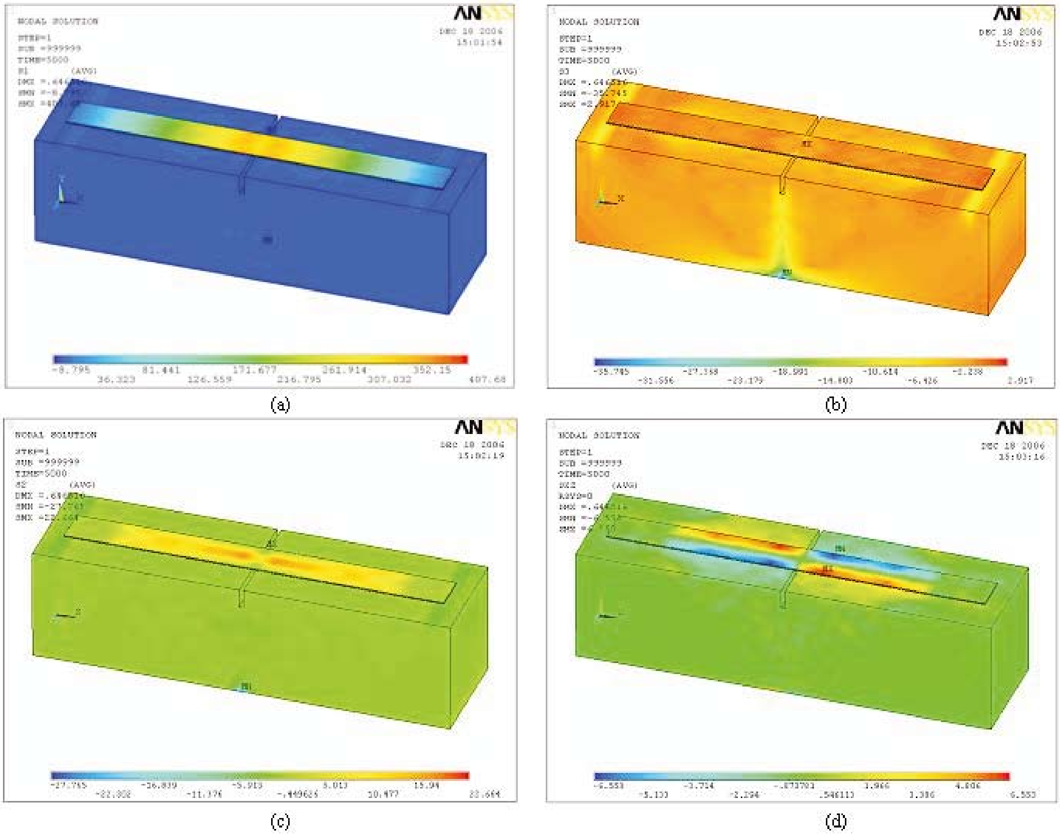
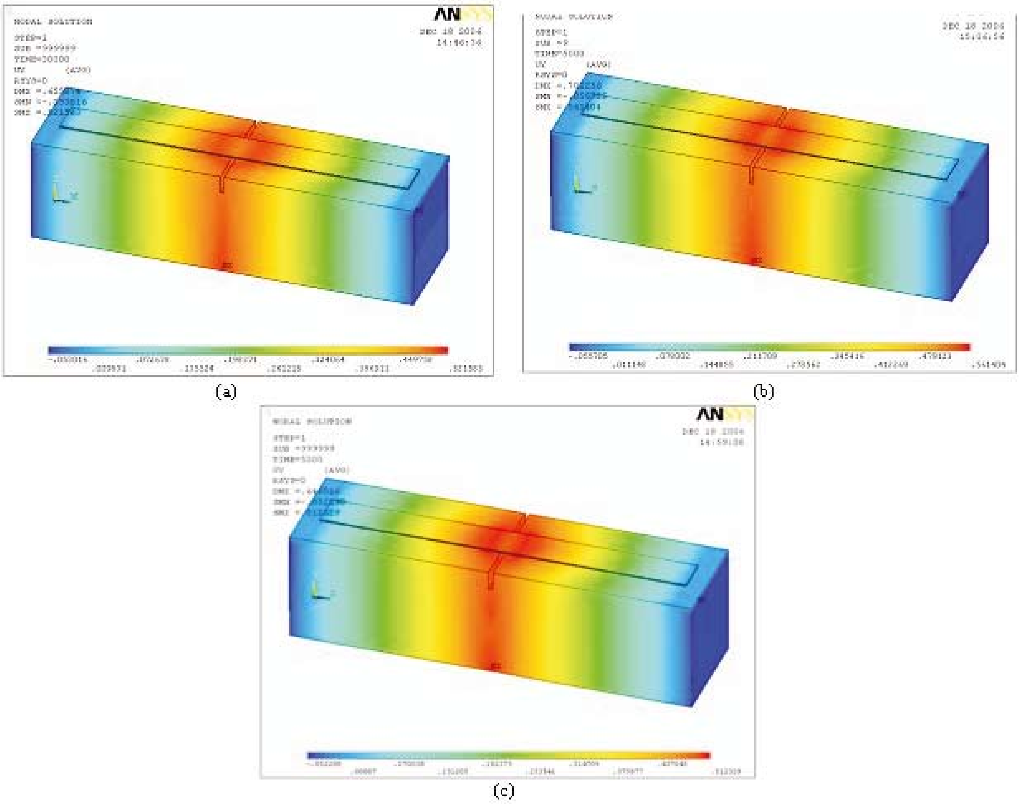

(a) (b) (c) (d)

Figure 17 – ANSYS results of mid-span vertical displacements: (a) Sikadur®-30 adhesive; (b) ACG VTA™ 260 adhesive; (c) HAF 8400 adhesive


(a) (b) (c)

analyze their response in fatigue tests. Some of these tests are being carried out at EMPA.
Prestressing seems to be one of the most promising avenues for further advancement of FRP strengthening systems. In this scenario, this work shows that the use of thermal activated films, which allow the rapid polymerization of the adhesive, might become an important requirement for the development of automated prestressing devices, which have already started to be applied.

7. Acknowledgements

Authors would like to acknowledge CNPq (Portuguese acronym of the Brazilian Ministry of Science's National Research Council) and CAPES (Portuguese acronym of the Brazilian Ministry of Education's Higher Education Human Resources Development Agency) for providing the financial support needed to develop this project. Authors would also like to express their appreciation for the technical support given by the research team at EMPA (Swiss Federal Laboratories for Materials Testing and Research), in Switzerland, and LEME (Portuguese acronym of the Laboratory of Testing and Structural Modeling) of the Federal University of Rio Grande do Sul – UFRGS, in Brazil.

8. References

[01] MEIER, U., STÖCKLIN, I., TERRASI, G. P. Making better use of the strength of advanced materials in structural engineering. In: FRP Composites in Civil Engineering, Hong Kong, 2001, Anais. [CD-ROM]
[02] CALLISTER, W. D. Materials Science and Engineering - An Introduction, United States of America: WILEY, 2003. 820p.
[03] RILEM TECHNICAL COMMITTEE. Test and design methods for steel fibre reinforced concrete: RILEM TC 162-TDF, Bagneux, 2002.
[04] FÉDÉRATION INTERNATIONALE DU BETÓN. Design and Use of Externally Bonded FRP Reinforcement (FRP EBR) for Reinforced Concrete Structures. Lausanne, FIB, 2001, Progress Report – Fédération Internationale du Betón.
[05] ADVANCED COMPOSITES GROUP. Data Catalogue, 2005. [CD-ROM]
[06] TESA. Fitas fílmicas termo-ativadas. www.tesatape.com.br , acesso em novembro de 2005.
[07] SIKA. Sika® Carbodur – Sistema de reforço com lâminas de fibra de carbono. www.sika.com.br, acesso em abril de 2005.