NISTIR 6288

NIST Workshop on Standards Development for the Use of Fiber Reinforced Polymers for the Rehabilitation of Concrete and Masonry Structures, January 7-8, 1998, Tucson, Arizona. Proceedings

Editor:
Dat Duthinh[1]

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DESIGN CONSIDERATIONS FOR THE USE OF FIBER REINFORCED POLYMERIC COMPOSITES IN THE REHABILITATION OF CONCRETE STRUCTURES

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ABSTRACT

Due to the high strength-to-weight and stiffness-to-weight ratios, corrosion resistance, light weight and potentially high durability, fiber reinforced polymer matrix composites (PMCs) are very attractive for use in civil infrastructure. Recently, their use has increased in the rehabilitation of concrete structures, due mainly to their tailorable performance characteristics, ease of application, and potential low life-cycle costs. This paper presents materials and design considerations for the use of fiber reinforced composites in the rehabilitation of concrete structures, and offers an approach to the development of a robust design methodology for future use of such materials.

1. INTRODUCTION

Fiber reinforced polymer matrix composites (PMCs), also known as fiber reinforced polymers (FRPs), are increasingly being considered for use in civil infrastructure for applications ranging from replacement for steel rebar and cables, to use in the rehabilitation of concrete structures, and for new structural components and systems. These applications can be divided into two general areas, namely structural rehabilitation to extend/enhance the service life of existing structures, and new structural members and complete systems. Over the past few years, there has been a dramatic increase in the use of both carbon- and glass-fiber reinforced PMCs for rehabilitation world-wide, driven largely by the interest in seismic retrofitting of bridge columns and the strengthening of beams and slabs. Although a large number of the early projects could be considered to be demonstrations, the technology is now at a point where its future use will depend primarily on the availability of validated design guidelines based on accepted performance criteria and on their economic competitiveness with conventional methods of rehabilitation. The myriad possibilities of reinforcement and resin combinations, and processing paths possible with PMCs make it important that the guidelines include procedures for materials selection and application. The need for performance based specifications coupled with materials guidelines, performance based design procedures, and systems for monitoring of quality control and structural response is clearly apparent.

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Within the scope of rehabilitation of concrete structures, it is essential that we differentiate between repair, strengthening and retrofit, terms which are often erroneously used interchangeably, but which in fact refer to three different structural conditions. In "repairing" a structure, the composite material is used to fix a structural or functional deficiency such as a crack or a severely degraded structural component. In contrast, the strengthening of structures is specific to those cases wherein the application/addition of the composite would enhance the existing designed performance level, as would be the case in attempting to increase the load rating (or capacity) of a bridge deck through the application of composites to the deck soffit. The term retrofit is specifically used as related to the seismic upgrade of facilities, such as in the case of the use of composite jackets for the confinement of columns. The differentiation is important not just on the basis of structural functionality, but also because the specifics related to the use of the material and its expected life have a significant effect on the selection (or rejection) of fiber-resin combinations from a variety of alternatives.

Hence, the objective of using composites for the rehabilitation of concrete structures is to restore or enhance the functionality and/or safety of existing structural components or systems. In keeping with this, rehabilitation measures must be designed such that within the intended period of operation and cost, (i) the structures remain functional with an accepted probability, and (ii) they are capable of sustaining all actions and influences likely to occur and have adequate durability with an appropriate degree of reliability. The purpose of this paper is to briefly address measures related to design considerations, materials capacity reduction factors, and design detailing for composites used in the rehabilitation of concrete structures.

2. DESIGN CONSIDERATIONS

In considering the rehabilitation of structures, it is important to keep in mind that structures must be designed to have reasonable safety margins, and must provide adequate warning of failure prior to reaching an ultimate limit state. Although this may appear to be redundant to most civil structural designers, it is stressed that unlike reinforced concrete members which show a ductile response to loading, composite structures for the most part are linear elastic to failure and fail catastrophically without significant warning. Design considerations must thus not only address the mechanical short- and long-term response of the composites and the characteristics of the bond between the composite and the concrete substrate [Karbhari, 1996], but must also address the combined response of the new structural system in terms of stiffness, service load behavior, overload response and failure modes. Although composites offer the ability to conform to a variety of shapes and to be applied to almost any surface, it is important that rehabilitation measures follow good conventional concrete design practice.

As with conventional materials, performance levels related to strength, stiffness and ultimate strain are important, and a comparison of representative properties of carbon fiber (AS4 or T300 type), E-glass fiber, carbon fiber composite, concrete and grade 60 steel is shown in Table 1. It should be noted, however, that unlike reinforcing steel, some reinforcing fibers such as carbon fibers are anisotropic, having different properties in the longitudinal (i.e., along the length of the fiber) and transverse directions. For example although the tensile modulus for T300 type carbon fibers in the longitudinal direction is 230 GPa, in the transverse direction it is only about 40 GPa, a fact that must be considered when designing with fibers or fabrics that have to conform to tight radii and corners. In the case of aramid fibers, the structure tends to fibrillate (break up into fragments/fibrils) on the compression side, again emphasizing the need for special consideration around edges and corners. Furthermore, although the carbon fiber has a negative coefficient of thermal expansion in the axial direction, it has a value of + 10 x 10^{-6} /°C in the transverse direction.

Table 1: Comparison of Representative Properties of Materials

Property	Concrete	Grade 60 Steel	E-Glass Fiber	Carbon Fiber	Carbon/Epoxy Composite ($V_f = 60\%$)	
					Fiber Direction	90° to Fiber Direction
Density (g/cm^3)	1.6	7.8	2.54-2.62	1.75-1.80	1.6	1.6
Tensile Modulus (GPa)	2.5	200	72.5	230	160	10
Tensile Strength (MPa)	3.5	400 (Yield level)	3450	3000	1725	40
Strain to Break	-	0.2 % (Yield level)	3 % to 5 %	0.9 % to 1.5 %	1.1 %	1.5 %
Poisson's Ratio	0.2	0.3	0.15-0.26	0.2	0.22-0.28	0.015-0.02
Thermal Conductivity [W/(m ° K)] at 23 °C	-	-	1.2-1.4	7.0-8.5	11-18	2-3
Coefficient of Thermal Expansion (x 10^{-6} /°C)	10	12	5	-0.4	0.02-0.04	20

Although composite materials have significantly higher strength levels, it is important to note that the limit of use is often dictated by strain limitations. One such example is in the use of composite jackets for the seismic retrofit of columns for the shear failure mode. This is primarily a strength and dilation problem. Shear strength can be added to concrete columns through the addition of hoop reinforcement in the form of fibers oriented at 90° to the column axis, such that the opening of inclined cracks, and with it the loss of aggregate interlock can be controlled by limiting the column dilation in the loading direction to experimentally determined dilation strains of 0.4 % [Priestley et al., 1996]. It is clear that this severely restricts the utilization of the high strengths of the composite materials (glass or carbon reinforced). It is also noted that the required thickness of jackets for retrofit in the case of shear strengthening, flexural hinge confinement, lap splice clamping, and bar buckling restraint can all be derived through proportionality relationships that are based on combinations of modulus in the hoop direction, strength, and ultimate strain of the material as given in Table 2.

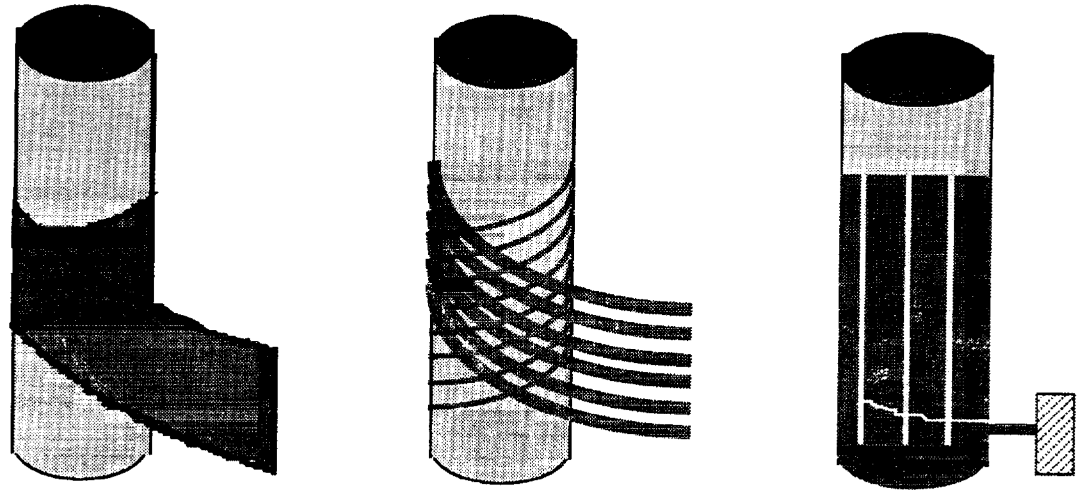
Table 2: Comparison of Hypothetical Jacket Thicknesses

System	Mechanical Characteristics	Normalized Jacket Thickness			
		Shear Strength	**Plastic Hinge Confinement**	**Bar Buckling Restraint**	**Lap Splice Clamping**
Proportionality Relationship		$t_j^v \sim \frac{1}{E_j D} \times C_v$	$t_j^c \sim \frac{D}{f_{ju}\varepsilon_{ju}} \times C_c$	$t_j^b \sim \frac{D}{E_j} \times C_b$	$t_j^s \sim \frac{D}{E_j} \times C_s$
System A	$E_j =$ 124 GPa $f_{ju} =$ 1,380 MPa $\varepsilon_{ju} =$ 1%	1	1	1	1
System B	$E_j =$ 76 GPa $f_{ju} =$ 1,380 MPa $\varepsilon_{ju} =$ 1.5%	1.6	0.7	1.6	1.6
System C	$E_j =$ 21 GPa $f_{ju} =$ 655 MPa $\varepsilon_{ju} =$ 2.5%	6.0	0.9	6.0	6.0

1 MPa = 0.145 ksi, 1 GPa = 145 ksi

System A is representative of a towpreg based graphite/epoxy composite similar to that used in automated winding of jackets, system B is representative of a Kevlar/epoxy composite, and system C is representative of an E-glass/Vinylester composite similar to that used in prefabricated adhesively bonded shells. All values in Table 2 are normalized to the thickness values derived for System A which represents the unidirectional prepreg carbon tow winding system with an epoxy matrix. It can be seen that jacket thicknesses for shear, bar buckling restraint and lap splice clamping are driven by the modulus of the jacket in the hoop direction, which favors higher modulus materials, whereas the flexural plastic hinge confinement can also efficiently be achieved with a lower modulus and higher strain capacity material. It is important to note that the characteristic properties listed in Table 2 have not been modified to account for deviations in properties accruing from materials variations, aging and deterioration, or process effects. In actuality the application of factors accounting for these effects is critical to the determination of actual values used in design.

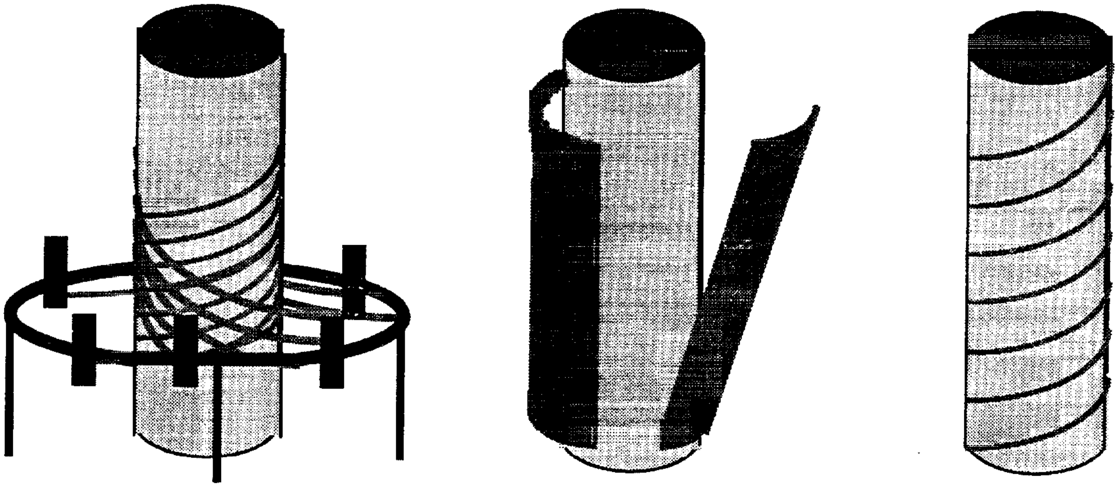
A variety of jacketing systems currently exist and can be differentiated into five basic types based on the method of processing/installation (Fig. 1), including the use of: (a) the wet lay-up process using fabric, tape or individual tow, (b) prepreg in the form of tow, tape or fabric, (c) prefabricated shells, (d) resin infusion processes, and (e) external composite cables. The wet lay-up process is generally associated with manual application and the use of ambient cure, although it is possible to heat the system after application to achieve higher cure temperatures and hence higher T_g. In the case of wet-winding of tow or tape, the process may be automated, although resin impregnation is still through the use of a wet bath and/or spray. The use of prepreg material generically uses an elevated cure, with the winding process for tow and tape being automated, and the fabric process being manual in terms of lay-down. In the case of prefabricated shells, the sections are fabricated in a factory and then adhesively bonded in the field so as to form the jacket. In the case of resin infusion, the dry fabric is applied manually and resin is then infused using a vacuum with cure being under ambient conditions. Irrespective of the method used, it is important to note that aspects related to material form (tow, dry fabric, impregnated fabric etc.), processing (lay-up, cure, etc.), and location of fabrication (field versus prefabricated) will have an effect on the final performance and longevity of the material system in use.



Wrapping of Fabric

Winding of Tow

Resin Infusion



Automated Winding

Bonding of Prefabricated Shells

Use of Composite Cables

Figure 1: Schematic of Processes for the Fabrication of Jackets for Seismic Retrofit of Columns

The use of composites for the strengthening of beams and slabs through its application on the bottom surface or soffit is another attractive use of composites. Although rather simple in concept, the method depends largely on the integrity of the bond developed between the composite and concrete substrate, and on the efficiency of stress transfer between them. Aspects related to design details of this method are described in section 4, and aspects related to potential failure modes and degradation are described in Karbhari et al [1997], Karbhari and Zhao [1997].

It is important, however, to emphasize that the efficacy of this system is affected significantly by the method of fabrication of the composite layer used for strengthening. The "plate" (or external reinforcement) can itself be fabricated in three generic ways as listed in Table 3.

Table 3: Methods of Application of External Composite Reinforcement for Strengthening

Procedure	Description
Adhesive Bonding	Composite strip/panel/plate is prefabricated and cured (using wet lay-up, pultrusion, or autoclave cure) and then bonded onto the concrete substrate using an adhesive under pressure.
Wet Lay-up	Resin is applied to the concrete substrate and layers of fabric are then impregnated in place using rollers and/or squeegees. The composite and bond are formed at the same time.
Resin Infusion	Reinforcing fabric is placed over the area under consideration and the entire area is encapsulated in a vacuum bag. Resin is infused into the assembly under vacuum with compaction taking place under vacuum pressure. Unlike the wet lay-up process, this is a closed process and the infusing resin can fill cracks and voids as well. In a variant the outer layer of fabric in contact with the vacuum bag is partially cured prior to placement in order to ensure a good surface.

Of these, the pre-manufactured alternative shows the highest degree of uniformity and quality control, since it is fabricated under controlled conditions. Application, and efficiency in use are still predicated by the use of an appropriate adhesive and through the achievement of a good bond between the concrete substrate and the composite adherent. Care must be taken to ensure that the adhesive is chosen to match as closely as possible both the concrete and composite vis-à-vis their elastic moduli and coefficients of thermal expansion, while providing an interlayer to reduce mismatch induced stresses. The wet lay-up process is perhaps the most used and gives the maximum flexibility for field application, and is probably also the cheapest alternative. However, it presents the most variability and necessitates the use of excessive resin, and could result in the wrinkling or shear deformation of the fabric used, decreasing its designed strengthening efficiency. Also the process carries with it the intrinsic entrapment of air voids, and the resulting potential for deterioration with time. The composite formed in this case is generally cured under ambient conditions. The in-situ resin infusion method is a fairly new variant and is capable of achieving uniformity and good fabric compaction, while making it easier for the reinforcement to be placed without excessive un-intended deformation. In the last two methods discussed above, the function of the adhesive is taken by the resin itself with the bond to the concrete substrate being formed simultaneously with the fabrication of the composite. This is both an advantage and a disadvantage, since the elimination of the third phase in the system, the adhesive, results in the formation of fewer interfaces at which failure could occur, but also eliminates the use of a more compliant layer.

3. CAPACITY REDUCTION FACTORS

In designing with composites it is important to keep in mind that although PMCs are attractive for use in a civil engineering environment because of their high strength-to-weight and stiffness-to-weight ratios, corrosion resistance, and chemical inertness, systems of the type that would be used have incomplete data records and must be treated as emerging materials. This is specifically true of the lower and ambient temperature cure systems involving polyesters, vinylesters and some epoxies, which do not have the well established databases generated by DoD sponsored research such as the AS4/3501-6 or 5208 based systems. It is thus important that designers consider the uncertainty in these materials based on aspects related to data generation, materials characteristics (as related to long- and short-term durability) and processing routes, and furthermore that these be considered within the context of the LRFD design philosophy now adopted by AASHTO for bridge design with conventional materials [AASHTO 1994]. Using this approach it is proposed that the design value for a material be determined as

$$F_d = \phi F_k$$

where F_k is the characteristic value, and ϕ is the derived partial safety (or knock down) factor, derived on the basis of effects related to materials and processing. It is proposed that at the ultimate state

$$\phi = \phi_{mat} * \phi_{proc} * [(\phi_{cure} + \phi_{loc})/2] * \phi_{degr}$$

wherein ϕ_{mat} is used to account for the deviation (and/or level of uncertainty) of material properties from the specified characteristic values, ϕ_{proc} is used to account for variation due to the processing method used, ϕ_{cure} is used to account for variation in properties due to the degree of cure achieved, ϕ_{loc} is used to account for the uncertainty in performance level due to the location of processing, and ϕ_{degr} is used to account for changes in material properties over time and due to environmental effects. It should be noted that effects due to cure and location are averaged since there is a substantial degree of interaction. Proposed values for ϕ_{mat} , ϕ_{proc} , ϕ_{cure} , ϕ_{loc} , and ϕ_{degr} are given in Tables 4-8 respectively.

Table 4: Values for Factor Based on Derivation of Material Properties (ϕ_{mat})

Value	Description
0.50 - 0.80	Properties based on constituent material test data and lamina and laminate properties derived from theory.
0.67 - 0.90	Properties for individual plies derived from tests and laminate properties derived from theory.
0.85 - 0.97	Properties derived from laminate or structural tests.

The levels proposed in Table 4 for ϕ_{mat} consider the differences due to the level or type of testing, as well as the approximations inherent in bridging theoretically derived and experimentally determined data. This procedure also allows for the uncertainty in using coupon level materials data for characteristics that must account for structural rather than mere materials response, such as in the case of composites jackets used for seismic retrofit of columns, wherein the NOL (Naval Ordnance Laboratory) ring test (see pp. 3.80-81) provides data that is much more suitable for structural characterization, than the flat coupon test which provides materials properties.

Table 5: Values for Factor Based on Processing Method Used (ϕ_{proc})

Value	Description
0.95 – 1.0	Prepreg based autoclave cure
0.95 – 1.0	Prepreg based filament winding
0.85 - 0.95	Wet-winding
0.75 - 0.80	Wet Lay-up of Fabric (Vacuum Bag)
0.60 - 0.75	Wet Lay-up of Fabric (Unbagged and without vacuum)
0.70 - 0.95	Pultrusion
0.75 - 0.87	Resin Transfer Molding (RTM)
0.70 - 0.85	Resin Infusion
0.60 - 0.65	Spray-Up

The levels proposed for ϕ_{proc} in Table 5 acknowledge that it is possible to process/fabricate composites using the same constituent materials (fiber, resin and filler) but that the properties may vary due to the choice of process used. For example, it is well known that the degree of compaction achievable through the use of a wet lay-up is less than that achievable through the use of an autoclave or RTM based process. Furthermore, the use of a spray-up process is likely to lead to a higher degree of void entrapment and non-uniformity than any other process and hence in comparison with composites fabricated through other processes, performance characteristics can be expected to be lower.

Table 6: Values for Factor Based on Type of Cure Applied (ϕ_{cure})

Value	Description
1	Autoclave cure
0.90 – 1.0	Elevated temperature controlled cure process
0.80 - 0.95	Ambient cure

The range of values used in Table 6 discriminates between composites on the basis of cure achieved. For most resin systems, cure through the use of an ambient cure procedure results in a lower degree of polymerization and a lower glass transition temperature, than one achieved through the use of an elevated temperature controlled or autoclave cured process. This serves as a more generic method of differentiating and factoring composites than on the basis of heat deflection temperature and temperature of use, which is subjective as related to location and extent of heat transmission over the period of time under consideration.

In addition to the method of cure utilized, the quality control of a composite can be largely affected by the location in which the composite is fabricated, since aspects such as moisture, temperature variation, humidity, and the presence of contaminants can greatly affect the process and the resulting properties. It should be remembered that almost all of the "high-performance" and "qualified" composites processed for use in aerospace applications were fabricated in controlled factory conditions which limited contamination and variability. In contrast, it is expected that a large number of civil infrastructure applications related to rehabilitation will be conducted in the field with little to no actual control over the surrounding environment, making the consideration of location an important factor.

Table 7: Values for Factor Based on Location of Manufacturing/Construction (ϕ_{loc})

Value	Description
1	Controlled factory environment
0.90 - 0.95	Uncontrolled field environment within an enclosure
0.80 - 0.90	Field environment without an enclosure

ϕ_{loc} is an important factor for consideration in a civil engineering environment where fabrication may either be in a factory or in the field. Obviously, it is assumed that quality and uniformity of composites is higher in the factory environment than in the field.

Table 8: Values for Factor Based on Materials Degradation/Aging (ϕ_{degr})

Material System	Short-Term	Long-Term
E-Glass composite	0.60 - 0.80	0.30- 0.50
S-Glass composite	0.75 - 0.90	0.55 - 0.80
Carbon composite	0.95 - 1.00	0.70 - 0.90

The ranges used in Table 8 attempt to bound the response of E-glass, S-glass, and carbon fiber reinforced composites for both short-term and long-term loading. It is implicitly assumed that the fiber is appropriately sized so as to achieve good wet-out and bond with the composite. The use of carbon fibers in a vinylester composite is currently not recommended due to poor adhesion resulting in significantly lower properties in compression and shear over time or at elevated temperatures. There are also concerns related to the use of glass fibers with isopolyester resins wherein the addition of wax in the formulation of the isopolyester is known to result in fiber-matrix debonding and changes in failure mechanisms after exposure to water. Another method of developing these factors is discussed in [Karbhari and Seible, 1997] but requires the development of significant fatigue or creep data.

In using these factors it is important to note that, in general, for unidirectional composites the strength and strain-to-failure of composites degrades over time, whereas in most cases the modulus either remains constant or degrades to a small extent. The user is thus cautioned against using these levels without recognition of the structural characteristic that is critical, i.e. is the design strength based, stiffness based etc., or whether resin integrity is important. Since the combined effects of the parameters listed above are evaluated through the use of products, it is essential that upper and lower limits be set for the use of these factors. Based on experimental observation and practice, it is proposed that the upper limit be 0.97, and the lower limit be 0.25. It can be seen that the lower limit corresponds to the well known factor of safety 4 used conventionally in the design of composites for marine structures based on the threshold for creep rupture of glass-fiber reinforced composites.

The above factors are intended to serve as guidelines only and to be used in cases where sufficient data does not exist to derive design characteristic values for materials based on actual tests. However, it is not expected that materials used in civil infrastructure applications will be qualified in the same manner as those in the aerospace industry (incorporating numerous tests with significant number of repetitions in order to arrive at good statistical bases for design), and hence variation between specimens should be expected and the probability included in design through the use of these partial safety factors.

4. DESIGN DETAILING

Because composites can be easily applied to concrete structures either through in-situ fabrication on the structure itself or through the adhesion of prefabricated panels or strips, there is a tendency to follow with the composite the contours of the element to be rehabilitated, without sufficient thought given to the consequences of such actions. Examples of some detailing practices are given in Figures 2-6, wherein methods of application of composites for rehabilitation of existing concrete structural elements are compared to those used in the construction of new conventional concrete structural elements. In each figure the (-) depicts an incorrect practice, and a (+) denotes the correct detailing practice for the use of composites.

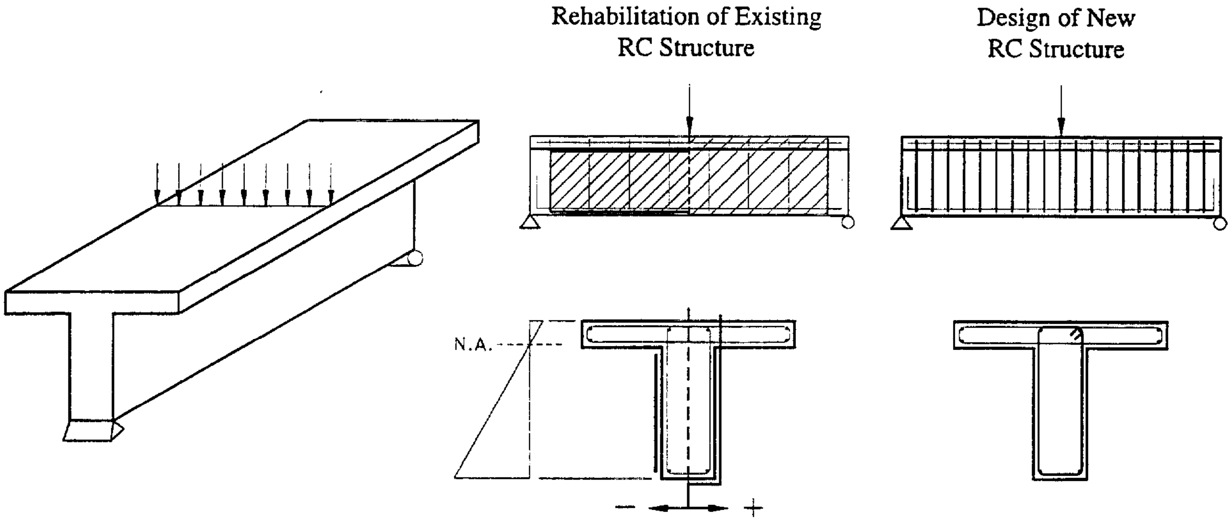


Figure 2: Design detailing for Shear Strengthening of T-Beams

A common example of the misuse of ease of conformance is shown in Figures 2 and 3 wherein composites are used for the shear strengthening of T and I-beams, respectively, through the covering of the beam on its sides and bottom by FRP fabric. As can be seen in the right hand side of Figure 2, in new conventional concrete construction, shear stirrups are not curtailed in the beam region, but are carried over into the slab section to be anchored in the compression zone and to provide the sought after truss mechanism.

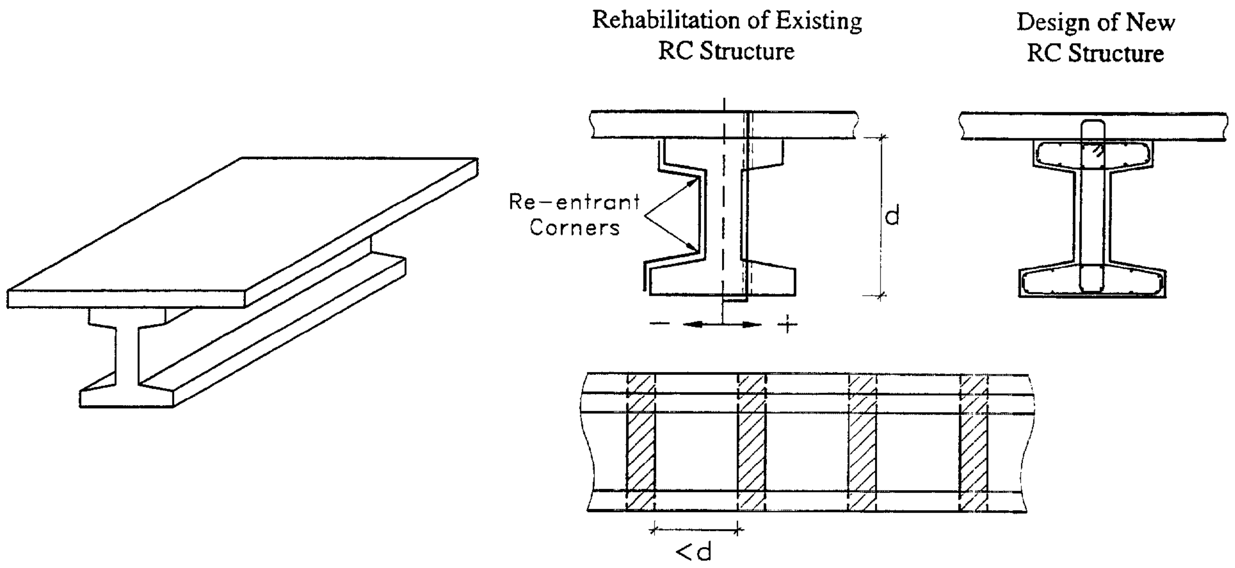


Figure 3: Design detailing for Shear Strengthening of I-Beams

When composites are curtailed in the vertical section below the slab, there is a distinct possibility that the composite will debond or delaminate at the bottom corner and along the vertical edge below the slab, significantly reducing safety and reliability margins. For good detailing, the composite should be continued directly into the slab and then anchored in that region.

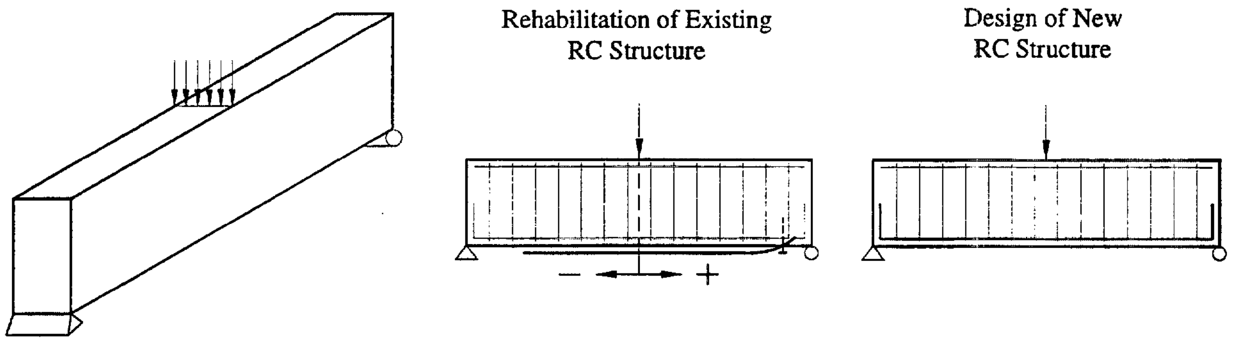


Figure 4: Design detailing for the flexural strengthening of beams

Composite plates are routinely adhesively bonded to the bottom of beams in order to strengthen beams flexurally as shown in Figure 4. This, however, disregards the fact that the presence of the discontinuity causes very high shear stresses at the end of the composite plate resulting in peel stresses and ultimate failure due to premature debonding of the plate/strip from the concrete. Appropriate detailing should follow the procedure prescribed for internal rebar which would be carried through to the support. FRP strengthening can be developed through partial embedment of the composite in the concrete so as to provide anchorage and stress buildup over its length and, in case termination short of the support region is required, strict limits on the maximum allowable strength / capacity enhancement should be introduced.

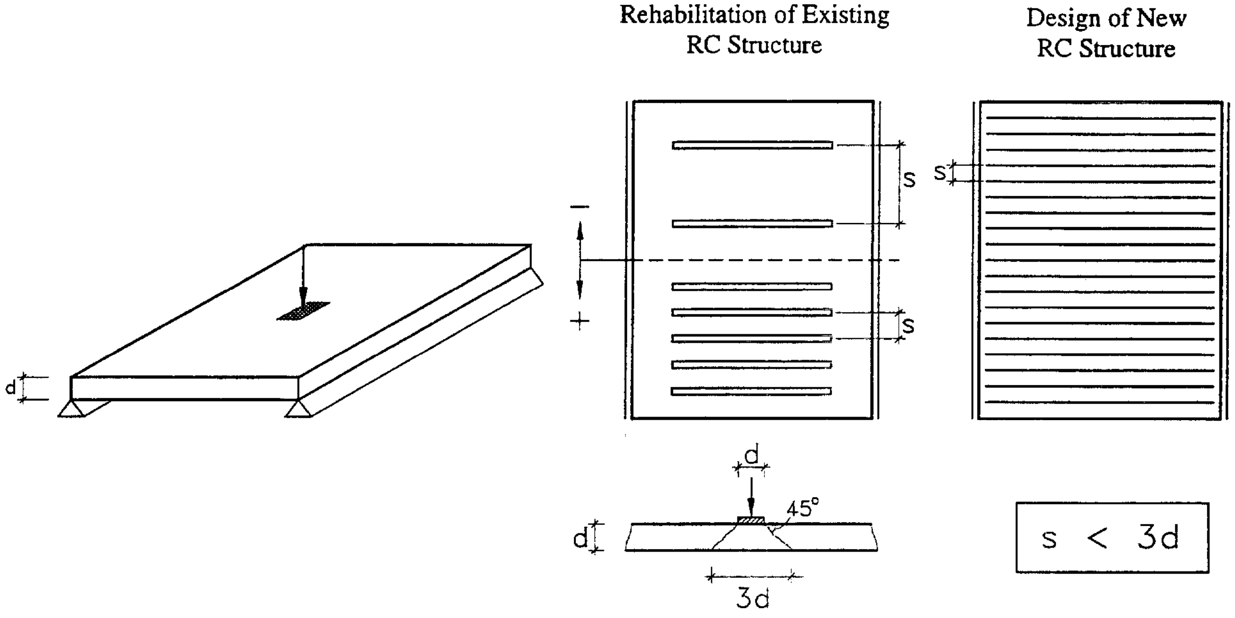


Figure 5: Design detailing for the flexural strengthening of slabs

The successful application of composites to the bottom surface of beams has resulted in some use of strips on the soffits of slabs with strips being adhesively bonded to the soffit at wide spacing. Again this is poor detailing practice due to shear lag between tension and compression mechanisms and since it allows for punching shear failure in the large unreinforced gaps between the external composite strips as shown in Figure 5. Correct procedure would be to place the strips closer together similar to the placement of internal steel rebar or to use continuous fabric over the entire soffit.

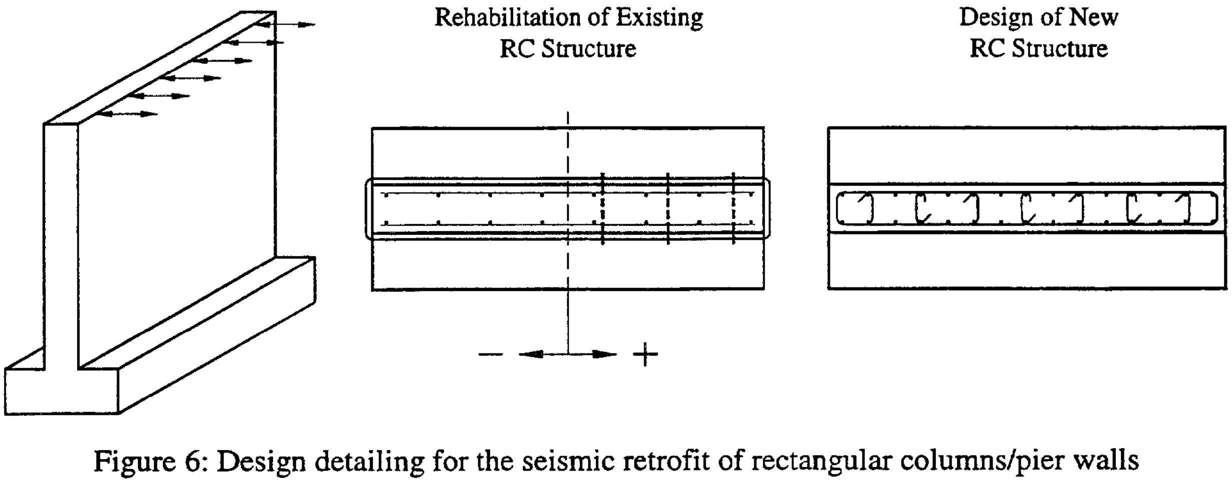


Figure 6: Design detailing for the seismic retrofit of rectangular columns/pier walls

Composite sheets can be easily applied to large aspect ratio rectangular columns or pier walls. However due to the long length between corners, the composite does not in actuality confine the internal concrete structure if just applied to the surface. In order to achieve confinement, the composite wraps need to be constrained on both sides along the length through the use of dowels or bolts that anchor the composite to the pre-existing structure, thereby creating shorter distances which are confined between bolts. This is actually similar to the technique used in conventional construction (Figure 6) wherein the transverse reinforcement on the two side faces is tied together through the use of J-hooks.

As a general rule, external FRP rehabilitation measures on concrete structures should emulate conventional internal reinforcement detailing as much as possible. In cases where this is not practical, strict limitations on the **allowable** capacity enhancement for the rehabilitation measure should be applied. It is noted, that in the majority of applications completed in Switzerland, the enhancement of strengthening is restricted to a 50% increase so as not to exceed the safe allowable capacity of the original structure.

5. SUMMARY AND CONCLUSIONS

The use of fiber reinforced composites for the rehabilitation of concrete structural elements requires that appropriate design detailing be used and that the design be conducted using a methodology that ensures appropriate use of the material. It is essential that design values for materials be determined from characteristic values through modification based on the specifics of constituent materials and processes used, and based on potential for aging/deterioration of the material or rehabilitation system. Design detailing is also important and if not attended to will lead to premature and often catastrophic failure of the rehabilitated structure. Although composites present immense opportunity for rapid completion of rehabilitation procedures without significant increases in thickness of existing components, or changes to the structural profile, it is critical that ease of use and application not translate to poor detailing practice. Composites must be applied in such a way that they conform to conventional practice applicable to reinforcement placed internal to the concrete. Furthermore, although the application of composites can result in significant enhancement of performance, care must be taken to ensure that failure be gradual and non-catastrophic, and that the actual capacity of existing structures is not exceeded.

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