

STRUCTURAL RETROFITTING USING FIBER REINFORCED POLYMERS

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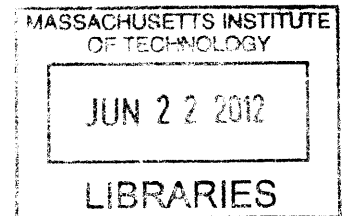
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Abstract :

Over the past decades, fiber reinforced polymers (FRP) have been widely used in the aeronautical and naval industries. Being more costly than conventional Civil Engineering materials such as steel or concrete, they have not been used on a large scale yet. However progress in understanding their limitations and possible applications for construction has led to increasing applications in structural retrofitting. When compared with other solutions to retrofit bridges or buildings that are in poor state or need to be able to withstand greater loads than the one they were designed for originally, fiber reinforced polymers appear to be an economical, efficient and particularly time saving alternative.

This thesis analyses the properties of fiber reinforced polymers and their various applications in the field of Civil Engineering. Flexural and shear strengthening, column retrofitting, blast and seismic applications are presented as well as the different modes of failures encountered when fiber reinforced polymers are used. For each of these applications recent examples are provided and analysed.

Fiber reinforced polymers have been used in different countries and therefore different standards for their applications have been defined, under different assumptions. This thesis provides a comparison of the standards regarding shear strengthening in the main codes used in the USA, Canada and Europe and analyses the origin for such differences.

Thesis Supervisor : Jerome J. Connor

Title : Professor of Civil and Environmental Engineering

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A kind thanks to my mother.

A tender thought to Guy and Andrée.

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Introduction

Some buildings or bridges that have been built in the early 20th century are in poor state and therefore need to be replaced or retrofitted. Others do not comply with the newest standards of earthquake engineering or have experienced significant damages due to earthquakes and can not be used in their current state.

In times of economical restrictions and decreasing state budget, replacing aging infrastructures is too costly. In the past few years, the development of innovative techniques to strengthen structures allows for low retrofitting cost of this infrastructures. This possibility is particularly relevant for building that are critical for the purpose of safety of the population such as hospital or main bridges that are essential in the transportation system of a city. Sometimes they need to be retrofitted to have better behavior under earthquakes. One of the very effective way to increase the structural performance of these buildings is to use fiber reinforced polymers (FRP). It is an interesting option as the cost to retrofit structures with fiber reinforced polymers is obviously less than the cost to replace the entire structure.

This thesis aims to explore the different fields of application, limitations and review of fields of research that have been explored. Given their mechanical properties, fiber reinforced polymers are being used for the retrofitting of buildings. At first the properties of FRP are studied. Then the different applications of these fibers in the attempt of improving performances is described.

Depending on the application and use of FRP, several standards and guidelines have been developed in different areas of the world. A focus and a comparison on the efficiency of the standards used for shear strengthening is provided in the final paragraph of this thesis.

I-Fiber Reinforced Polymers :

1. Constitutive Material and Mechanical Properties

Fiber reinforced polymers are made of two entities : a matrix, which is usually made of resin such as epoxy, and fibers. The fibers are the constituent that will give its mechanical properties to the material. There can be a mix of the different types of fibers used such as Glass, Carbon or Aramid (Kevlar). These fibers are embedded in what is called the matrix which is basically a resin made of polyester, epoxy that also gives some properties to the whole material. They are two different kinds of matrix, thermosetting plastics and thermoplastics.

At first one must consider that the compressive and tensile strength of this fiber reinforced polymers is much higher than the one of concrete or steel. High Performance Concrete will only have a compressive strength of 150 MPa and a tensile strength of about 3 MPa. Steel has a better capacity to withstand tensile action, however its tensile strength is only 400MPa. Compared to those figures a FRP material made of E-Glass can reach a tensile strength of 1770 MPa. This highlights the potential of this material.

In the table below one can see a comparison of the different material properties of fiber reinforced polymers depending on the fiber that is used and also the stress-strain diagram for different FRP such as Carbon Fiber Reinforced Polymers (CFRP), Aramid Fiber Reinforced Polymers (AFRP), Glass Fiber Reinforced Polymers (GFRP) and mild steel.

Comparison of common fibers			
Materials	Density(g/cm ³)	Tensile strength(Mpa)	Young Modulus(Gpa)
E-Glass	2,55	2000	80
S-Glass	2,49	4750	89
Alumina	3,28	1950	297
Carbon	2	2900	525
Kevlar 29	1,44	2860	64
Kevlar 49	1,44	3750	136

Table 1 : Properties of common fibers

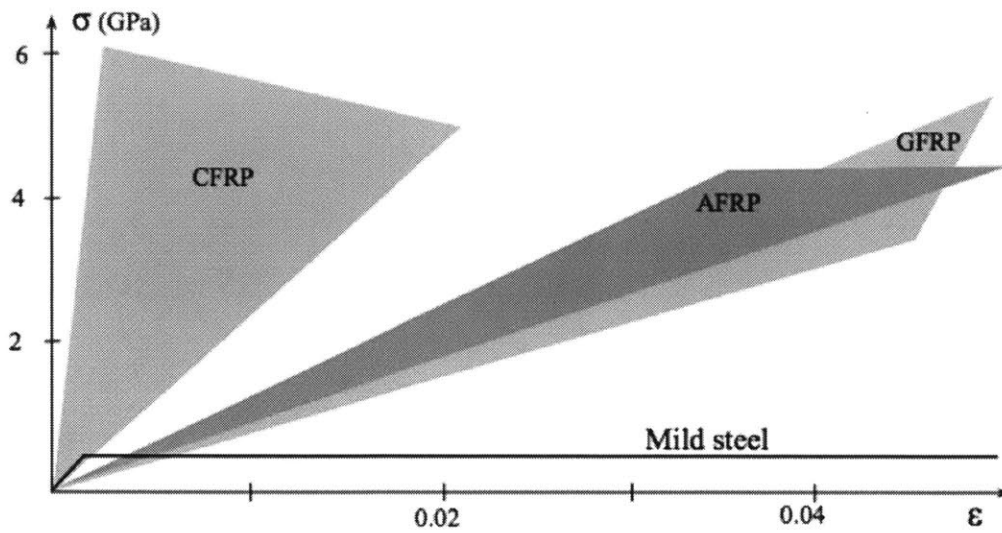


Figure 1 : Stress-strain diagram for different FRP and Steel (Source : "Seismic retrofitting using externally bonded FRP" Triantafyllou)

a) The different types of fibers

-Glass Fibers :

Glass fiber have been commonly used for 50 years in the aeronautical industry given their very high strength to weight ratio. They also commonly find applications for wind turbines blades or in the field of naval engineering.



Figure 2 : Offshore wind turbine

E-Glass or Electrical Glass is the most widely used glass fiber for reinforcement given its very low cost of production. There are also other glass fibers available that have an even better strength such as S-Glass as shown in the fiber comparison chart.

-Carbon Fibers

Carbon Fiber Reinforced Polymers are being the most commonly used in structural engineering for the retrofitting of old structures that may have been damaged by earthquakes, chemical environment, etc. Their tensile strength of 2900 MPa and their young modulus of 525 GPa are mechanical properties that are more important than the one of glass fibers.

-Aramid or Kevlar

These fibers are less used as regards applications for civil engineering and retrofitting of structures. However one must note that these fibers are the one that offer the best strength to weight ratio.

Comparisons of the fibers :

The best advantage of glass fibers and particularly E-Glass is their low cost compared to Carbon or Aramid fibers. However some concerns have been raised as regards their durability. Indeed in terms of alkaline resistance they are less resilient.

The main drawback of Aramid fibers are their inadequate compressive strength. Despite their higher cost, carbon fibers are the most commonly used for civil engineering applications. To give a simple cost comparison, E-Glass fibers are sold at around 2\$ per pound whereas High Strength Carbon Fibers are about the same price as S-Glass fibers, around 8\$ per pound.

b) The matrix :

In order to make a simple comparison, the fibers play the role of reinforcement bars (rebars) in concrete, they actually increase the strength of the material in which they are embedded called the matrix. This matrix can be made of thermoplastics (material that melt when heated) or thermosets (material that can not become liquid again). The matrix is commonly made of polyester, vinylester or epoxy in the case of aeronautical applications.

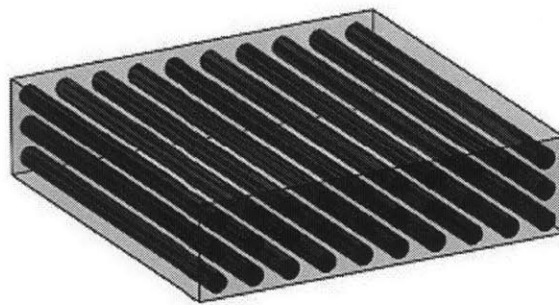


Figure 3 : Fibers embedded in the polymer matrix (Source : "Use of fiber reinforced polymer composite in bridge structures" Tuakta Chakrapan)

Fibers in the matrix :

The main function of the matrix is to transfer the stress between the different layers of fibers and to protect them from aggressive environment. They act as a screen and have the same function as the spacing of rebars from the exterior layer of concrete.

An important property of this material is that it behaves as a linear elastic material until failure as can be seen on the figure below for different types of fibers. There is no plastic zone as for steel or concrete. This is a particularly important issue as regards failure of this material which is very brittle. It raises safety issues. This also leads to oversecured reinforcement which are therefore more costly. Given the current price of FRP this has to be avoided. However given the raising demand for this type of innovative material, its price should decrease further.

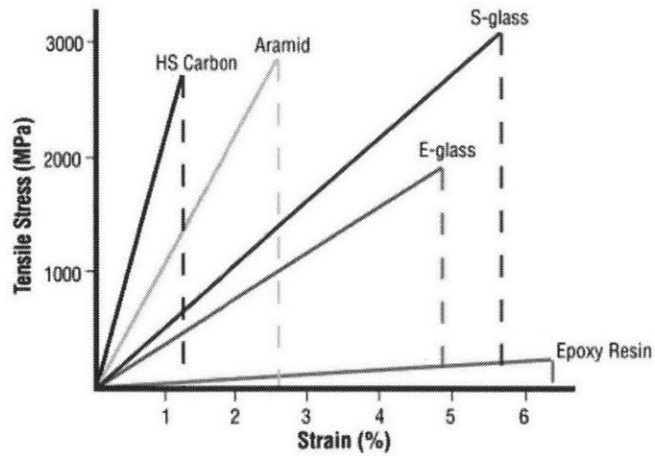


Figure 4 : Stress-strain curves for different types of fibers (Source : Gurit, Guide to composites)

2. Durability considerations

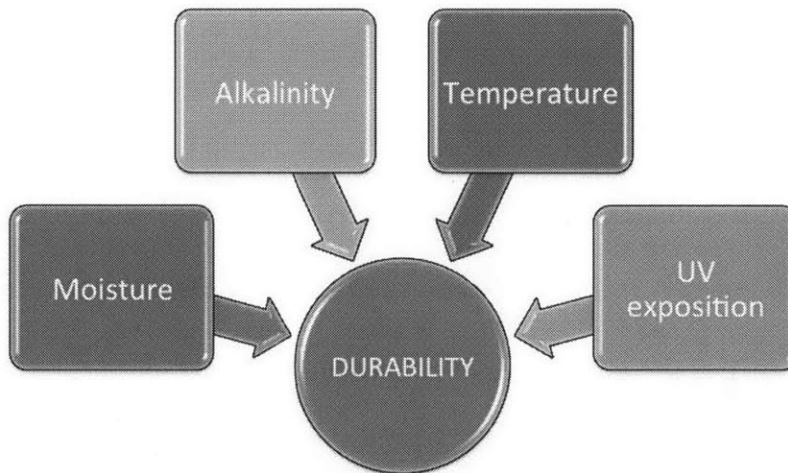


Figure 5 : Factors that have an impact on Fiber Reinforced Polymers durability

a) Moisture

First, important moisture is likely to cause a decrease in the strength of the matrix because of soft molecular bondings (Van der Waals). The moisture is more important for important stresses as moisture will develop in the microcracks. An appropriate choice in the matrix resin, for example vinylester matrix, can decrease the effect of moisture. It has also been shown that polyester resin has to be avoided in environment where moisture is important. For CFRP, the degradation has been linked to the rate of saline water in the environment.

Studies that involved wet-dry accelerated cycles have shown a decrease in the FRP plate performance that range between 20 to 30%. In this study the failure mode is usually due to debonding of the FRP plate from the concrete beam. This is caused by the deterioration of the interface between the FRP plate and the concrete which is one of the most oftenly faced mode of failure.

b) Alkalinity

Alkalinity consideration is particularly relevant when the FRP is used as a reinforcement bar in a concrete structural member. Another problem that has been shown is the loss of 20% of the tensile strength in alkaline environment such as concrete for E-Glass fibers. Indeed, concrete is very porous and its pH is usually more than 11. Therefore the sensibility to alkalinity of the material used as reinforcement must be carefully looked at. This sensibility is particularly important for fiberglass such as E-Glass where a deterioration of both matrix and fibers will substantially decrease the tensile strength of the reinforcement bars made of FRP. For moisture and alkalinity issues research studies show that the most efficient resin is vinylester. Again, polyester must be avoided. One of the simple solution to limit the effect of this problem is to apply a protective coating on the FRP material that will be moisture and alkali resistant. AR-Glass (Alkali Resistant fibers) are very insensitive to alkalinity but are more expensive than other glass fibers (2\$ per pound for E-Glass but around 20\$ per pound for AR-Glass).

c) Temperature

It has been shown that FRP lose their mechanical properties when exposed to high temperatures. The typical temperature of this deterioration is the glass transition temperature which range is between 60° and 120° celsius or between 140° and 248° fahrenheit. This is one of the reason, but not the only one to be taken into consideration. And it is one of the reason why FRP have not been as widely used for buildings as compared for bridges. Indeed, for buildings the security as regards fire is clearly more demanding. One of the main concern as regards fire in buildings using FRP is that the smoke resulting from the burning FRP is extremely toxic and dangerous for humans.

Besides for temperature above 500° celsius or 932° fahrenheit, the fiber reinforced polymers lose about 80% of their tensile strength.

However one of the solution to solve that issue is to use CFRP, indeed carbon fibers are almost insensitive to high temperature, until 1000° celsius or 1832° fahrenheit, which is, among other, one of the reasons it has been used in the aviation industry.

The American Concrete Institute (ACI) has finally published an interesting paper in 2006 that does not recommend the use of FRP for buildings where structural integrity has to be maintained in case of a fire.

d) Cold temperatures

As discussed afterwards in this thesis, one of the application of FRP laminates is the retrofitting of bridges that have been deteriorated by deicing salts in Northern America and Canada. Therefore one of the issue is the impact of low temperatures on FRP materials. The main problem is differential strains that may appear at the concrete-FRP bonding or even between the resin and the fibers. This differential strains may result in micro-cracking and loss of the tensile strength of the material.

One of the interesting features of glass fibers is that their coefficient of thermal expansion is the same as the one of concrete. Moreover some studies, which are however not extensive have shown an increase of tensile strength for temperature in the zone of -10° to -40° celsius or between 14° and -40° fahrenheit.

e) Loss of material properties due to UV exposition

It is well understood that UV damage polymers by "breaking chemical bonds" between chains (photodegradation) for particular wavelengths. However this phenomenon only appears on a thin surface layer of the polymer and glass or carbon fibers are not subject to this phenomenon. Again FRP can be protected by appropriate coating.

CONCLUSION :

The outstanding mechanical performances of fiber reinforced polymers have been shown in the first part of this thesis. Despite of their higher cost than typical civil engineering materials such as concrete or steel, their very interesting strength to weight ratio and resilience capacity against aggressive environments give to this material a great potential to be used in various structural upgrading that are describe in the next chapter.

II-FRP Applications : Performances Improvement and Limitations

1. Flexural and shear upgrading

Fiber reinforced polymers materials have been used for seismic strengthening of structures as well as for simple repair of bridges that have been damaged by attacks such as corrosion given that FRP are a non corrosive material. This kind of retrofitting remarkably enhances the life of the structure. It is estimated in the United States that about 30% of the highway bridges need maintenance as their performance as regards load capacity has decreased or because they have to sustain more important loads. It means that they are still in service and safe but they need careful monitoring and maintenance to monitor their performance. Their deterioration may be due to errors during the construction phase but also to attacks due to chemical components. This is particularly true in Northern areas where salt is heavily used on highways against snow. Sodium chlorides attack concrete decks and when the concrete is not treated against this component (such as XF concrete in the Eurocodes) reinforcement bars are likely to be altered, diminishing the performance of the bridge deck.

Also one of the main advantage of fiber reinforced polymers in addition to being a high performance material in term of strength is that they are corrosion resistant and therefore are not altered by salt or other chemical components. Retrofitting a bridge or a building using FRP is much less costly and much quicker than replacing the entire structure. Besides as composite materials are extremely light compared to other civil engineering materials it is much easier and therefore cheaper to put them in place even if the cost of the material is much higher.

For example let us consider the example of a beam that needs to be upgraded in order to be able to withstand more important loads than the one it was designed for. In that case the beam will fail due to increasing tension. One of the way to increase the tensile capacity of the beam is to increase the area of the steel reinforcement bars, which means adding reinforcement bars or external post-tensioning elements to the beam which is a complicated and extremely costly operation. It also requires the structure itself to be closed during the retrofitting. However when retrofitted with fiber reinforced plates the bridge or the building can be repaired while still being in service. This is one of the main

competitive advantage of composite materials as major infrastructure can not be closed for a long time.

There are also cases where steel reinforcements have been forgotten by the contractor and the building or bridge can be easily repaired using externally bonded FRP plates.

The usual way a bridge is repaired for flexural or shear improvements is by bonding to it FRP laminates using adhesive, typically epoxy. The failure of the bonding skin is something that has been extensively studied in the past years and particularly by the Infrastructure Science and Technology (IST) group at the Department of Civil and Environmental Engineering of the Massachusetts Institute of Technology (MIT).

The main goal of the bonding material is to transmit the efforts of the interface, shear and tension between the laminates and the bridge component.

The way the FRP laminates work is quite similar as reinforcement bars in a concrete beam. For flexural upgrading, a CFRP or GFRP plate is usually attached to the lower flange, the one that encounters tension which is usually the limiting factor for bending beams such as bridge decks.

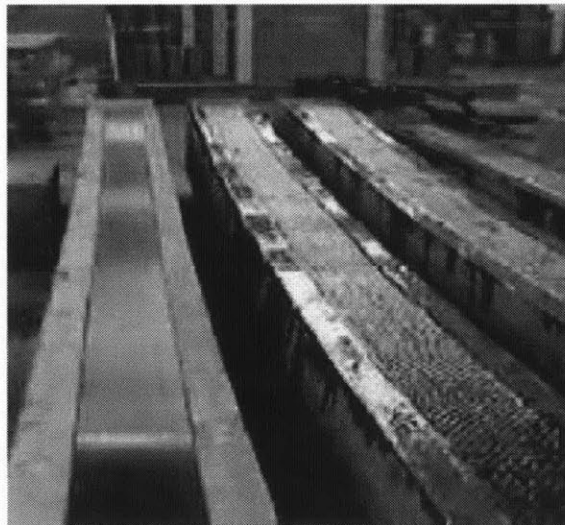


Figure 6 : Flexural strengthening of beams using Fiber Reinforced Polymers strips

The commonly used adhesive is epoxy and as cement its composition can be tailored to the needs using different types of additives such as tougheners, etc.

Usually a structural member is strengthened for flexural, shear or compressive capacity and for each case FRP plates are placed in different manners.

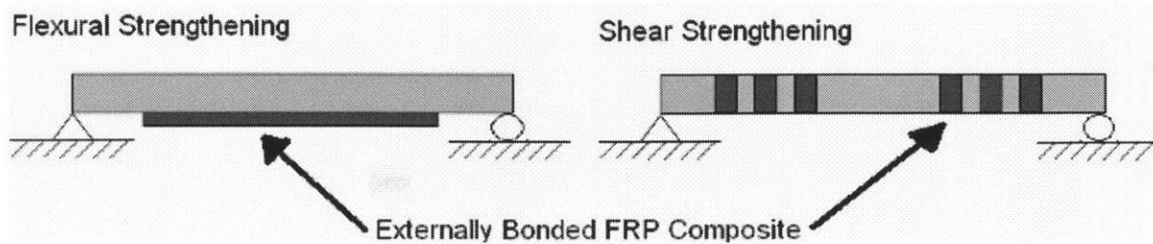


Figure 7 : Flexural and Shear strengthening of concrete beams by externally bonded FRP composites

As an application of beam upgrading using FRP a simple MATLAB program has been developed as can be seen at the end of this thesis. It outputs the moment capacity of the upgraded beam for a given fiber cross section of FRP added with as input the geometry of the original beam.

APPLICATIONS :

FLEXURAL STRENGTHENING : Oran M. Roberts Elementary School, Dallas, Texas

This application is a good example of a structural upgrading. An air system was added to the roof of the gymnasium of this high school and the original structure was not designed to withstand this amount of weight. With this in mind the flexural capacity of the beams was increased by wrapping fiber reinforced polymers to them. The main interest of FRP retrofitting in that case was that the activity of the gymnasium was not disturbed by the retrofitting and the project was completed in a very small amount of time.



Figure 8 : Beam flexural upgrading of Oran Roberts Elementary School (Source : QuakeWrap)

SHEAR STRENGTHENING : Challenger Middle School, Tucson, Arizona

This case also shows the interesting feature of FRP retrofitting as regards time consideration. Indeed this project was completed in a few days and this is the main reason the company was chosen for the completion of this project.



Figure 9 : Beam shear retrofitting of Challenger Middle School (Source : QuakeWrap)

As can be seen on the figure above, the retrofitting was made in the area of large shear stress where cracks had appeared (next to the supports).

2. Column retrofitting

Upgrading of old structures :

The first field of application of FRP for column retrofitting is the enhancement of the performances of old structures that have to sustain higher load requirements or that have faced corrosion of the reinforcements which decreases the performances of the column, etc. In that case FRP is used to increase the compressive strength of the column by confinement. For years, steel plates have been used for this application. However, FRP are much more easier to handle and to transport. Besides they can adapt easily to the particularity of the field. When compared with steel plates, FRP are also a non corrosive material.

Confining a concrete column allows to have higher compressive strength. On the figure below one can see that confined concrete has much better stress-strain behavior and this behavior is greater as the confinement pressure increases.

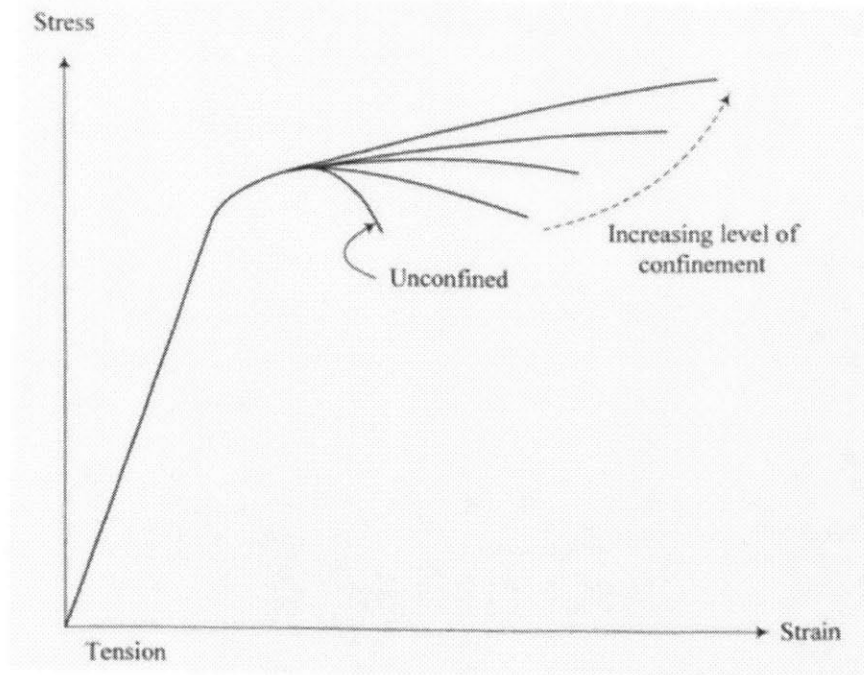


Figure 10 : Stress-strain curves for concrete under various levels of confinement (Source : Master Builders, Inc. and Structural Preservation Systems, 1998)

Actually the level of pressure of the FRP concrete confinement will induce an increase of the compressive strength of the column. The improved compressive strength has been defined by the ACI Committee as follows :

$$f'_{cc} = f'_c \left[2.25 \sqrt{1 + 7.9 \frac{f_{cp}}{f'_c}} - 2 \frac{f_{cp}}{f'_c} - 1.25 \right]$$

with : $-f'_c$ the compressive strength of the concrete without confinement

$-f_{cp} = \frac{E_f \varepsilon_{fe} \rho_f}{2} \cdot E_f$ being the young modulus of the fibers used, ε_{fe} the effective strain of the FRP at failure and ρ_f the confining reinforcement ratio.

From this new compressive strength the column axial capacity can be derived.

However when there is an eccentric loading the increase in the load capacity is not as important as for axial loading and must be looked at carefully. This feature is equivalent to the case of an eccentric loading for a reinforced concrete column, the eccentric loading adds a bending moment and therefore a possible tension in parts of the structural member.

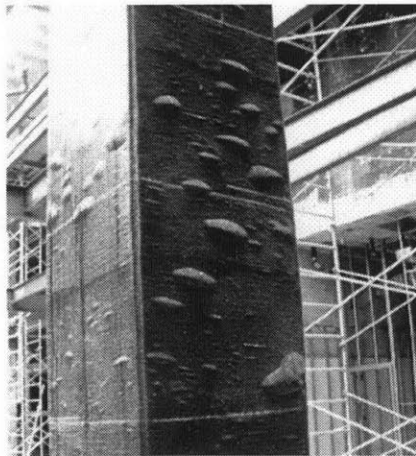


Figure 11 : Column retrofitted with FRP

COLUMN UPGRADING : Port Clinton Garage, Port Clinton, Ohio

In that case, a load was added on the roof of a garage but the structure was not designed for this load. Two conventional solutions were available : construct a new column or increase the diameter of the old ones. However in such an environment this procedure would have been time consuming and extremely costly. Therefore FRP retrofitting was chosen as the final solution. This FRP strengthening allows for higher compressive strength in the column.

Again this is an example of an upgrading of a structure that has to carry a greater load.

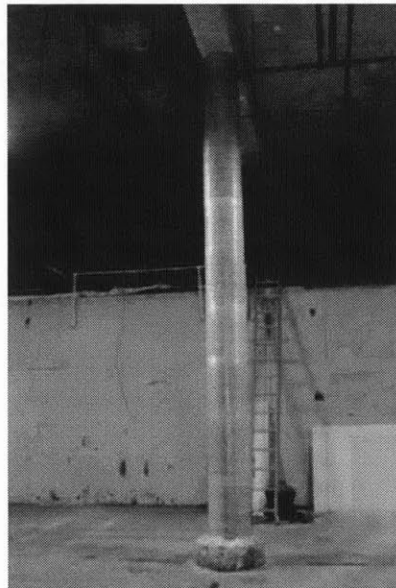


Figure 12 : Colum performance improvement. Port Clinton garage (Source : QuakeWrap)

REINFORCED CONCRETE COLUMN RETROFITTING : Plaza in Clayton, Saint Louis, Missouri



Figure 13 : Plaza in Clayton tower (Source : Clayco website)

This is an interesting case similar to the case when a structural member has not been designed properly or when the contractor has forgotten to put in place reinforcement before casting. Here, longitudinal reinforcements were forgotten in a new residential building that was just being occupied.

Again one can see the competitive advantage of fiber reinforced polymers. They can be applied after a building is completed, and there is a minimal disturbance during the retrofit.

3. Seismic Retrofitting

In the case of seismic retrofitting the failure mode will have to be studied for cycle loading effect. And a particular emphasis will have to be made on brittle failure so as to be able to ensure that the building is safe in case of an extreme earthquake event. The case of cyclic loading is studied in the following section. There are at least two different kinds of FRP applications that can be designated as seismic retrofitting. The first case is when a structure has been damaged by an earthquake and has to be repaired. As said before, FRP retrofitting is a fast and economical solution.

The second application is the improvement of the performances of a structure for earthquakes that may appear in the future.

In areas where earthquakes are a probable risk, one of the weaknesses of structures are the columns. The lateral movement due to earthquakes creates an important shear stress in the columns. This causes spalling of the concrete structure. The shear failure will be particularly important at the tip of the column where plastic hinges develop. To avoid failure, lateral reinforcement are supplemented to face this lateral loading. The main structural challenge is that high performance concrete could be used to increase the strength. However in seismic areas the ability of the material to deform is critical. This kind of concrete is very brittle and fails. Therefore the main interest of columns wrapping by FRP material is a gain in the ultimate compressive of the columns and an increase of their ductility which is capital for a safe earthquake response of the structure. This is one of the advantage of the application of FRP.



Figure 14 : Failure of several columns, Foothills Freeway overpass. Spalling due to an earthquake

One of the study shows interesting results as regards the behavior of repaired columns. The resistance of the columns is monitored after being damaged by simulated earthquakes loadings and repaired with different layers of fiber reinforced panels. The study shows that the resistance of the column damaged and then repaired is greater than the one of

the original undamaged column even though the damage of the column was as impressive as the one shown on the figure above.

The columns face a dramatic gain in ductility which allows for more important loading before failure of the members.

However when this type of retrofitting is not enough, one of the very efficient solution is to jacket the colums with fiber reinforced polymers panels. With this reinforcement the confined concrete structure has enhanced structural properties that enable it to withstand much higher lateral loadings due to earthquakes. Besides the use of FRP enhances the ductility of the structure which is particularly important. The structure is then able to deform and prevent from danger the users of the building.

The other application of FRP for earthquake column retrofitting or for the improvement of the performance of the column is plastic hinge confinement. Flexural plastic hinges develop in location of maximum bending moment.

This zone must be able to allow for large rotation. One of the solution is to confine this areas by jacketing the column with FRP material (usually close to the foundations). As composites behave elastically at high strain they are particularly efficient for reversible loading such as earthquake and are able to absorb an important quantity of energy.

Various methods of design have been developed to design the thickness of the jacket. Therefore FRP show great promises in the field of earthquake retrofitting.

SEISMIC RETROFITTING : Arroyo Quemado Arch Bridge, Santa Barbara County



Figure 15 : Arroyo Quemado Arch Bridge

This bridge was built in 1916 and in its original design had only $1/10$ th of the strength required to meet the design earthquake requirements. The new design by Buckland and Taylor Ltd in 1997 encompassed several solutions among which confinement of sprandles and columns by fiber reinforced polymers to allow for a greater ductility as well as displacement. The retrofitting came "17% under budget".

4. Blast retrofitting

Many different solutions to protect buildings from blast have been developed, and this focus has grown with the terrorist attacks that happened in the year 2000's. The most common one is to provide space between public space and the building, however in urban environments this is not achievable. Therefore the focus has turned on materials that have the ability to absorb a large amount of energy by deforming and that will not cause fragmentation of the structure. In this situation researchers have explored the application of fiber reinforced polymers for buildings that have to perform effectively in case of a blast such as embassies, government buildings or infrastructures at risk such as nuclear power plants, dams, etc. Research has been conducted for beams, columns as well as for slabs and walls. In every case a substantial decrease in the deflection of the structural member has been noticed when retrofitted with FRP materials. The choice of the fibers has also been explored and particularly the use of aramid fibers (Kevlar) that have an important resistance to impacts. However studies show that the high stiffness of carbon fibers may be more interesting as it decreases the expansion of concrete and strengthens its structural capacity to resist blast loads.

A limitation that has also been shown and which is cited in the paper of Buchan & Chen is that an increase in the number of FRP layers does not increase the performance linearly due to a decrease of the stress transmitted at the interface of these layers.

A blast load is in this case compared to an impulse forcing function that the retrofitted wall has to sustain. Research also emphasizes the interest of FRP in case of an explosion inside a building. Indeed in slabs or other structural members of a building, reinforcement bars are located so that to be able to withstand gravity loads, and are therefore located on

the lower side of beams, slabs, etc. However when a blast occurs the blow due to the blast may "invert" gravity loads.

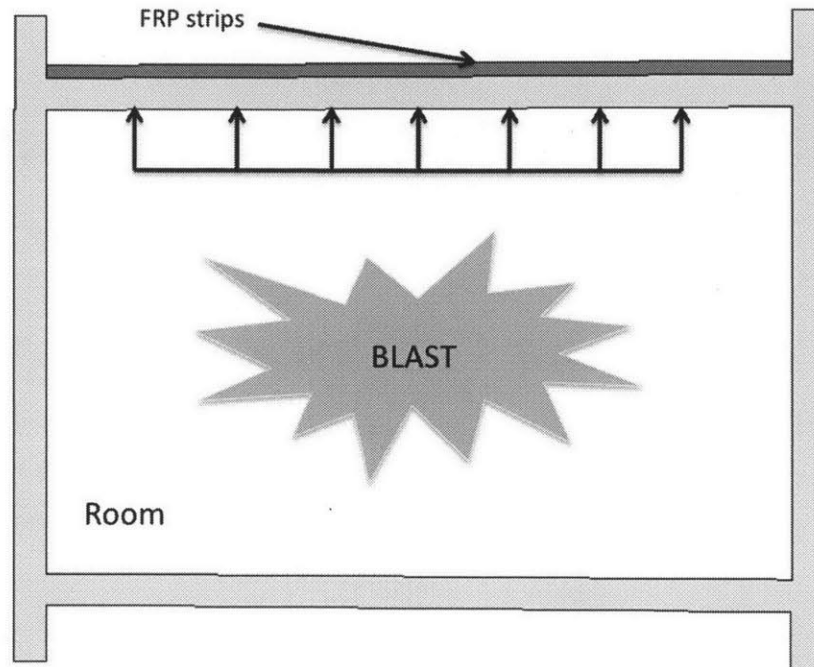


Figure 16 : Blast and inverted loading case. Possible FRP retrofitting

Structural members will therefore be massively damaged as they are not designed to carry this kind of "reversed" loading. Therefore these members can be secured by adding FRP layers at the upper face, where the failure of the beam is likely to occur in case of a blast inside the building. This design will allow safety for the persons that are inside the building as the structure prevents from collapse. Also it permits to avoid high speed projectiles due to the blast. FRP reinforcement also allow to avoid spalling of the concrete surface. However the pression inside the closed room is a variable that has to be accounted for as it is a factor of danger for humans.

Studies have also shown that as it is very common with FRP use, the main cause of failure is the debonding of the FRP plate, but when it was due to static loading in the cases studied before, in the case of a blast the debonding is due to dynamic loading which has not been thoroughly studied yet.

Blast reinforcement is only at the beginning of its development but already shows remarkable promises.

5. FRP reinforcement bars

Another application of FRP materials in the area of civil engineering is to use FRP reinforcement bars instead of the conventional steel reinforcement bars. One of the main advantage of FRP rebars is that they are not affected by corrosion and have much higher tensile strength than steel. Therefore their use is particularly relevant in marine or submerged infrastructure where salinity may cause fast deterioration of the structure reinforced by steel rebars. In 2006 the ACI has published an extensive code about FRP rebars.

	Steel	GFRP	CFRP	AFRP
Nominal yield stress, ksi (MPa)	40 to 75 (276 to 517)	N/A	N/A	N/A
Tensile strength, ksi (MPa)	70 to 100 (483 to 690)	70 to 230 (483 to 1600)	87 to 535 (600 to 3690)	250 to 368 (1720 to 2540)

Table 3 : Tensile strength of FRP fibers (Source : ACI 440)

The use of FRP also finds applications and emerging markets for new construction in Northern America and Canada where salt is massively used against ice, and deteriorates structures such as bridges or garages. Previous studies have shown that the cost of repairing these structures is more than 5 billion dollars. Therefore the use of FRP rebars, even if it implies an higher upfront cost (the price of FRP rebars is about two times and a half (2.5) higher than the one of steel reinforcement bars), allows for a sustainable development of new structures that will be able to last longer without the need of being repaired.

When FRP rebars are used the most common type of failure is crushing of the concrete on the compressive fiber as, given the high tensile strength of FRP, the fiber reinforced polymers are not working at their full capacity.

Therefore the failure due to tension is not the limiting factor.

Besides, whereas FRP are not widely subject to corrosion, the fibers and the matrix may be damaged by moisture. And as FRP have only be used on a small scale during the last twenty five (25) years thoroughfull datas about their durability in harsh environment is

not yet available. Therefore their use on the long term still has to be answered by different researches.

6. Limitations

Another issue stated in this thesis is the brittle behavior of FRP reinforced structures. The problem with brittle failure is that the failure once started is violent and unpredictable. If brittle failure appears when the structural member is being used it can be extremely dangerous for the person using the structure. In concrete, larger cracks show that failure may be occurring, however when FRP are used there are no heralding signs that it will fail which make the failure of this material unpredictable.

a) Bond Failure

This mode of failure must be carefully monitored as it is the most common mode of failure of reinforced concrete beams strengthened with FRP laminates.

A comparison between the action of reinforcement bars and the one of FRP plate in the tension area of beams has already been made, and it is understood that the effect on the overall structure is quite the same. The same comparison could be made about on one side the bonding between these steel rebars and the concrete and the one between the FRP laminate and the concrete beam.

For reinforcement bars the bonding is assumed to be perfect and therefore the strain in both material is compatible. In that case the stress is fully transferred from the concrete to the steel bars. In the case the adhesion was not perfect the concrete beam would be ruined at the failure point of the concrete, f_{ctm} and not at the one of the reinforced beam. Therefore the bonding of the FRP plate to the concrete and more particularly the transfer of stress from one material to the other is something that has to be carefully looked at. In simple terms it is about knowing how much the material slips.

The higher the concrete compressive strength, the better the adhesion for all other properties held constant.

For the adhesion between concrete and steel reinforcement bars formulae have been developed to ensure a perfect adhesion, the anchorage overlapping length defined as :

$$l_{b,rqd} = \left(\frac{\varphi}{4}\right) \left(\frac{f_{sd}}{f_{bd}}\right)$$

Different studies have been made to define some equivalent definitions for FRP plates added to reinforced concrete beams such as the one of Nguyen et al. (2001) :

$$l_{dev} = c_c + \frac{d_p}{2} + \frac{4.61}{\lambda}$$

$$\lambda^2 = \frac{1}{E_p t_p} \frac{G_a G_c}{G_c t_a + G_a c_c}$$

This means that if the FRP laminate is applied with respect to this formulae composite behaviour will be observed. If not the composite beam will lose its properties and fail for substantially smallest loading (close to the one of concrete). On the chart below one can see the impact on the bonding failure some changes in the properties have :

Property change	Effect on the bonding
Plate thickness	No effect or negative
Bolt for external anchorage	Good but brittle behavior
Laminate orientation	Brittle behavior may be avoided if fiber orientations is combined smartly
Plate stiffness decrease	Good
Reinforcement ratio	If important, failure may occur by crushing of compression zone

Table 2 : Impact on bonding failure as a function of property changes

Bond strength of FRP-Concrete connection :

As failure often occurs at the bond between the FRP plate and the concrete, the bonding must be looked at. The quality of the bonding relies more on the preparation and the way it is put into place than on the material itself. The concrete surface must be cleaned before

the application of the FRP plate to get rid of "loose particles" and cracks or spalling must be refilled with concrete, grout or other materials. This is the only guarantee of a good bonding with the FRP layer. It is commonly done via sandblasting, etc.

Also, to allow an appropriate bonding, an interface layer of matrix has to be applied between the FRP plate and the retrofitted concrete beam.

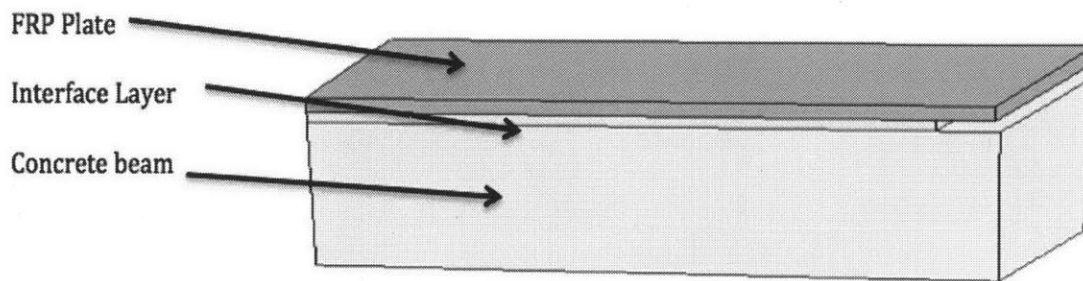


Figure 17 : Concrete beam, interface layer and FRP plate

Studies have shown that the reduction coefficient (safety coefficient) is much smaller when a very thin layer of FRP is applied. It allows for a smaller stress within the bond layer where failure may occur and therefore for a more efficient use of the composite material.

They are different modes of debonding failure : the most common is due to cracking of the concrete and to a loss in the ability to withstand tension and transmit it to the FRP plate. This mode has to be carefully monitored as the rupture is brittle. Another one is due to the failure of the steel reinforcements at yield stress. In every case the failure happens in areas of high stress, this is to say at the interface between concrete and steel reinforcements and/or between concrete and fiber reinforced laminates.

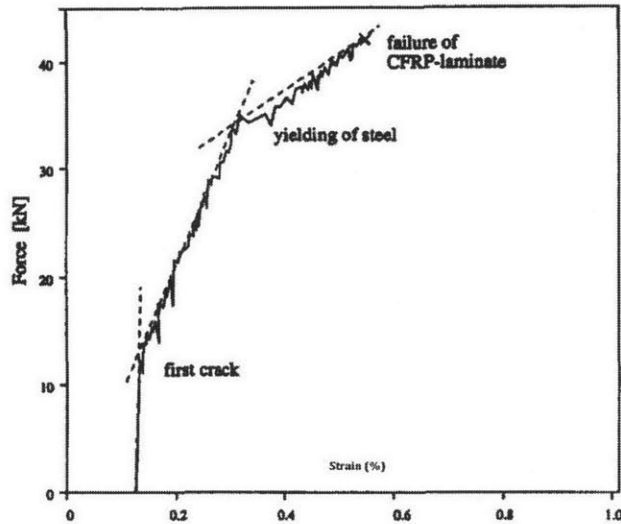


Figure 18 : Forces versus strain in CFRP composite applied to concrete beams (Source : Meier and Kaiser 1991)

On the following figure, one can see some of the different modes of debonding of the FRP plate :

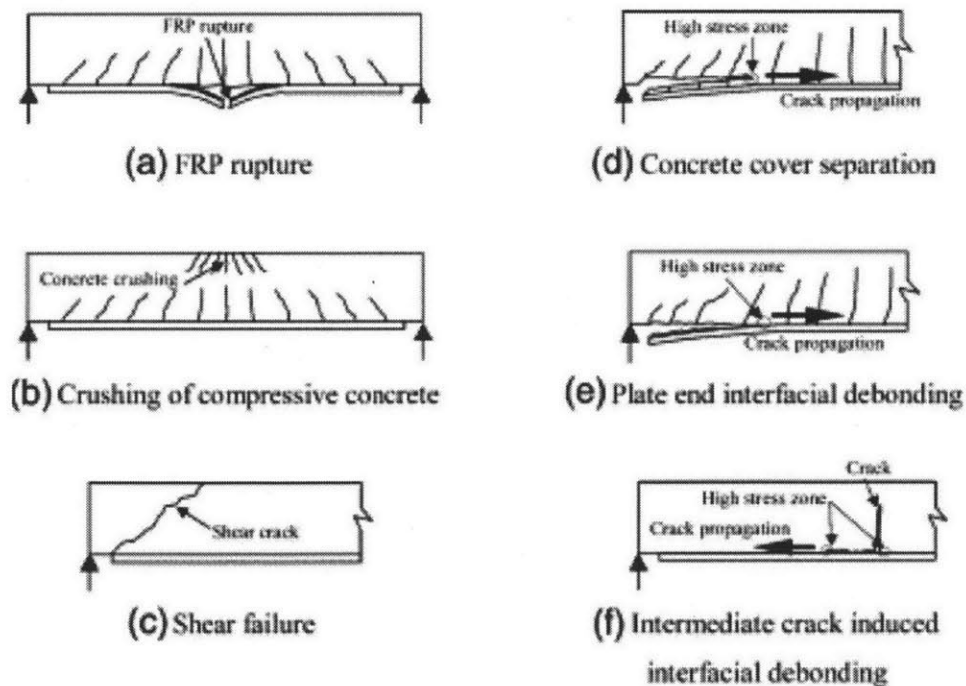


Figure 19 : Failures Modes of FRP Strengthened RC beams (Source : "FRP strengthened RC beams. I : review of debonding strength models" S.T. Smith, J.G. Teng)

As can be seen on this figure the first three modes of failure are modes that are common to non-reinforced concrete beams. Unlike the FRP rupture in figure (a) that appears at the failure of the FRP material, the failure modes represented in figure (d), (e) and (f) are known as "premature bond failure" as they occur before the yield of the concrete or of the FRP material. The failure (d) and (e) that occurs at the end of the plate are the ones that happen the more often. What generally happens is that this discontinuous area of the beam is a zone of extreme shear. Cracks develop from the material interface to the concrete and as the crack reach the reinforcement bars they then develop horizontally. Then when the load is increased (or for less important but long and continuous loading) the concrete fails and is detached from the beam as can be seen on the figure below.

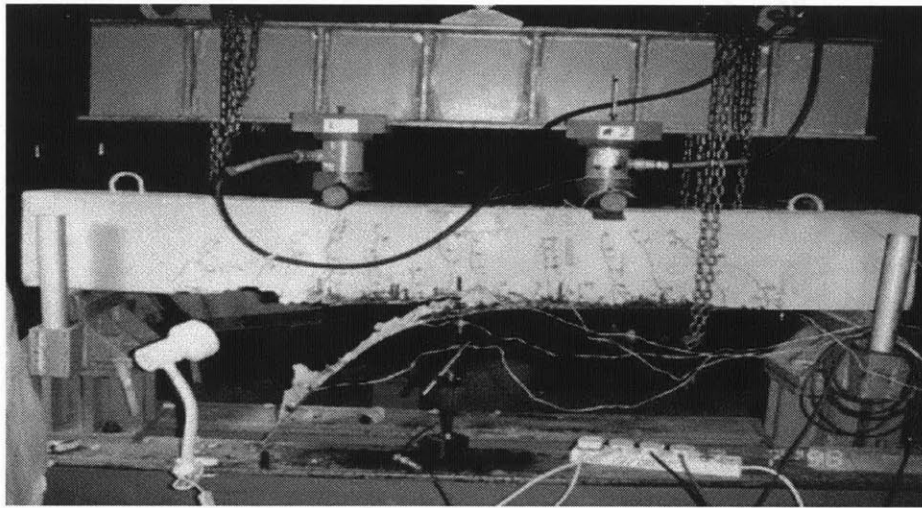


Figure 20 : Concrete cover separation (Source : FRP strengthened RC-beams II : assessment of debonding models)

The main mode of failure of reinforced concrete beams strengthened by fiber reinforced polymers is the ruin of concrete right above the surface where the FRP was added. This is a limiting factor as the debonding of the system happens before the failure of the FRP laminate itself. And this failure is brittle. Therefore this mode of failure must be carefully monitored. However it must be noted that this type of failure only appears for beam retrofitting and not when columns are retrofitted.

One of the main concern that must be taken care of in the failure mechanism is that the extreme fiber of the concrete beam that is facing strong tension will crack under the load.

This will enhance the failure of the bonding of the FRP/concrete joint. Besides one of the concern of many studies (IST-MIT) is the effect of moisture at the bonding.

This mode of failure is one of the many examples where the failure actually happens in the concrete adjacent to the FRP plate and not at the bonding itself. What happens is that the important stress carried by the FRP plate is not able to be carried by the concrete next to it, which has much smaller stress resistance capacity than the FRP layer.

One of the main conclusion of many different studies to avoid this type of failure is that the FRP plate must be as long as possible which means bringing it as close as possible to the support. This will increase the load capacity of the beam and at the same time its ductility.

In some cases, increasing the plate thickness has no effect and does not prevent the beam from failing as the failure will occur at the end of the FRP laminate.

b) Other modes of failure

Many different other modes of failures have been shown by research studies. As seen on the figure shown before, one of the mode is the failure of the FRP plate at yield stress of the steel. It can also be due to failure of the compressed fiber of concrete or shear failure in the beam. One of the problem that has to be taken care of upfront is the increase of the shear capacity of the beam. Indeed the beam will fail in shear around its typical shear capacity even if a FRP plate is added (only in case the FRP plate is added on the tensile face of the concrete beam). Therefore when upgrading a bridge for larger loads, one must verify that the new shear encountered by the beam is still within its limits.

The contribution of the FRP plate to the shear plate as stated in the Eurocodes as been defined as :

$$V_f = \rho_f E_f \varepsilon_{fe} b_w 0.9d (1 + \cot \beta) \sin \beta$$

With :

- ρ_f the ratio of FRP
- E_f the FRP young modulus
- b_w the width of the FRP plate
- ε_{fe} the strain relation defined as below
- β the angle between the fibers of the FRP and the orientation of the beam

$$\varepsilon_{fe} = 0.0119 - 0.0205(\rho_f E_f) + 0.0104(\rho_f E_f)^2 \text{ for } 0 \leq \rho_f E_f \leq 1 \text{ GPa}$$

$$\varepsilon_{fe} = 0.00245 - 0.00065(\rho_f E_f) \text{ for } \rho_f E_f > 1 \text{ GPa}$$

Solutions have been developed to increase substantially the shear capacity of beams such as adding FRP plates on the sides of the beam or wrapping the beam with FRP.

CONCLUSION :

The first chapter highlighted the mechanical performances of fiber reinforced polymers. This second chapter described how to use these properties to set the FRP as a competitive material in the field of civil engineering retrofitting. Whether it is applied for flexural or shear upgrading or as a way to meet the standards of seismic codes, FRP allow for quick and low cost of application.

This chapter has also shown the different modes of failure of FRP's and particularly bond failure which can be worsened by effect such as moisture or inadequate preparation of the existing structure.

These limitations have been taken into account in the different standards that have been written. These standards and particularly their differences as regards shear strengthening is the topic studied in the last part of this thesis.

III-Comparison of the Standards for shear strengthening

1. Standards for shear capacity

Since the use of FRP laminates on reinforced concrete structures has increased during the last 20 years, countries such as Japan that has been using this material for the retrofitting of its structures facing earthquakes loadings have developed codes and standards of calculation to allow a more intensive and safer use of this material. In Europe, the Eurocodes that are related to the use of FRP are still being written.

When strengthening a structure in the goal of increasing its shear capacity, they are different ways of placing the FRP laminates. One of the variables are the angle of the strips and their angle, another is the spacing of the strips that can also be discontinuous.

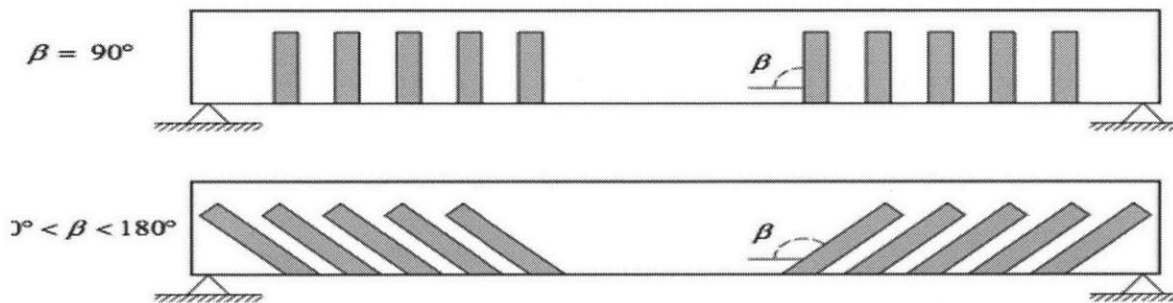


Figure 21 : Shear strengthening and FRP strips angles

Also one must consider how the structural member is wrapped. The beam can be completely wrapped or wrapped only on the sides as shown on the following figure.

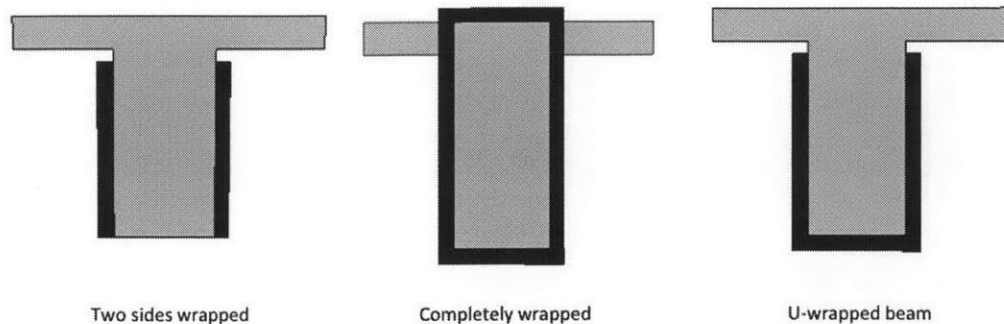


Figure 22 : Wrapping of concrete beam with FRP

All of these properties will have to be taken into account when calculating the contribution of the FRP plates to the shear capacity with the different standards. In most cases the assumption was made that cracks will spread at an angle of 45° and that the FRP strips are verticals. In order to gain practical application experience, three standards were chosen for comparison. Shear retrofitting standards were chosen as there is less available data than for flexural retrofitting.

CSA S806-02 (Canadian Standards Association) :

$$V = V_c + V_s + V_f$$

- With :
- V_c, shear strength of concrete
 - V_s, shear strength of steel reinforcement
 - V_f, shear strength of the FRP plate

$$V_f = \frac{A_f E_f \varepsilon_{fe} d_f}{s_f}$$

- With :
- A_f the area of the FRP plate
 - E_f the young Modulus of the FRP used
 - ε_{fe} the contribution to the deformation that is equal to
- $$\varepsilon_{fe} = 4000 \times \mu \times \varepsilon \text{ if the FRP plate has a U - Shape}$$

- ε_{fe} = 2000 × μ × ε if the FRP plate is bounded only on the side of the beam
- d_f distance of the composite top edge to the steel reinforcement bars location
- s_f is the spacing of the FRP reinforcement strips

The CSA S6-06 :

This standard is a general form of the standard described before where the diagonal cracks appear with an angle θ instead of 45°. However it also takes into account

reduction factors that account for the variable adhesion, which implies that failure could be due to delamination of the FRP plates. In that case ε_{fe} is defined as :

$$\begin{aligned}\varepsilon_{fe} &= k_{\theta} \varepsilon_{fu} \\ k_1 &= \left(\frac{f'_c}{27} \right)^{2/3} \\ k_2 &= \left(\frac{d_f - L_e}{d_f} \right) \\ L_e &= \frac{23300}{(n t_f E_f)^{0.58}}\end{aligned}$$

ACI-440 08 (American Concrete Institute) :

As said before the American Concrete Institute has produced extensive standards in the application of FRP material that enables engineers to apply simple calculation rules for the design of structures using FRP.

In the case of shear contribution of FRP, the ACI uses the same method but input a security coefficient ψ_f so that the contribution of each material is given by the following equation :

$$V = V_c + V_s + \psi_f V_f$$

FIB TG9.3 (International Concrete Federation) :

This standard is based on the guidelines of the Eurocode 2.

In that case the contribution of the FRP plate is given by the equation :

$$V_f = 0.9 \varepsilon_{fk,e} E_f \rho_f b_w d (1 + \cot \alpha) \sin \alpha$$

To simplify the comparison of the norms the shear reinforcement bars are supposed to be vertical which implies that : $\alpha = 90^\circ$ and therefore this assumption simplifies the FRP contribution to :

$$V_f = 0.9\varepsilon_{fk,e}E_f\rho_f b_w d$$

With : $-\varepsilon_{fk,e} = 0.8\varepsilon_{fe} \leq \varepsilon_{max} \approx 0.006$

$$-\varepsilon_{fe} = \text{Min} \left[10^{-3} 0.65 \left(\frac{f_c'^2}{E_f \times \rho_f} \right)^{0.56}; 0.17 \left(\frac{f_c'^2}{E_f \times \rho_f} \right)^{0.30} \varepsilon_{fu} \right] \text{ depending if the FRP is}$$

bonded as a U-shape on the beam or just on the side of it

$$-\varepsilon_{fe} = 0.48 \left(\frac{f_c'^2}{E_f \times \rho_f} \right)^{0.30} \varepsilon_{fu} \text{ if completely wrapped member}$$

TR55-04 (UK Concrete Society) :

$$V_f = \varepsilon_{fd} E_f A_{fs} \frac{\left(d_t + \left(\frac{n}{3} \right) l_{t,max} \right)}{s_f} (\sin \alpha_f + \cos \alpha_f)$$

$$\text{With : } -\varepsilon_{fd} = \text{Min} \left[\frac{\varepsilon_{fd,u}}{2}; 0.64 \sqrt{\frac{f_{ctm}}{E_{fd} \times t_f}}; 0.004 \right]$$

-n=1 for a U-Shape FRP plate

-n=0 for a completely wrapped structural member

$$-s_f = \text{Min} \left[0.8d_f; d_f - \frac{n}{3} l_{t,max}; b_f + \frac{d_f}{4} \right]$$

$$-l_{t,max} = 0.7 \sqrt{\frac{E_f t_f}{f_{ctm}}}$$

CNR DT200-04 :

The Italian "Advisory Committee on Technical Recommendations for Construction" has produced in 2004 an extensive research and guidelines for the calculation of structures strengthening using FRP and in particular one standard about the calculation of the FRP shear capacity contribution.

Again to simplify the comparison of the standards it is assumed that cracks will appear at an angle of 45° and that the FRP is placed vertically which implies $\beta = 90^\circ$.

In the case of a rectangular cross section with FRP only on the side of the beam, this guideline recommends an FRP shear contribution equal to :

$$V_{Rd,f} = \frac{1}{\gamma_{Rd}} \text{Min}(0.9d, h_w) f_{fed} 2t_f \frac{\sin \beta w_f}{\sin \theta p_f}$$

With : $\gamma_{Rd} = 1.2$

-d the member depth

- h_w the stem depth

$$f_{fed} = f_{fdd} \frac{z_{rid,eq}}{\text{Min}(0.9d, h_w)} \left(1 - 0.6 \sqrt{\frac{l_{eq}}{z_{rid,eq}}} \right)^2$$

$$f_{fdd} = \frac{1}{\gamma_{f,d} \sqrt{\gamma_c}} \sqrt{\frac{2E_f G_{Fk}}{t_f}}$$

$$\gamma_{f,d} = 1.2$$

- γ_c is the partial factor for concrete

$$G_{Fk} = 0.03 k_b \sqrt{f_{ck} f_{ctm}}$$

$$k_b = \sqrt{\frac{2 - \frac{b_f}{b}}{1 + \frac{b_f}{400}}} \text{ and the length is mm, b stands for width}$$

$$z_{rid,eq} = z_{rid} + l_{eq}$$

$$z_{rid} = \text{min}(0.9d, h_w) - l_e \sin \beta$$

$$l_e = \frac{s_f}{f_{fdd} / E_f} \sin \beta$$

In the case of U-wrapped or completely wrapped sections, the FRP contribution is computed using the equation :

$$V_{Rd,f} = \frac{1}{\gamma_{Rd}} 0.9d f_{fed} 2t_f (\cot \beta + \cot \theta) \frac{w_f}{p_f}$$

And here :

$$f_{fed} = f_{fdd} \left[1 - \frac{1}{3} \frac{l_e \sin \beta}{\text{min}(0.9d, h_w)} \right] \text{ for U-wrapped members.}$$

2. Comparison of the different standards :

When standards or guidelines are established they always take into account large security coefficients, increasing the amount of material used and therefore increasing the price of the structure itself. Therefore when there is a lack of information about guidelines, firms could compare the different standards to understand which one is likely to be the most efficient (the one that minimise the amount of material used). It is in this perspective that the different guidelines for FRP shear reinforcement were compared. The standards that were chosen to be compared are the Canadian norm : CSA S806-02, the one established by the American Concrete Institute : ACI-440 08 and the standard TR 55-04 designed by the United Kingdom Concrete Institute which is partly similar to the calculation rules of the Eurocode.

For the purpose of this case study a rectangular reinforced concrete beam that has the following dimensions was considered.

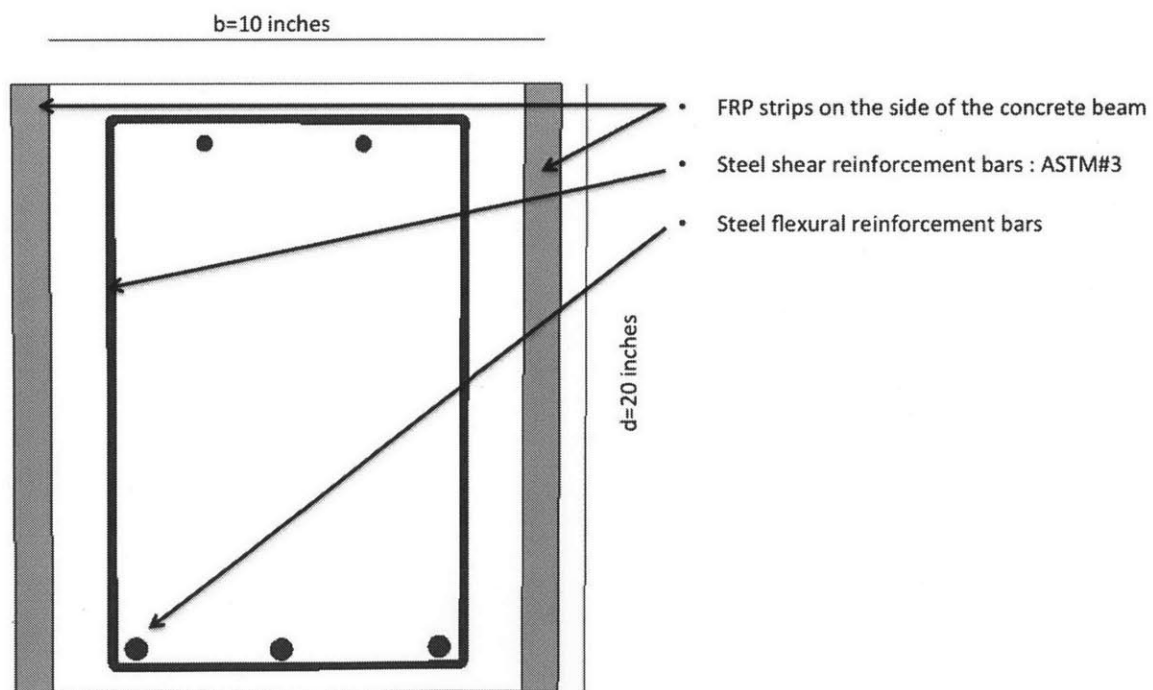


Figure 23 : Details of the concrete beam taken as example and wrapping of the FRP strips

One of the assumption is that steel shear reinforcement bars are in this section ASTM #3 at 15" spacing.

Also it is considered for each calculation that the concrete compressive strength is $f'_c = 4000$ psi and that the yield strength of the rebars is $f_y = 63\ 091$ psi. In order to be able to compute the shear contribution of the concrete itself using the FIB TG9.3 that is based on the calculation of the Eurocodes the assumption is made that the rate of longitudinal reinforcement bars is 2%, which is reasonable.

The critical shear at distance d from the support is supposed to be equal to $V_u = 60\ 000$ lb.

To be able to carry that important shear force, which can be due for example to an increased load that a bridge could have to carry, the choice is made to apply the FRP only on the side of this beam. This FRP is assumed to have a young modulus $E_f = 33 \cdot 10^6$ psi and a fracture strain $\epsilon_{fu} = 0.0167$. The fiber thickness is taken equal to $t_f = 0.015$ inch per layer and in every calculation only one layer of FRP material is used.

In that case, these assumptions imply that for the value of $\left(\frac{A_f}{s}\right)$ the design criteria is the spacing of the FRP strips. This is the same method as the one used in the Eurocode when the vertical steel reinforcement is computed.

In the table below the different properties of the material used are summarized :

Geometrical properties								
	Inch-Psi	Metrics		Inch-Psi	Metrics		Inch-Psi	Metrics
bw	10	0,25	f_y	63091	435	E_f	3,30E+07	2,28E+05
d	20	0,51	A_v	0,2	1,29E-04	nf	1	1
f'_c	4000	27,58	V	35000	1,56E+05	t_f	1,50E-02	3,81E-04
ssteel	15	3,81E-01	ϵ_{fu}	1,67E-02	1,67E-02	df	20	5,08E-01

Table 3 : Geometrical and Mechanical properties of the beam taken as example

The first calculation is derived from the Canadian Standard for which the value of $\left(\frac{A_f}{s}\right)$ is equal to 0.310% as can be seen on the figure below.

CSA S806-02		
Vc	2108,19	9377,67
Vs	16824,37	74838,54
FRP reinforcement is needed		
Vfneeded	41067,44	
ϵ_{fe}	0,0150	
(A_f/S_f)	0,310%	

Table 4 : Calculation using the CSA Standard

If the FRP strips used were chosen to have a width equal to 4" we would need a spacing equal to 38,65"

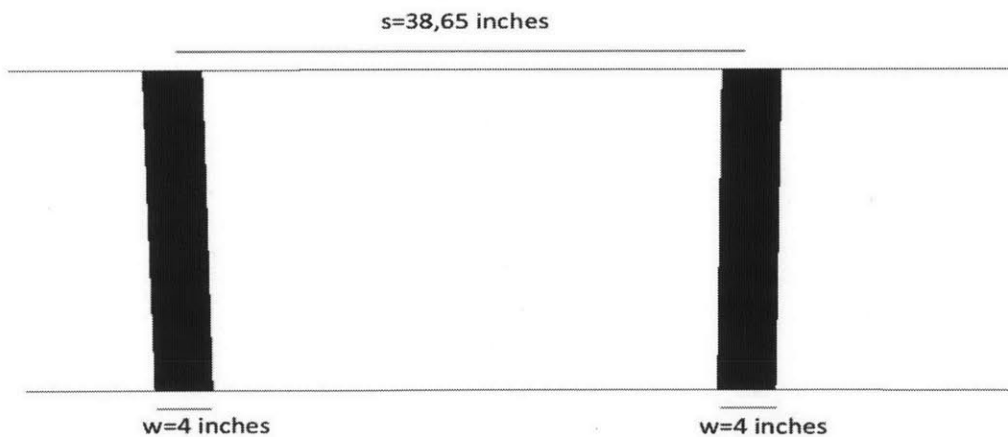


Figure 23 : Details of the strips spacing and width

When the ratio $\left(\frac{A_f}{s}\right)$ is calculated using the American Concrete Institute code it is then equal to 0,497% which is substantially greater than the calculation using the Canadian

Standard. This is mainly due to the fact that the ACI-440 08 uses a larger coefficient due to the uncertainty of the quality of the adhesion of the FRP strips to the concrete which is directly related to the bond failure described in the second part of this thesis. Its computation can be seen on the chart below :

ACI-440 08					
Vc	2108,19				
Vs	16824,37				
FRP reinforcement is needed					
Vfneeded	41067,44	Le	11,60	k'	0,69
		k1	28,00		
		k2	0,42		
kv	0,69				
εfe	0,0125				
ffe	413325,00				
(Af/sf)	0,497%				

Table 5 : Calculation using the ACI 440 Standard

In that case, using the same FRP strips of 4" width, the spacing between the FRP strips becomes 24.15".

When the British standard is used, the value derived for the ratio $\left(\frac{A_f}{s}\right)$ is between this two values and equal to 0.33% as can be seen on the following table :

TR55-04		
	Metrics	Inch-Psi
Vc	1,66	0,37
Vs	/	16824,37
fctm	2,74	397,18
Vf	192054,73	43175,25
ϵ_{fd}	0,015	0,015
lt,max	3,94	24,71
(Af/Sf)	/	0,33%

Table 6 : Calculation using the TR55 Standard

From these different standards, it appears that the issue that has the most important effect in the computation of the area of FRP needed to carry shear force in the beam is how the strain is computed. As shown, the fact that the strain has to be limited such as defined by the American Concrete Institute standard increases significantly the area of FRP needed. This decrease of the FRP strain is due to the risk of debonding of the FRP and to the unperfect and not yet thoroughly defined adhesion of the FRP material to the concrete beam.

Also in order to facilitate the calculation of the FRP thickness in the case of flexural retrofitting, a Matlab code was developed. Depending on the geometry and the material properties the program outputs the moment capacity of the FRP retrofitted beam.

This code has been developed using the book FRP Composites for Reinforced and Prestressed Concrete Structures (p. 120) and takes into account the different standards developed by the American Concrete Institute.

As this programs outputs the composite moment capacity of a reinforced concrete beam from the input of the material properties, the way to use it is to increase the moment

capacity of the beam by increasing the fiber area up to the target value of the bending moment capacity.

In order to provide an example, the beam considered has the same geometrical properties than the one considered for the comparison of the shear reinforcement. The target for the moment capacity is $M=200\ 000\text{lbs/inch}$ and $d=18"$. A concrete young modulus of $4\ 351\ 131\ \text{psi}$ is assumed. The fiber are chosen to be carbon fibers with a young modulus equal to $76\ 144\ 792\ \text{psi}$.

Geometrical properties								
	Inch-Psi	Metrics		Inch-Psi	Metrics		Inch-Psi	Metrics
bw	10	0,25	fy	63091	435	Ef	76144792	525GPa
h	20	0,51	Av	0,2	1,29E-04	nf	1	1
f'c	4050	27,58	Ec	4351131	30GPa	tf	1,50E-02	3,81E-04
ssteel	15	3,81E-01	ϵ_{fu}	1,67E-02	1,67E-02	d	18	5,08E-01

Table 7 : Geometrical and Mechanical properties used for the Matlab example

By doing a few iteration, using this program it is shown that by adding one layer of 2inch fiber reinforced polymers the moment capacity is $197\ 000\ \text{lbs/inch}$. This program can be used for any kind of beams when it needs to be retrofitted up to a certain value for the moment capacity. It is the equivalent of the light programs used to calculate the area of reinforcement bars needed in reinforced concrete.

CONCLUSION

In this thesis an understanding of the properties and performances of fiber reinforced polymers (FRP) has been developed through the study of their different applications for structural retrofitting. This innovative technique shows a great potential when disruption of traffic or activity of the building is not possible or only for a limited time. Indeed, applying fiber reinforced polymers (FRP) layers is very quick and does not require specialized equipments (crane, etc). With increasing acceptance by the industry over the past years, FRP have become commonly used in different types of structural retrofitting.

The standard comparison highlights the limitations of the use of fiber reinforced polymers as most of the differences in the calculation comes from security coefficient related to the adherence of the fiber reinforced plates to the concrete. As described in the second part of this thesis the bonding is the main limitation and source of concern in the applications of fiber reinforced polymers and requires further research.

An interesting conclusion of this thesis is that the business related to fiber reinforced polymers retrofitting is a niche sector that encompass only a very few specialised companies in the United States. In Europe this retrofitting techniques has not yet been extensively developed and there is still room for entrepreneurs in this field.

APPENDIX 1

```
clear all
close all

%Define the geometry of the rectangle beam (in inches)%
b = input('Width of the beam =');
d = input('Depth of the beam =');
h = input('Thickness of the beam =');
As = input('Area of tension rebars in the beam =');
fcc = input('Compressive strength in psi. of the concrete used
=');
Ec = input('Young Modulus of the concrete used =');

%Property of the steel%

fy = input('Yield Strength of the steel used in psi. =');

%Define fibers properties%

Sfu = input('Fracture strain of fibers at failure recommended
by manufacturer ='); %around 0.015 for carbon fibers T300%
Af = input('Area of added fibers =');
n = input('Number of layers of fiber plates =');
Ef = input('Young modulus of the fiber used =');
tf = input('Thickness of each layer of fiber =');

%Computing of Beta1=B to know the contribution of concrete and
check for rhomin, rhomax%

if fcc<4000
    B=0.85;
elseif fcc>4000 & fcc<8000
    B=-0.00005*fcc+1.05;
else B=0.65;
end

%Then, a security coefficient K is computed and account for the
possible delamination or debonding of the FRP plate before
reaching Efu%

Z=n*Ef*tf;

if Z<1200000
K=1-Z/2400000;
else K=600000/Z;
end

Sfe=K*Sfu; %usable fracture strain taking into account security
coefficient%
```

```

%Now we seek c to know the area of the beam in
compression/tension%
%In order to do that we solve this equation : F=a*c^2-t*c-i;%
a=0.85*fcc*b*B;
t=As*fy-Af*Ef*0.003;
i=Af*Ef*0.003*h;

D=(t^2+4*a*i)^.5;

x=(t-D)/(2*a);
y=(t+D)/(2*a);

c=(1-(x-y)/abs(x-y))*y/2 + (1-(y-x)/abs(y-x))*x/2;

%Compute strain at failure%

Sf=0.003*(h-c)/c;

if Sf<Sfe %In that case failure occurs by crushing of concrete
first%
    a=B*c;
    Mn=As*fy*(d-a/2)+Af*Ef*Sf*(h-a/2);
else %In that case failure by fracture of composite%
    a=(As*fy+Af*Ef*Sfe)/(0.85*fcc*b);
    Mn=0.85*fcc*b*a*(c-a/2)+As*fy*(d-c)+0.85*Af*Ef*Sf*(h-
c);
end

```

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