Repair of Concrete Elements Using CFRP: Parametrical Study and Evaluation of Dynamic Properties

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ABSTRACT

As is well known, repair, rehabilitation and strengthening of old concrete or seismically vulnerable structures is a technique that is used very often in order to extend the operational life of buildings and concrete structures. Such techniques are usually based on traditional, often inefficient techniques and on conventional materials, which may soon exhibit new durability problems. For structural upgrading, reinforced concrete jacketing and surface-bonded steel plates are mostly used. However, during the last decades high-performance advanced composites of the type routinely used in aerospace, such as carbon fibre reinforced plastics, are entering the stage, despite their much higher material costs.

In the present work different methods of repairing, using CFRP laminates, of a concrete beam having a center crack are discussed analytically. The stresses and the deformations calculated are analytically discussed and the different repairing methods are evaluated systematically. Problems concerning the dynamic characteristics of the repaired structures are also presented, and a new approach for the repair strategy is introduced.

Key words: Repair, reinforced concrete, CFRP, Finite element.

1. INTRODUCTION

In recent years the necessity for improved techniques concerning the repairing of concrete structures has rapidly increased. It is well known that such structures are experiencing corrosion problems and as a consequence a significant deterioration of their mechanical properties is occurring. In the Western world this problem is especially noticeable, due to the environmental conditions and the fact that the majority of buildings are rather old, some of them more than 100 years old. In addition, road network structures are experiencing the same problems in combination with the chemical attack from the humidity and the exhaust gases that lead to the corrosion of the reinforcement steel bars /1/. Apart from this traffic conditions have dramatically changed over recent years, and as a consequence these structures have to deal with a much higher volume of vehicles than they did some years ago when they were designed and constructed. Another important aspect in the serviceability of these structures is the resistance to impact loading. The speed of modern vehicles combined with their increased weight can prove very dangerous in case of an accident. For this reason special techniques, using composite materials like Kevlar, are used in order to reinforce sensitive parts of such structures as columns. These techniques are applied in order to protect the structure in case of an accident or to reinforce the structure after such an incident.

Apart from the above-mentioned problems, in the seismically prone areas, the problem of rehabilitation of concrete structures is of significant importance. After a seismic event, concrete structures experience severe damage and thus the reinforcement is the only solution in order to have this building in service again. In such cases the reinforcement procedure is very demanding due to the fact that the structure must be ready to take a dynamic load in a future event. Due to this requirement a dynamic evaluation of the structure after the reinforcement is necessary in order to find whether the eigenvalues of the structure are different compared with

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the undamaged state. However, this approach is far from being applied in the majority of actual cases.

Until now most of the reinforcing techniques have been based on the application of resin or, in more severe and demanding cases, on the application of concrete jacketing and/or steel plates in the area of repair. There is no doubt that the application of such techniques can provide limited reinforcement. The mechanical properties of the epoxy resin, as is well known, are low. On the other hand steel plates are experiencing corrosion problems and it is necessary to establish a procedure for maintaining the structural integrity of such reinforcements. It is obvious that the cost is further increased while on the other hand the result is not the expected one, since a procedure for monitoring the situation of the reinforcement is necessary. Apart from that, steel reinforcements are heavy and difficult to put in place. They require specially trained personnel, which increases the cost of the whole procedure. Another disadvantage of this method is that it is difficult to form the steel plates to the required shape when a special reinforcement has to be placed. However, the application of such techniques for many years and the experience of their performance that has already been gained are significant advantages. There is no doubt that the interaction between concrete and steel has been studied thoroughly and it is possible to predict the behavior of this technique for a long period of time.

As is well known, GFRP and CFRP have been in use in the marine and aerospace industries for almost half a century. Due to their excellent properties, their use has been extended during the last fifteen years in the domain of concrete structures reinforcement /2, 3/. The list of advantages of these materials over the traditional materials like steel is extensive. These materials have excellent elastic properties while at the same time their weight remains low. Their corrosion resistance is remarkable and, furthermore, reinforcements using this type of material can be easily formed in the appropriate shape, when it is necessary to reinforce a structure of specific shape, offering an easy method of application. However, even though these materials have excellent properties compared to traditional steel, their use for reinforcing concrete structures is still limited. The cost of such materials, and the lack of experience regarding their application on concrete elements, are some of the reasons that have limited their use until now. Apart from this, the lack of knowledge of the long term behavior of such materials in combination with concrete is a very significant drawback. Finally, the anchoring techniques and the role of the adhesive material are still under investigation, since these parameters are very important for the successful application of this technique.

In order to investigate all the parameters that have to be analyzed in order to find the optimum solution for each type of reinforcement, a number of different tests on actual concrete beams using different anchoring techniques and reinforcements have been performed /4/. In addition, the effect of chemicals on the reinforced structure has been also studied /5/, and parametric studies using different amounts of reinforcement have been also carried out using experimental setups /6/.

However, the work that has been performed on the realization of a numerical model that could be used for the prediction of the required reinforcement and the behavior of the concrete structure after the repair is rather limited. In the work of Ascione and Feo /7/, a numerical model has been developed in order to investigate the stress distribution on the adhesive layer between the plate and the concrete. This is an important parameter considering that this layer is responsible for the stress transferring from the concrete to the reinforcing plate.

In the present work the investigation of the overall performance of a notched concrete structural element before and after the application of the CFRP reinforcement was performed. Two different reinforcing strategies applied on a typical notched concrete beam have been analyzed, using numerical methods. It is very important to notice the influence of the interface layer between the reinforcement and the concrete on the functioning of the repaired beam. For this reason a detailed evaluation of the behavior of this layer was performed, and the possibility of different methods of reinforcement anchoring has been discussed. This was done in order to have a clear view of the effectiveness of a possible solution in case the reinforcement, due to geometrical and structural restrictions, cannot be placed in the intended position. It is very important to mention here that in the present work the bending behavior of the concrete beam is addressed. Many researchers have already addressed the problem of shear reinforcement of concrete beams /8/.

One of the aims of this work was to contribute a reliable numerical model for the prediction of the behavior of a notched concrete element before and after its repair. This type of modeling allows for detailed parametric studies. This is very important considering that in the literature significant experimental work exists that can only give answers to one specific problem.

Thus, in real cases using numerical models and paying only the experimental cost for the model calibration, one can simulate accurately the real situation and provide a solid answer for the application, the position and dimensions of the reinforcements that have to be applied for the repair of the structure, thus minimizing the cost. In addition, different reinforcing methods can be evaluated and an optimization of the repair strategy can be performed.

Therefore the present study deals with the numerical modeling of a notched, reinforced concrete beam where the notch is located at the bottom surface of the beam, and investigates two different repair approaches using CFRP. According to the first, two CFRP patches have been placed at both lateral surfaces of the cracked beam, while according to the second, a single CFRP patch has been placed at the bottom surface of the reinforced concrete beam over the existing crack. In both cases a parametric study concerning the dimensions of the patches used for the repair has been performed. The performance of the repair has been evaluated statically and dynamically.

For the static evaluation, results concerning the maximum developed stresses at the concrete beam and the maximum shear and peel stresses at the concrete beam at the adhesive have been provided. For the dynamic evaluation, the eigenfrequencies of the repaired beam have been calculated and compared to the eigenfrequencies of the intact (undamaged) beam.

As an optimal repair scheme, it is proposed to use the one that secures acceptable values of stresses in the concrete, the adhesive layer and the composite patch at the maximum design load of the beam, accompanied with no eigenfrequency shifting. Failure and post-failure scenarios of the repair beam under the presence of an impulsive-seismic type loading are outside the framework of the present work.

2. MODEL DESCRIPTION

In the present work a thorough examination of the simply supported concrete beam was performed in order to end up with a feasible and convenient Finite Element Model that would help in the evaluation of the response of the composite patch reinforced concrete beam.

The steel reinforced concrete beam configuration (cross section 300mmX200mm) is depicted in Figure 1. A load P (=100kN) is applied at the center of the beam span L (=1000mm). This configuration was selected according to the work of Garden *et al.* /9, 10/. A crack is assumed to be in the middle of the span up to the half-thickness of the beam section and through the width as shown in Figure 1.

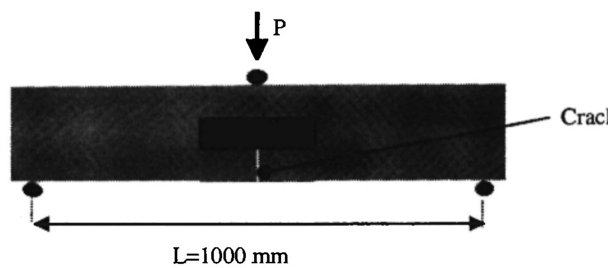

Fig. 1: Problem Description

In the present analysis only 3D models were used. This was decided in order to result in a detailed stress field, since a 2D model can provide only some general qualitative trends concerning the stresses developed in the beam. The analysis was performed using the NASTRAN commercial FEM code.

It is important to mention here that the solution of a finite element model for a cracked structure requires a very fine and dense mesh as well as the application of special crack elements. Since the response of the beam far from the crack region is not of significant importance in the present study only a part of the concrete beam around the crack was analyzed. For this reason the principles of hierarchical modeling were implemented. The beam with the corresponding boundary conditions was solved without the crack and the loads and moments resulting from this analysis were used for examination of the crack area. The implemented Finite Element Model was only 260 mm long and as a consequence it was possible to form a very dense and fine mesh.

However, in order to reduce the computational cost further, symmetry conditions were applied at the concrete beam as shown in Figure 2. The crack area as well as the strengthening patch is modeled using symmetry conditions.

3. MODELING PRINCIPLES AND MATERIAL PROPERTIES

Within the framework of the present study three different group of models were analyzed.

- A notched reinforced concrete beam (model 3D-A)
- A notched reinforced concrete beam repaired using composite patches at both lateral surfaces (model 3D-B)
- A notched reinforced concrete beam repaired using composite patch at the lower cracked surface (model 3D-C)

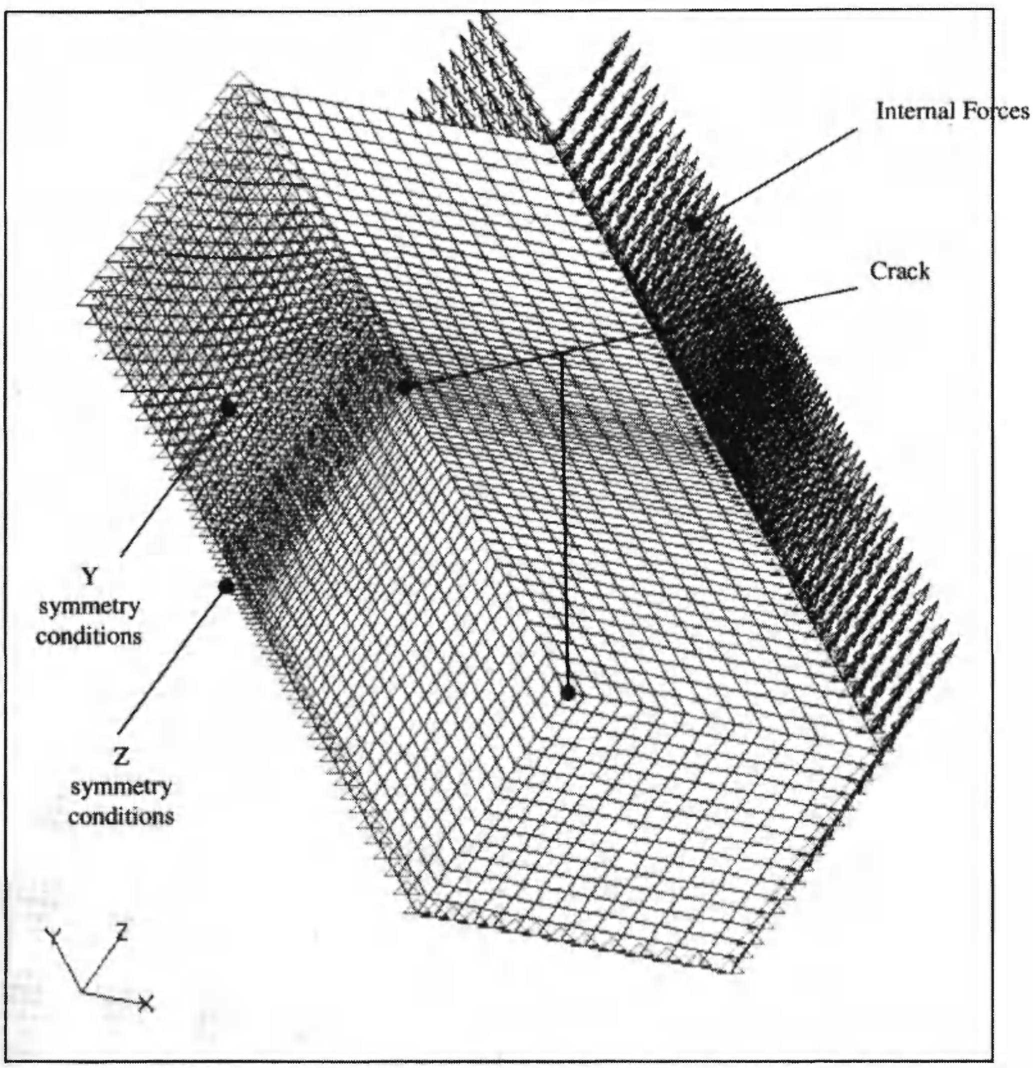

Fig. 2: FEM model (3D-A) for the analysis of the notched reinforced concrete beam

The material properties and the type and number of the elements used for the analysis of the above models are presented in Tables 1, 2 and 3.

The finite element models used are given in detail in Figures 2, 3 and 4, respectively.

All the materials used as well as their properties

Table 1
Properties of 3D-A model

Model 3D-A				
Material	**Material Model**	**Properties**	**Elements**	**No of Elements**
Steel Reinforced Concrete	Isotropic C30 Class	E = 30 GPa, ν =0.2	3D Brick	12532

Table 2
Properties of 3D-B model.

Model 3D-B				
Material	**Material Model**	**Properties**	**Elements**	**No of Elements**
Steel Reinforced Concrete	Isotropic C30 Class	E = 30 GPa, ν =0.2	3D Brick	12532
CFRP Patch $[0^{O}]_{16}$	Orthotropic	E_1 = 156 GPa, E_2 = E_2 = 9.09 GPa G_{12} = 6.96 GPa, ν_{12} = ν_{13} = 0.228 ν_{23} = 0.4	2D Layered Plate	416
Adhesive	Isotropic	G = 10 GPa, ν=0.25	3D Brick	416

Table 3
Properties of the 3D-C model.

Model 3D-C				
Material	**Material Model**	**Properties**	**Elements**	**No of Elements**
Steel Reinforced Concrete	Isotropic C30 Class	E = 30 GPa, ν =0.2	3D Brick	12532
CFRP Patch $[0^{O}]_{16}$	Orthotropic	E_1 = 156 GPa, E_2 = E_2 = 9.09 GPa G_{12} = 6.96 GPa, ν_{12} = ν_{13} = 0.228 ν_{23} = 0.4	2D Layered Plate	195
Adhesive	Isotropic	G = 10 GPa, ν=0.25	3D Brick	195

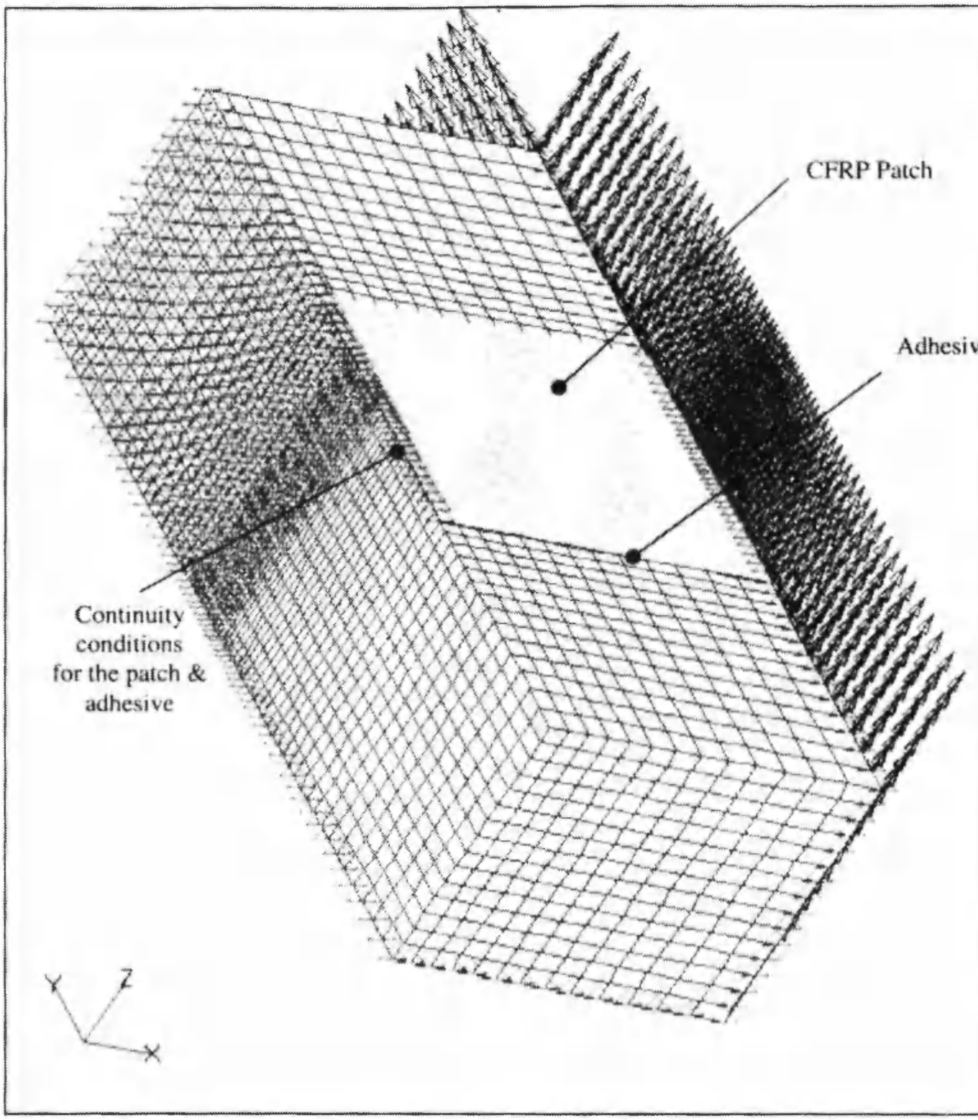

Fig. 3: FEM model (3D-B) for the analysis of the repaired concrete beam. Two lateral CFRP patches have been used.

have been selected according to what is used in real applications, like building rehabilitation and concrete structure strengthening after major devastations. Furthermore, the adhesive material used to bond the reinforcing patch to the concrete structure was selected based on commercially available products. The thickness of the adhesive layer was assumed to be 0.5 mm, a typical adhesive thickness for this type of repair. The reinforcing composite patch was assumed to be a CFRP unidirectional plate consisting of 24 layers yielding a total thickness of 3 mm in the case of the 3D-B model and of 16 layers yielding a thickness of 2 mm in the case of the 3D-C model. As stated earlier, three different groups of models were investigated. One 3D-A model, where no repair patch has been applied on the notched beam, was analyzed in order to have reference values for the evaluation of the two different repair strategies, which were applied. Then the two models of the repaired concrete beam were analyzed. The main reasons for the investigation of the alternatives for patch repair of the notched concrete beam are:

- The need for having different positions for the

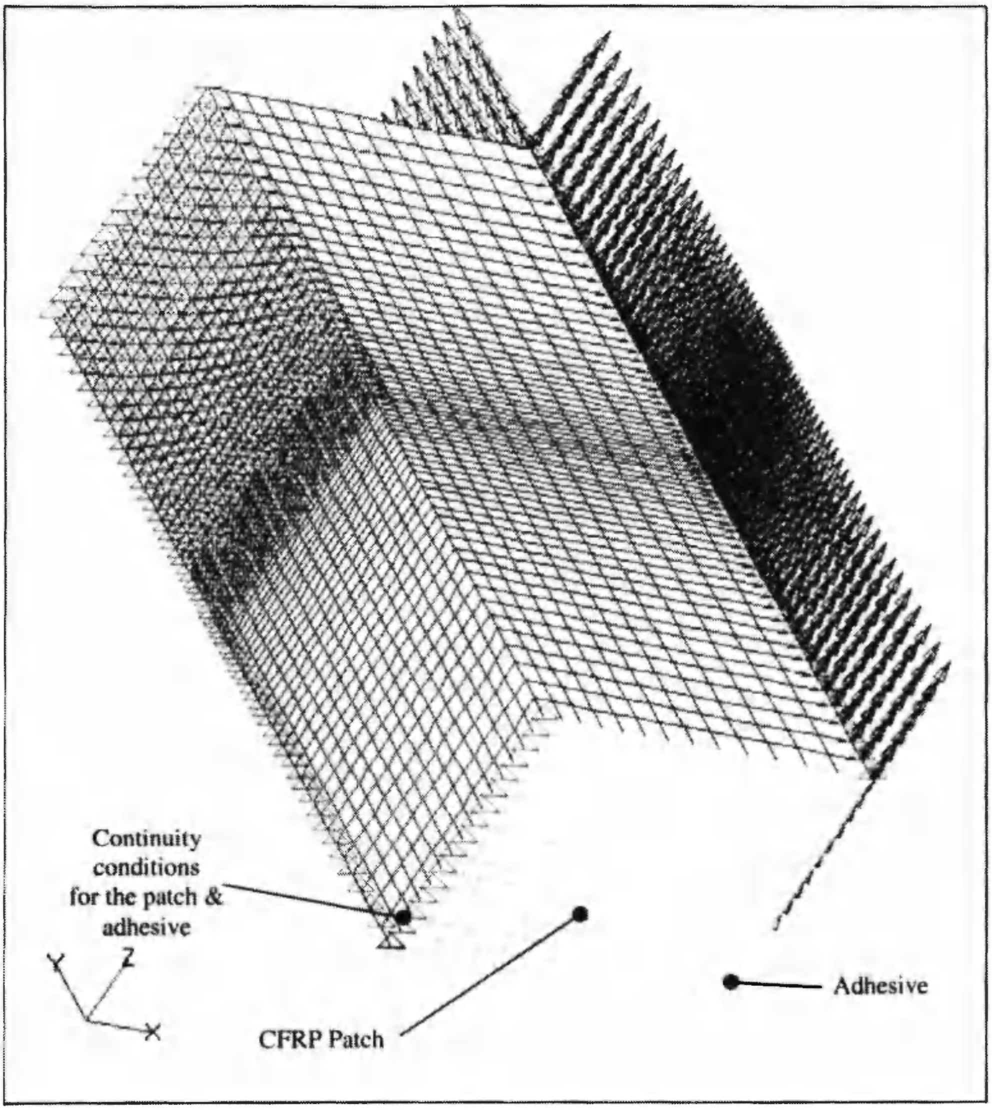

Fig. 4: FEM model (3D-C) for the analysis of the repaired concrete beam. One CFRP patch has been used at the lower surface of the beam covering the notch.

placement of the patch reinforcement, which in practice is imposed by the geometrical configuration of the structure under repair.

- The need for optimization of the repair scheme based on the dynamic characteristics of the repaired beam and the resulted cost.

It is important to notice at this point that the use of 3D brick elements for the adhesive layer is dictated by the shear loading which mainly faces the adhesive layer. Although the aspect ratio of the 3D brick elements used for the modeling of the adhesive layers slightly violates the recommended rules, this is the only way to account for shear stresses into the adhesive film. All the necessary computational tests for convergence have been passed successfully and a fine balance finally was kept between the precision of the analysis and the computational time needed for the solution of the models.

Extensive presentation of the results obtained for the different repair configuration is presented in the next section.

4. FEM MODELS

Three different groups of models were analyzed within the framework of the present work, as stated at the beginning of section 3, for the investigation of the behavior of an initially notched (Figure 2) and then repaired notched reinforced concrete beam.

Two repair strategies were studied. According to the first, two CFRP patches were placed at the lateral surfaces of the concrete beam as shown in Figure 3. Half of the patch width covers the notch. For this case a detailed stress analysis was performed assuming a CFRP patch length of 260 mm, and an eigenfrequency analysis followed in order to identify the basic eigenfrequencies of the repaired concrete beam. During the step of the eigenfrequency analysis different patch lengths were considered. Since the repair of a damaged concrete element helps the strength and stiffness recovery of the notched component, eigenfrequencies represent a global measure of the stiffness of the repair component.

According to the second repair approach a CFRP patch was placed at the lower surface of the notched concrete beam covering the notch mouth completely as shown in Figure 4. Once again in this case the length of the CFRP patch was 260 mm and its width was 200 mm. A detailed stress analysis was also performed in this case which was followed by an eigenfrequency analysis for the global evaluation of the stiffness recovery attained by the repair. During the eigenfrequency analysis different lengths for the CFRP patch were considered.

In all the cases analyzed all the materials involved (reinforced concrete, CFRP patch, adhesive layer) were assumed to exhibit a linear elastic behavior. Furthermore, in the cases of static analysis of the simple notched, and the repaired concrete beam, a hierarchical modeling approach was implemented, as has already been mentioned.

This was done in order to achieve a fine mesh that would permit a detailed and accurate stress analysis, reducing the computational time. To this end, initially the complete simply supported reinforced concrete beam was analyzed assuming that no crack exists. This analysis provides the exact displacement field, the shear forces and the bending moments at any cross section of the beam. These loads and displacements, that correspond to cross sections defining a symmetrical 260mm long part of the concrete beam, have been used for the detailed analysis.

5. RESULTS AND DISCUSSION

5.1 Static analysis

5.1.1 Notched beam without patch repair (Model 3D-A)

The analysis of the notched reinforced concrete beam model where no patch repair has been applied provides an expected deformation profile at the notch sides. More precisely, the beam under the load of 100 kN gives a maximum crack opening up to 0.250 mm. The FE model used in the present analysis behaves well as if the entire simply supported beam was fully modeled. This was confirmed by the analysis of a fine model of the complete reinforced concrete beam that has a central notch, and is subjected to simply supported boundary conditions and an external load of 100 kN applied at middle span. The results obtained are completely identical to the ones excluded by the analysis of the part of the beam as it is loaded after the hierarchical modeling approach for both the displacement and the stress fields. This is due to the fact that the translation boundary conditions and the internal loads were imposed into the reduced model configuration successfully. The corresponding results of the un-patched model are summarized in Table 4.

Table 4
Results of the Model 3D-A

Max. Crack Opening (mm)	Max. X stress at free edge (MPa)	Max. Y stress at free edge (MPa)
0.250	12	4

The corresponding total displacement and the X stress contours are presented in Figures 5 and 6 respectively.

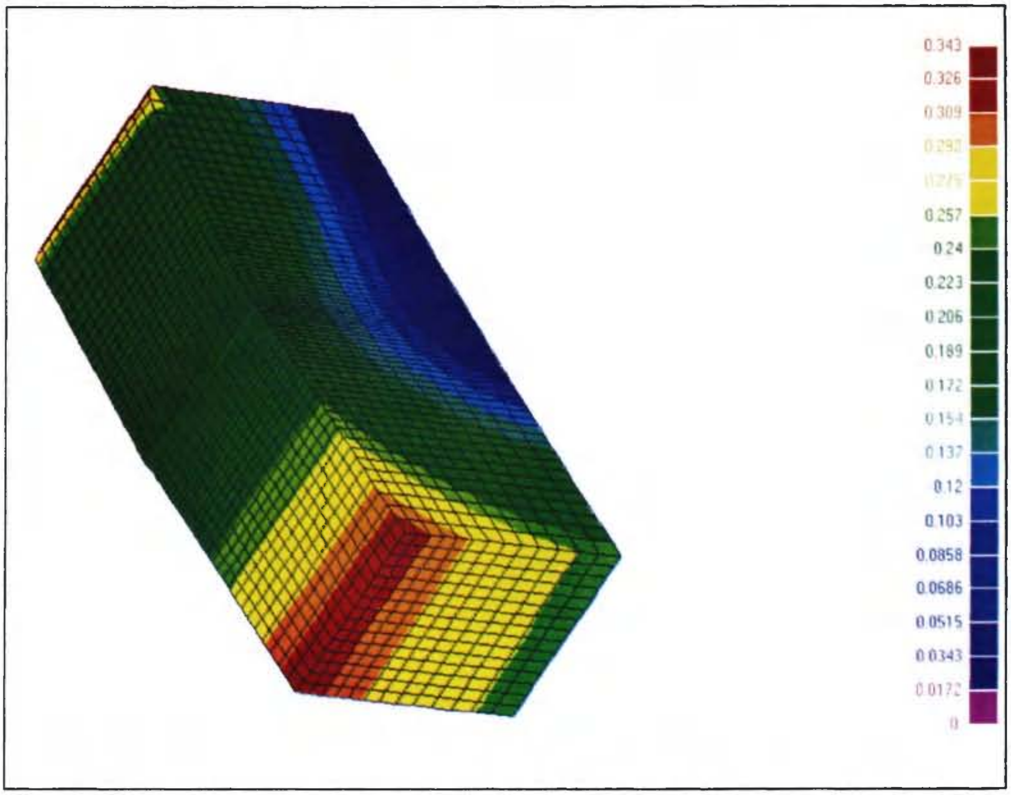

Fig. 5: Total displacement contour for MODEL 3D-A (mm)

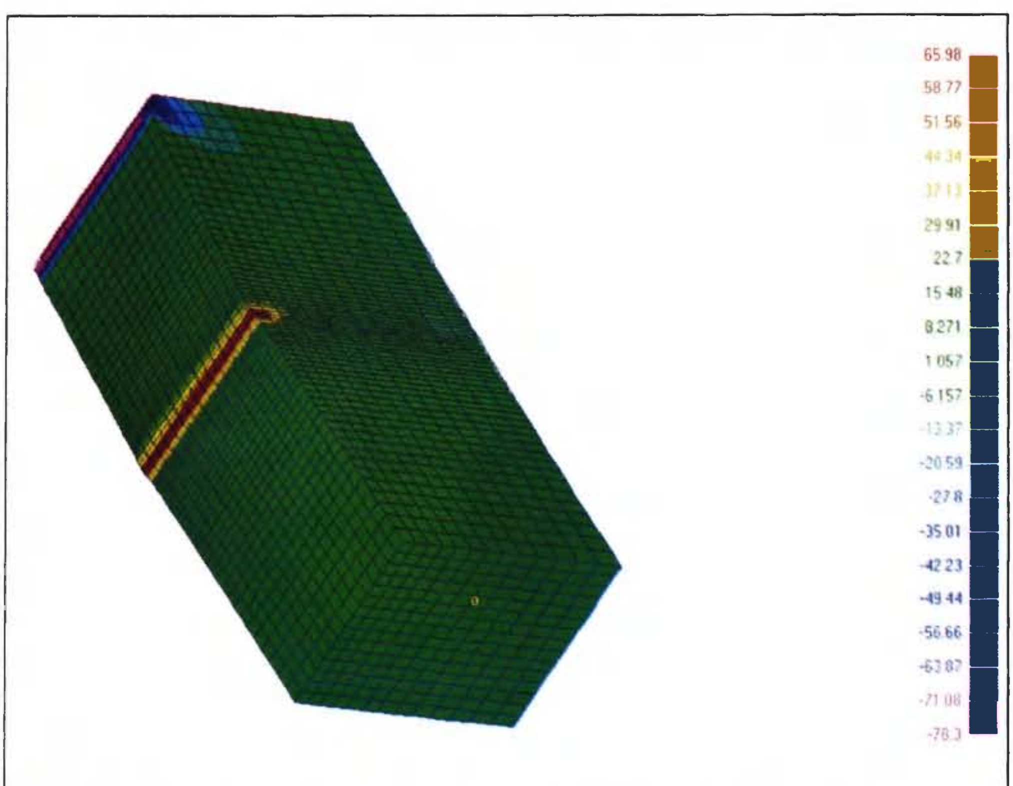

Fig. 6: X normal stress contour for MODEL 3D-A (MPa)

As shown for the X stress contours in Figure 6, the X normal stress contours close to the tip of the crack are very high and exceed the value of 3 MPa, which is the maximum permissible value for tensile stresses in the concrete. This model was analyzed in order to have a reference point for the evaluation of the patch repair, which will be analyzed in the next steps of the present work. It is obvious that in this state the beam cannot carry the load that is applied and thus the retrofitting is necessary.

5.1.2 *Repaired beam using composite patches at the lateral sides (Model 3D-B)*

The analysis of the notched concrete beam, repaired using CFRP patches at the lateral sides, leads to a significant reduction of the deformation profile. The beam gives a maximum crack opening up to .175 mm. The corresponding results of the 3D-B model are summarized in Table 5.

Table 5
Results of the Model 3D-B

Max. Crack Opening (mm)	Max. X stress at free edge (MPa)	Max. Y stress at free edge (MPa)
0.175	5	0

The corresponding total displacement and X stress contours for the concrete and the adhesive part are presented in Figures 7 and 8. The shear stresses in the adhesive are presented in Figure 9 and the X, Y stresses and shear stresses for the CFRP patches are presented in Figures 10, 11 and 12 respectively.

As shown in the previous figures, the stresses into the concrete component are highly reduced by the present CFRP patch, as was expected. However, the maximum X stresses that exist in the concrete are still above 3 MPa in some areas that are close to the most loaded position of the CFRP patch. In these regions one

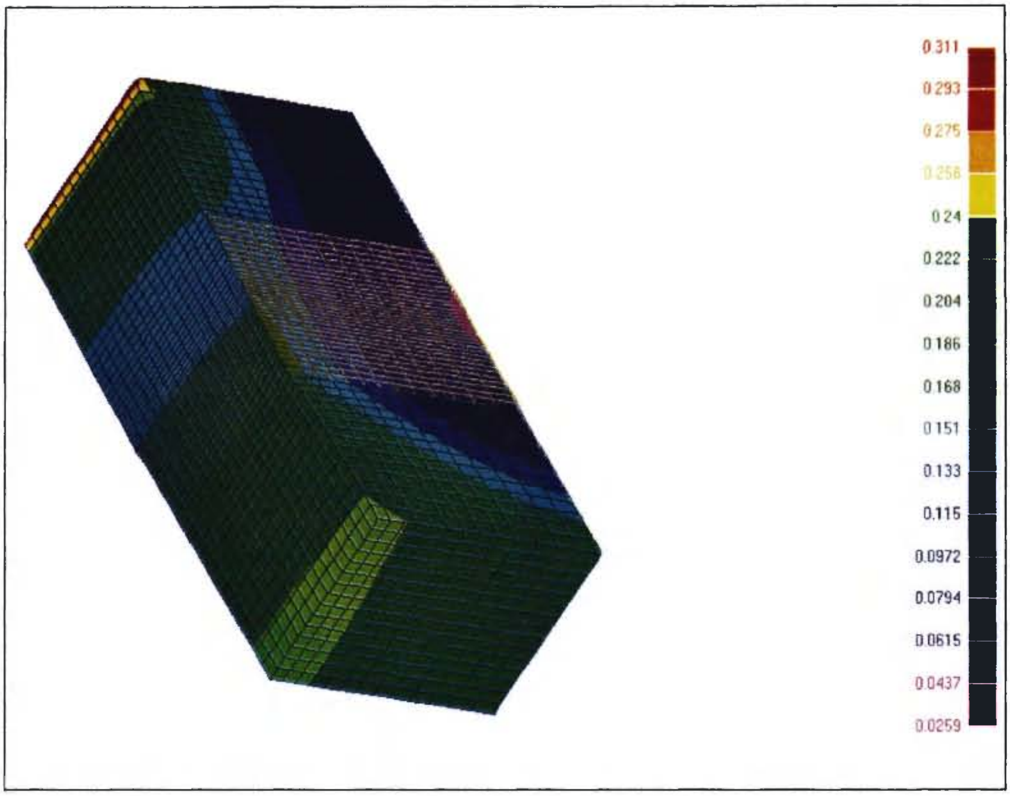

Fig. 7: Total displacement contour for MODEL 3D-B (mm)

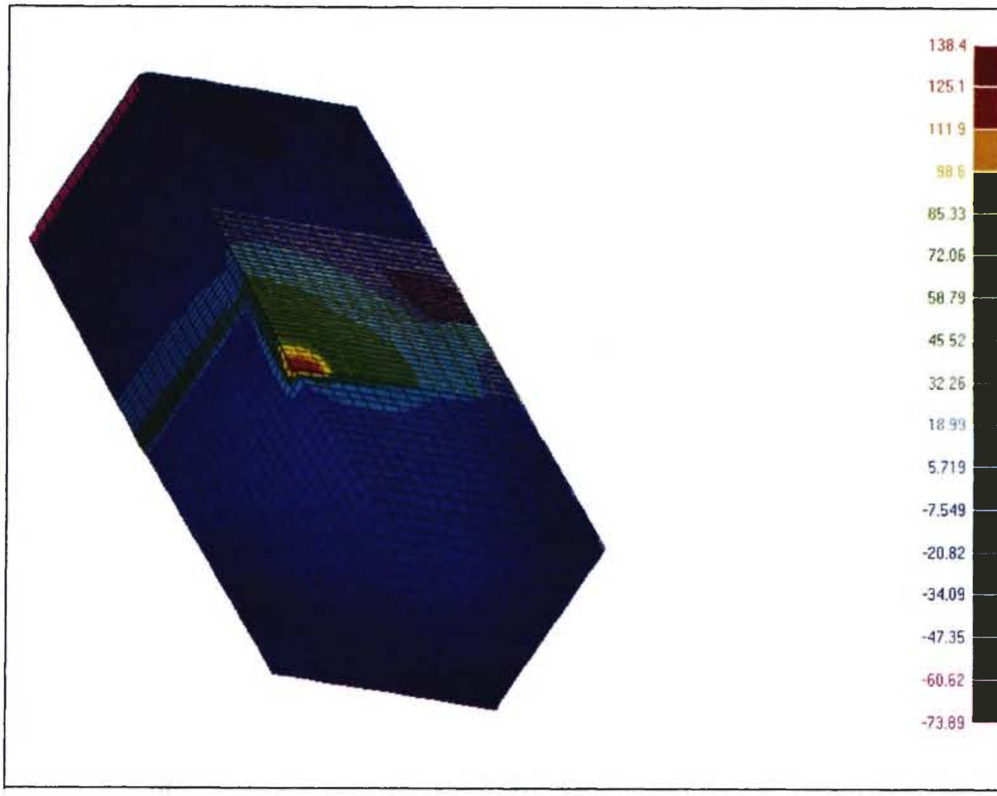

Fig. 8: X normal stress contour for MODEL 3D-B (MPa)

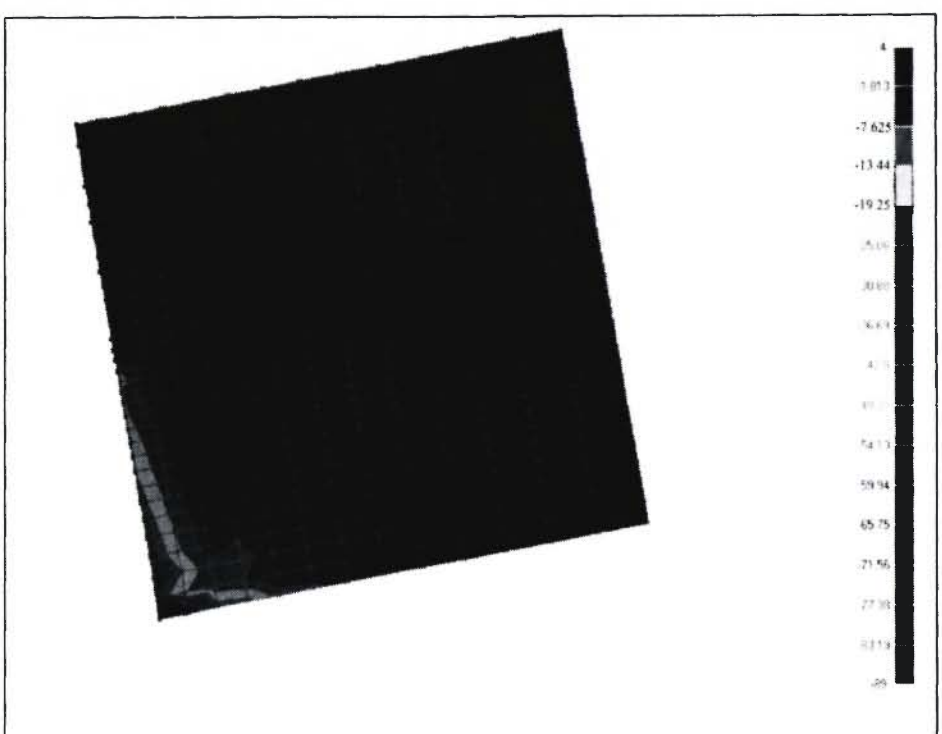

Fig. 9: XZ shear stresses in the adhesive.

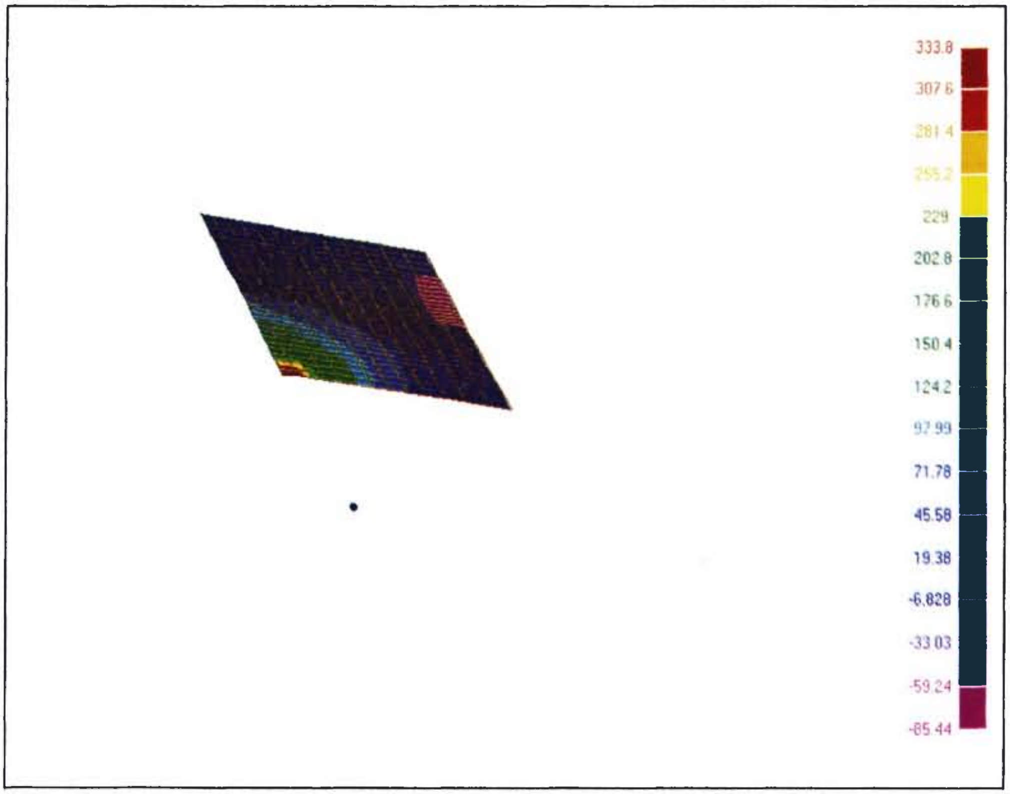

Fig. 10: Patch X stress contour for MODEL 3D-B (MPa)

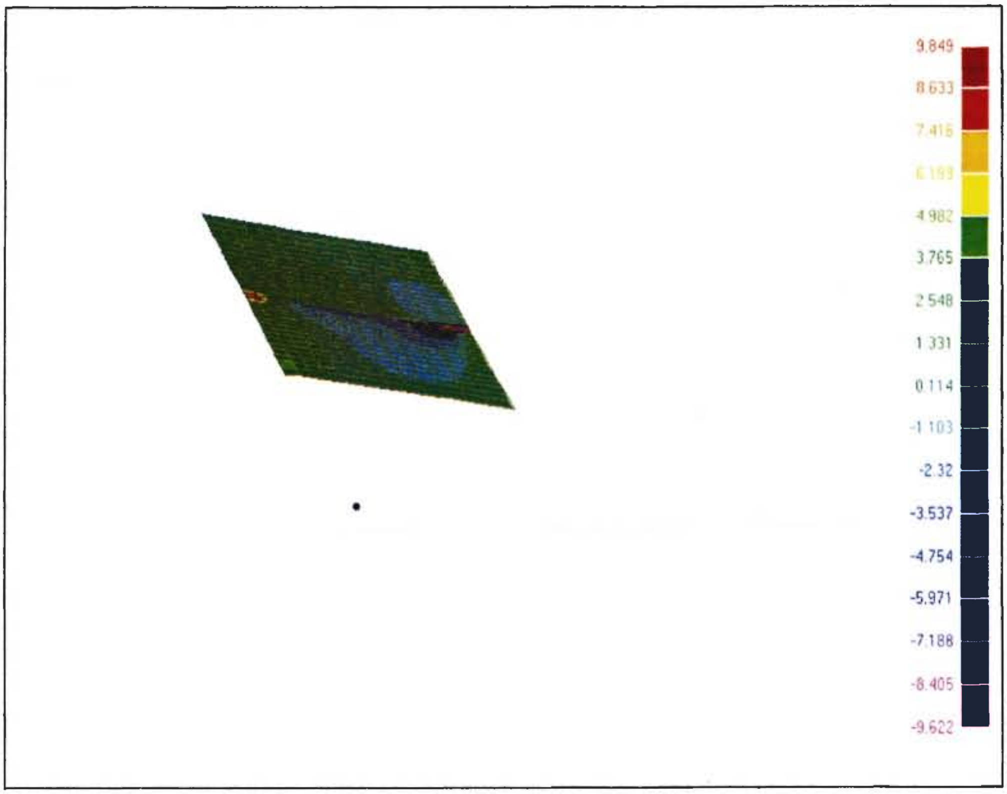

Fig. 11: Patch Y stress contour for MODEL 3D-B (MPa)

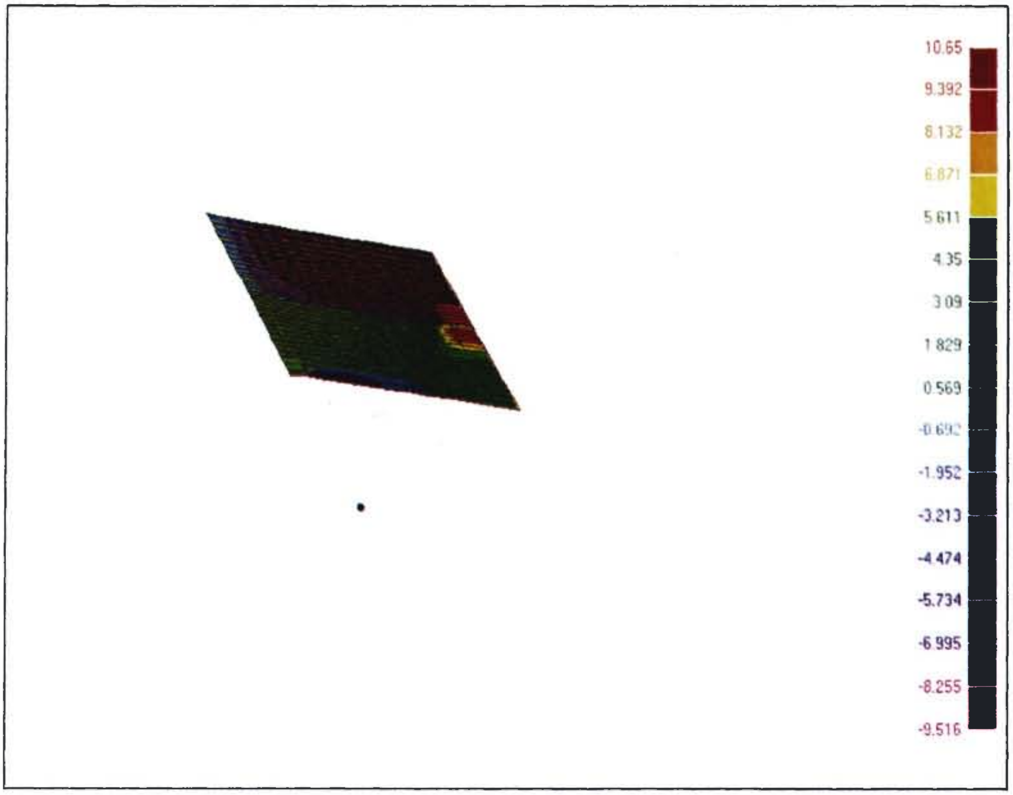

Fig. 12: Patch shear XY stress contour for MODEL 3D-B (MPa)

can notice that there is a transition from high stress values to low stresses. In addition this transition takes place in a very small depth within the concrete block. In fact, this could be a numerical artifact since it is necessary to have the continuity of the stresses in the contours.

In the reinforcing patch the maximum X stresses are below its ultimate strength. It is thus concluded that this type of CFRP plate is adequate for this kind of reinforcement.

One of the most important parameters of the reinforcement is the XZ shear stresses that are developed in the adhesive layer, as shown in Figure 10. These stresses are very high at the edge of the reinforcing patch, as expected. The value of these stresses is the main drawback for this application and in case no other solution for the placement of the CFRP patch exists, an additional anchoring method should be used at this position.

All the results shown above correspond to the given geometrical configuration of the patches, which cover part of the lateral profile of the notch. However, this configuration allows for large deformation of the crack geometry and finally high stress levels at the tip of the notch. Increasing the width of the patches for full coverage of the lateral notch profile, the tensile loads at the concrete decrease significantly. Furthermore, this reduces the deformation gradients that the adhesive material has to accommodate and this finally has a very positive effect in reducing the shear stresses at the adhesive film.

5.1.3 *Repaired beam using a single composite patch at the lower side (Model 3D-C)*

The analysis of the notched concrete beam, repaired using a CFRP patch at the lower side of the beam in such a way that covers the crack opening and does not allow significant deformation of the crack flanks, leads to the most reduced deformation profile of all cases. The beam gives a maximum crack opening of 0.02 mm. This patch configuration provides the best reinforcement for the notched concrete structure since it protects the concrete from the development of high tensile stresses around the crack tip region. The only drawback of the proposed model is the increased stresses in the adhesive layer. The corresponding results of the 3D-C model are summarized in Table 6.

Table 6

Results of the Model 3D-C

Max. Crack Opening (mm)	Max. X stress at free edge (MPa)	Max. Y stress at free edge (MPa)
0.02	2	0

The corresponding total displacement and X stress contours for the concrete and the adhesive part are presented in Figures 13 and 14. The shear stresses in the adhesive layer are presented in figure 15. The X,Y local stresses and the shear stresses for the composite patch are presented in Figures 16,17 and 18 respectively.

As shown in the previous Figures the X stresses into the concrete are very small after the application of the CFRP reinforcement at the bottom of the concrete notched beam. The value of these stresses indicates whether the reinforcement is successful or not. At the upper side of the concrete beam one can see that the X compressive stresses are high enough. This is a local effect due to the method of application of the load in the present analysis (concentrated loads were considered). The value of the X stresses in the rest of the concrete beam and in the region of the notch tip is lower than 3 MPa except from the area of the application of the reinforcement. In this area there is a transition from the high values that appear in the reinforcement to the low values of the concrete. This is a position where special attention should be paid in order to avoid possible failure that can be initiated.

For this type of reinforcement the critical stresses for the adhesive are the XY shear stresses as they are shown in Figure 15. As shown in this Figure the stresses vary between 0 and 8 MPa, which is an acceptable value for the adhesive film.

Furthermore all the stresses developed in the CFRP patch are very easily accommodated by this type of material.

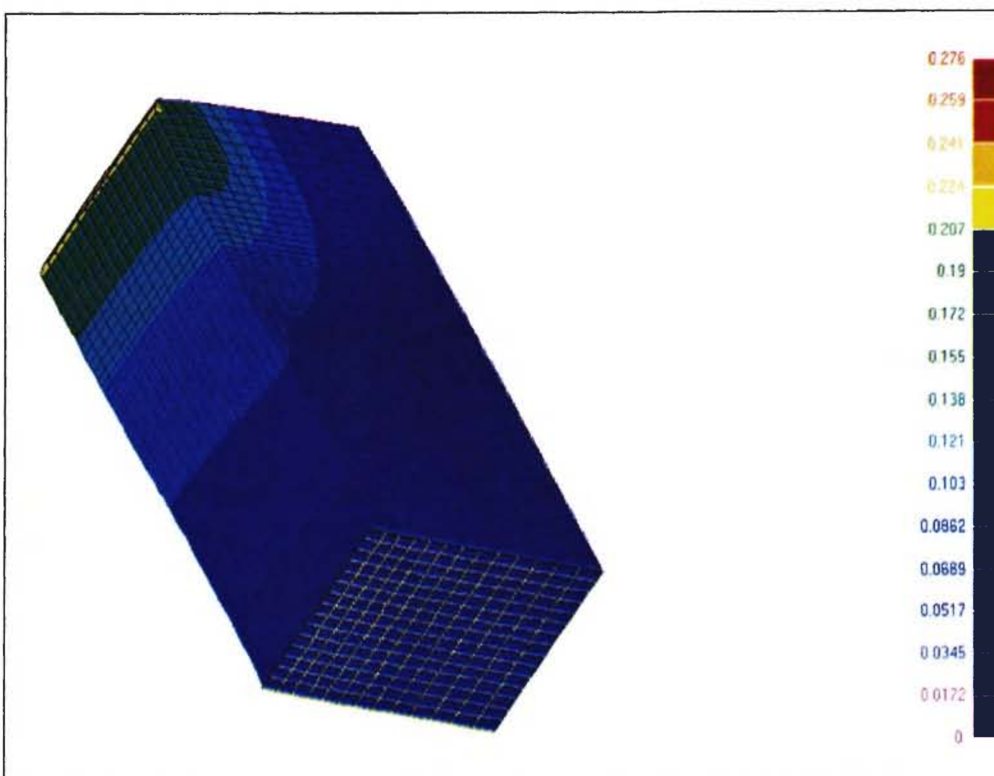

Fig. 13: Total displacement contour for MODEL 3D-C (mm)

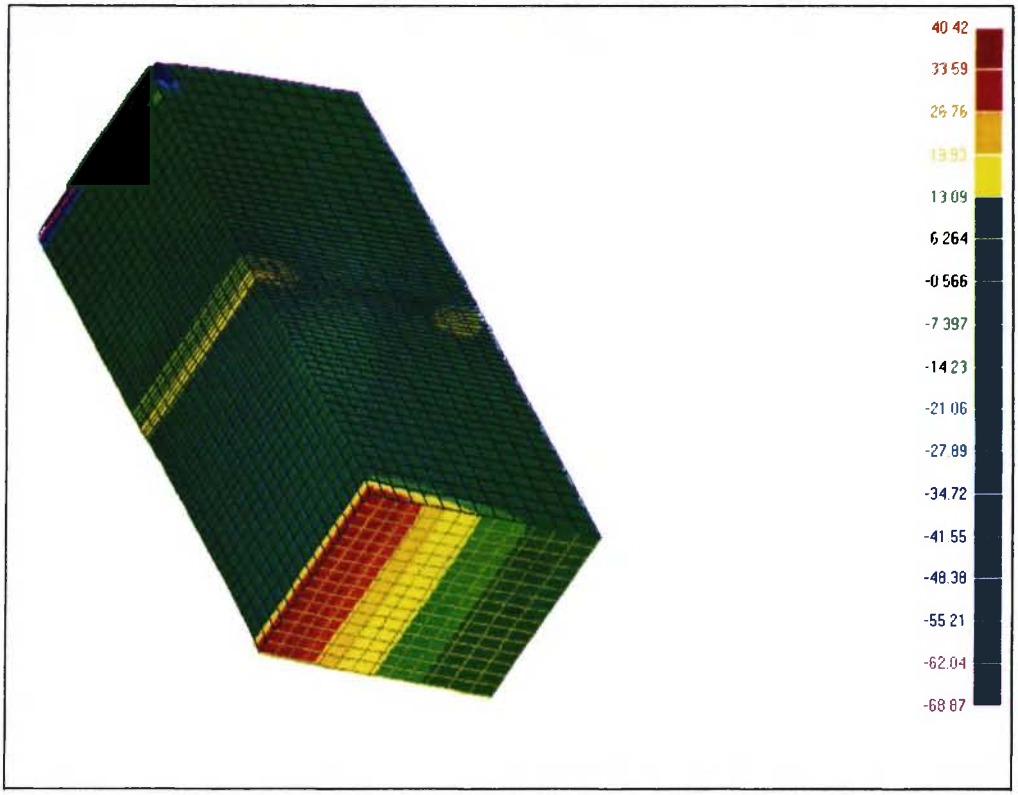

Fig. 14: X normal stress contour for MODEL 3D-C (MPa)

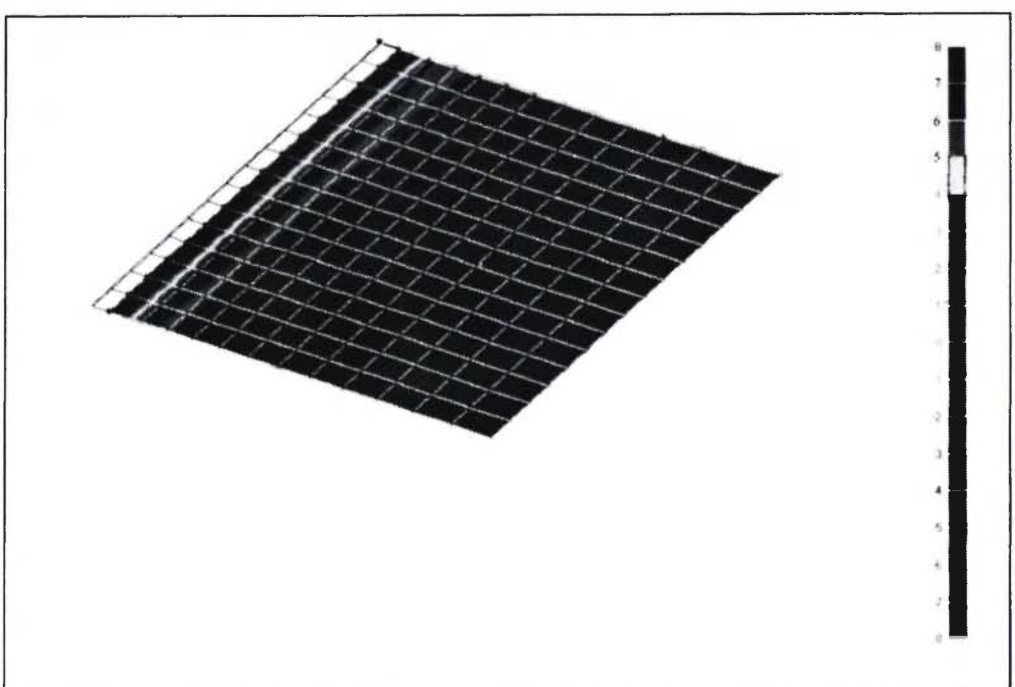

Fig. 15: XY shear stresses in the adhesive.

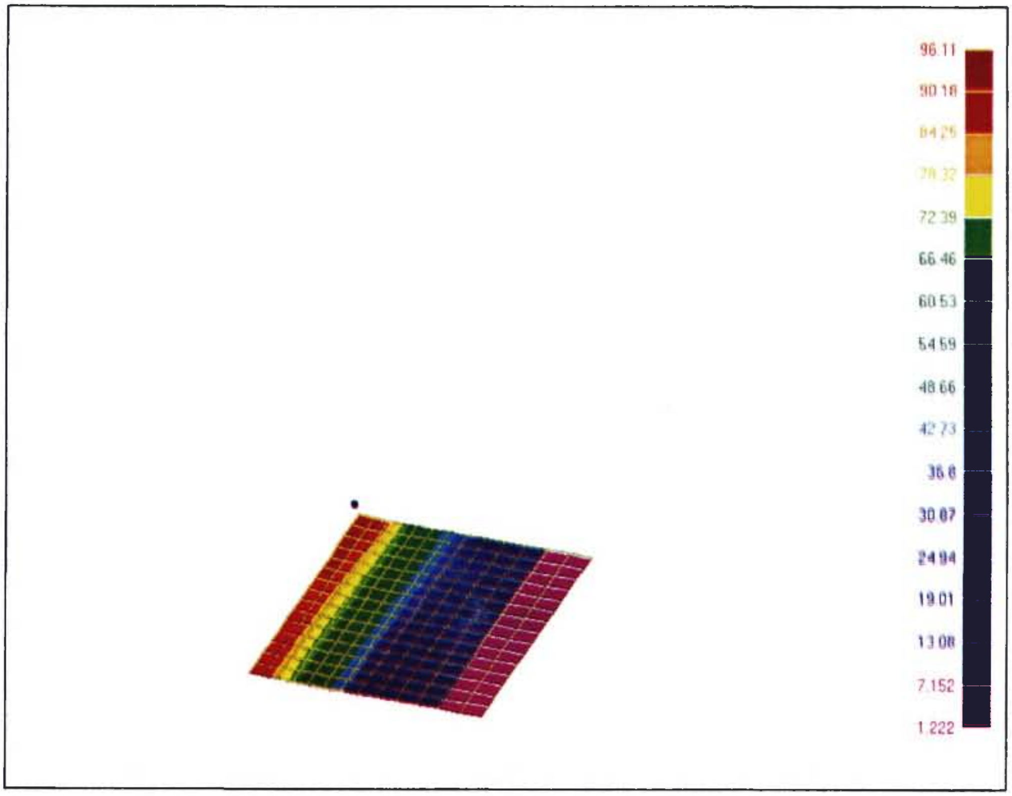

Fig. 16: Patch X stress contour for MODEL 3D-C (MPa)

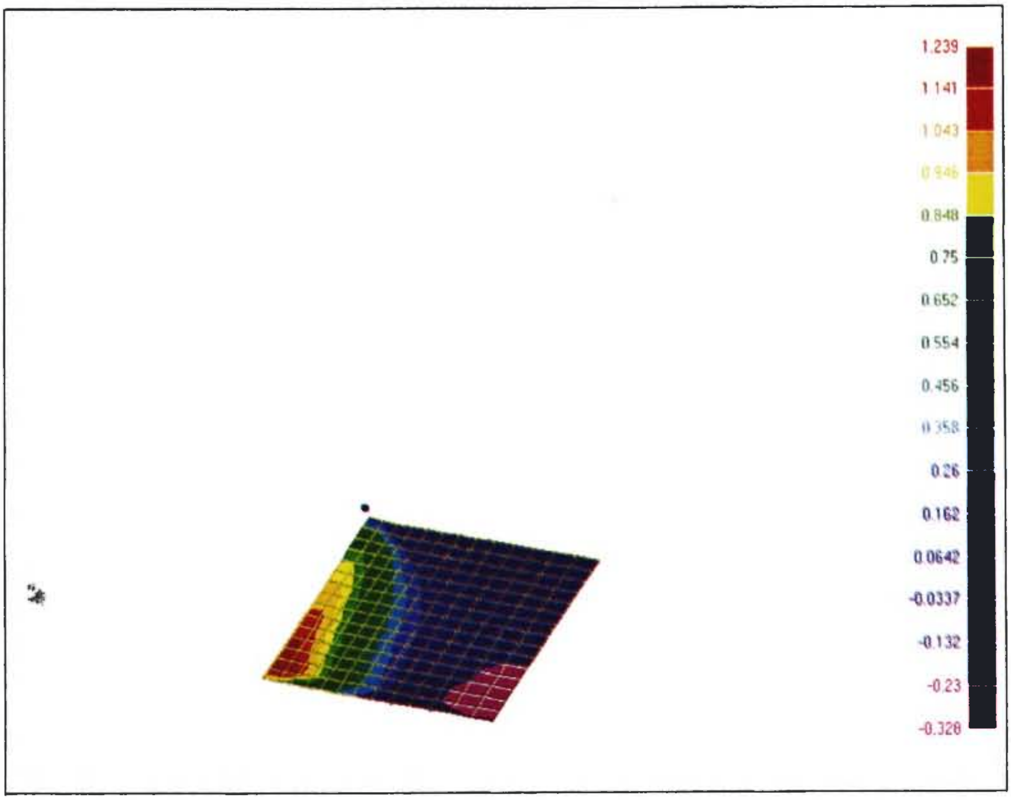

Fig. 17: Patch Y stress contour for MODEL 3D-C (MPa)

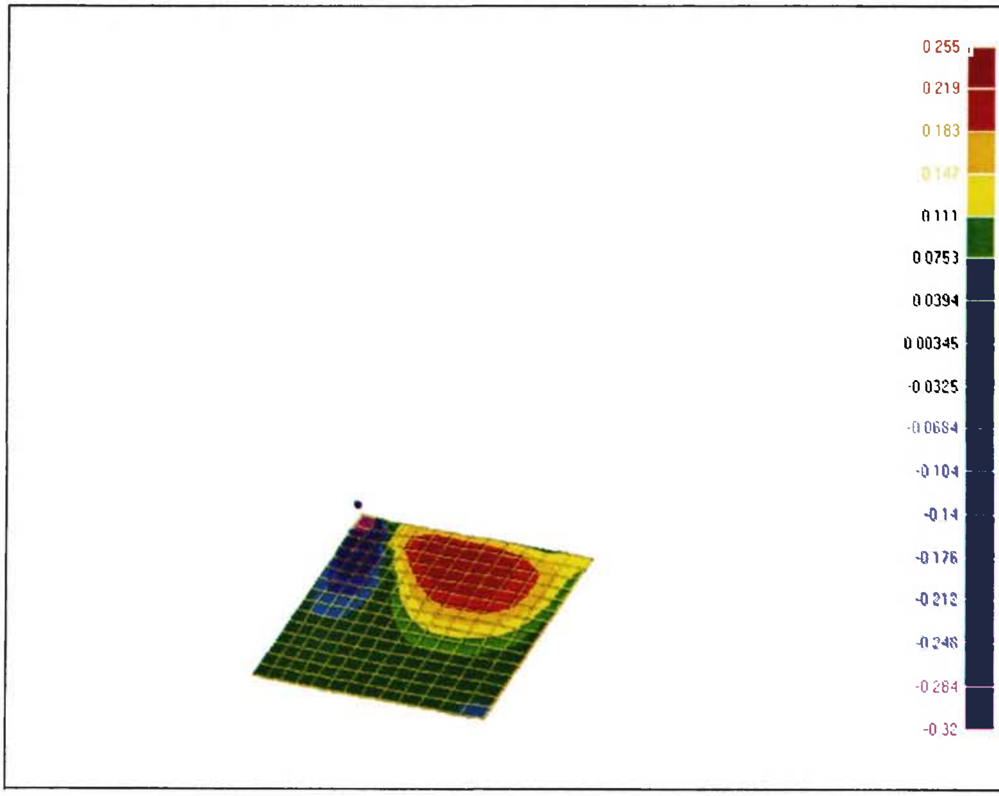

Fig. 18: Patch shear XY stress contour for MODEL 3D-C (MPa)

5.2 Eigenfrequency analysis

The stresses which are developed at the different components of the repaired concrete structure comprise the basic criteria for decisions on the repair strategy. However, it is obvious that the kind of repair affects the dynamic characteristics of the structure significantly. Thus, among the parameters that the person who designs the repair strategy must take into consideration is that the resulting structure, after its repair, must keep dynamic characteristics that are very relative to the initial undamaged one.

This is obvious, since an over-stiffening of a repaired part of a structure completely affects the way it vibrates after a possible seismic excitation. Therefore, in the next part of the present section the results of the eigenfrequency analysis of the intact and the repaired concrete beam are presented.

In the case of the repaired beam the eigenfrequency analysis has been performed for different geometrical characteristics of the CFRP patches. Table 7 shows the first bending and first torsional eigenfrequencies of the intact and repaired concrete beams for the geometries, which have been analysed quasi-statically at the running section.

Table 7
Eigenfrequency analysis results

Eigenfrequency	**Eigenefrequency**	
	1st	**2nd**
Intact beam	54.69	236.44
Lateral repair	36.41	184.53
Bottom Repair	52.18	235.78

As is clearly shown in Table 7 concerning the dynamic response of the repaired beam, the restoration strategy that gives the 'best results' is the one with the application of the reinforcing patch at the lower side of the beam. In this case the 1st bending eigenfrequency shows that after the application of the reinforcement the concrete beam behaves as if there was no damage on it. On the other hand, using the lateral repair approach, there is insufficient stiffness recovery of the structure concerning the in-plane bending and the torsional vibration modes. In this case the 1st eigenfrequency of the structure remains relatively low, which reflects a stiffness decrease concerning the first bending and torsional mode, and thus the total dynamic behaviour of the complete structure that contains the repaired structural element is also affected. This is a very important parameter that is usually not taken into consideration when a part of a structure needs to be reinforced.

In order to investigate what is the behaviour of the structure in different length reinforcements two (2) 3D-C models were investigated with different patch lengths. In the following table the results obtained from this analysis are presented.

Table 8

Eigenfrequency analysis for different reinforcement lengths (model 3D-C)

Reinforcement Length (mm)	Eigenfrequency	
	1st	2nd
185	52.16	235.5
140	52.12	235.4

It is clearly shown in the previous table that there is no significant difference in the results of the eigenfrequency analysis when the length of the reinforcement is changed. This is due to the fact that after a small distance from the edge of the crack the stress field on the reinforcing patch is very low and thus there is not much difference when its length is reduced. However, it is very important to take into consideration the fact that the smaller the reinforcing patch becomes, the higher will be the shear stresses in the adhesive. This is a very critical issue and thus it is preferred to use a longer reinforcing patch in order to reduce the shear stresses in the adhesive.

In order to investigate the behaviour of the lateral reinforcements, changing the thickness of the reinforcing patch, a parametric study was also performed. This analysis was conducted in order to investigate whether the poor results of this type of reinforcement are due to the thickness of the patch or due to the position of the reinforcement.

It is clearly shown in Table 9 that the thickness of the reinforcing patch when applied at the lateral sides of the concrete structure has a limited effect on the eigenfrequencies of the structure. It is thus obvious that this reinforcing technique should only be applied in the case that no other alternatives exist due to the position of the notch and the geometrical configuration of the structure. Even in cases where the thickness of the patch is increased to 5 mm the attained stiffness increased is practically negligible compared to the case of patch thickness of 3 mm, as it is elucidated through the 1st bending and the 1st torsional vibration modes

Table 9

Eigenfrequency analysis for different reinforcement thickness (3D-B model)

Reinforcement thickness (mm)	Eigenfrequency	
	1st	2nd
4	37	184.74
5	37.51	184.92

In addition another parametric study was performed by changing the length of the reinforced as in the case of the 3D-C models. In the following table the corresponding results are presented.

Table 10

Eigenfrequency analysis for different reinforcement lengths.

Reinforcement length(mm)	Eigenfrequency	
	1st	2nd
185	36.41	184.53
140	36.13	184.4

As shown in Table 10, the length of the reinforcement patch has a limited influence on the eigenvalues of the repaired structure. For this reason it is concluded that in this case the position of the patch and the covering area are not sufficient to provide the necessary upgrade of the concrete beam.

6. CONCLUSIONS

From the results listed in the previous paragraphs some very important observations can be drawn considering the selection of the reinforcing method as well as the possible problems that may occur in each case.

The application of the reinforcements in the lateral side of the structure is not an efficient reinforcing technique. Apart from the fact that the structure is not upgraded in the most efficient way considering its dynamic response, the shear stresses developed in the adhesive in this case are much higher and this is a parameter that has to be taken into account in order to avoid a failure of the adhesive layer placed between the CFRP patch and the concrete beam. However, in case the application of the reinforcement on the lower side of the structure is not possible, its application on the lateral sides can be used. In such a case the covering area by the reinforcing patch should be significantly increased. Thus, this method should be only applied when no other available repair alternatives exist.

Based on the results shown in the present work, the best reinforcing technique is the one where the reinforcing patch is placed at the lower side of the beam, covering the crack opening. The only drawback with this case is that in a small area close to the free edge of the crack the X stresses are high. This can lead to a failure of the concrete just above the reinforcing patch. This is fairly predictable, considering the variation of the stress path into the concrete block due to the application of the CFRP patch. Apart from this, the behavior of this type of reinforcement is ideal considering the other critical parameters. The shear stresses in the adhesive are rather limited and the stresses in the reinforcing patch are also very small.

It is obvious that the analysis performed with the models proposed in this work can be very useful for the optimum design of a retrofitting of a given concrete structure and detailed prediction of the stress field attained by the application of a given reinforcement. Using numerical analysis tools it is possible to avoid a large amount of experimental work and the design of the repair strategy can be faster and more cost effective, providing the option for detailed parametric studies. However one must keep in mind that the application of such an approach demands a calibration phase of the numerical model against experimental results that correspond to similar conditions to those involved in the given problem.

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