# STRENGTHENING BY FRP – A WORD OF CAUTION

**Dr. Vasant Kelkar* & Prabhat Pandey***

## Introduction

In recent times strengthening of columns and beams of various building is being commonly done using externally bonded FRP such as carbon or glass fibres. This is done not only for rehabilitation of old buildings but also in new buildings under construction where floors are to be added for using increase in FSI. The structural consultants seem to generally accept the proposals for strengthening given by the FRP vendor – use of carbon or glass fibres, their thicknesses, use of laminates where strength in bending is to be increased, methods used for anchoring laminates etc. without checking and approving the design or execution details.

Many times the calculations in the proposal are not correct, or the wrapping technique may not be quite effective in strengthening the structure. This will result in a structure deficient in strength although the structural consultant and the users will be under the impression that it is adequately strengthened. It is therefore, necessary that the structural consultant, who is finally responsible for the structural stability should thoroughly check the proposal, calculations and details given by the FRP Vendor, before approving them for use in a project.

This article briefly describes the problems that can arise if proposals are accepted by the structural consultant without scrutiny.

## References

Strengthening of structures by externally bonded FRP filaments is a relatively recent development but has been used extensively in countries like U.K and U.S.A and also recently in India. Filaments made of carbon or glass fibres are commonly used in India. The carbon fibres have higher tensile strength which occurs at relatively lower strains compared to glass fibres. Hence, glass fibres give more ductility. Properties of the fibres are available from the literatures of companies like Sika or BASF who market these fibres in India. Various references are available explaining the theory and also giving results of experiments done in this field. ACI Committee report 440.2R-7 [1], Report No. 55 of Concrete Society Committee of U.K. [2], and Report of International Federation for Structural Concrete (fib), Switzerland [3] discuss and give guidelines for such strengthening. There are also a number of other technical papers on this subject referred in these reports.

## Circular Columns in Axial Compression

FRP strengthening of structures is commonly done by wrapping the FRP around a structural element like column for increasing its concrete strength and/or by attaching FRP laminates (thin plates) for resisting tension due to flexure as done for slabs/beams and also columns. The theory behind strengthening of structures using FRP hoop wraps is similar to that used for strengthening a structure by jacketing with steel plates. It can be simply explained as follows:

Consider a circular column of concrete which is hoop wrapped with glass fibre filaments for increasing its strength. Under vertical compressive load the column tends to expand laterally as per Poisson's ratio of its concrete. This lateral expansion stretches the wrap filaments inducing hoop tensile stresses in them. Since the filament are curved (around the circular column) the induced tensile stresses give a resultant radially inward pressure on the column all around it due to change in curvature of the fibres – Fig 1. Under such lateral pressure and its axial compressive load, the column is then in a state of triaxial compression under which its axial compressive stress capacity increases significantly and hence it can sustain a higher compressive load.

For a circular column of an original concrete strength Fck and subjected to a lateral pressure $F_l$ from the hoop wrap, the increased strength $F_{cc}$ is given by the equation,

$$F_{cc} = F_{ck} \, [2.25 \, v \, (1 + 7.9(f_1/F_{ck})) - 2 \, F_l \, / \, F_{ck} - 1.25 \,], \qquad \ldots(1)$$

where all the strengths are cylinder strengths = 0.8 (cube strengths). This formula was originally derived for increase in strength of a column from steel jacketing. But it is applicable to FRP wraps also.

Knowing lateral pressure $F_l$ exerted by FRP it is easy to calculate increased strength $F_{cc}$ of the column from the above equation. Alternatively, knowing the required increase in strength $F_{cc}$, one can calculate the required lateral pressure Fl and hence the wrap thickness. If T is the tensile force in the wrap per mm height of column then, we get from statics:

$F_l = T/R$, where R = radius of the column

Or

$$T = F_l R \qquad \ldots(2)$$

Knowing the allowable tensile stress in the wrap fibre, its required thickness can be easily calculated from the above. But it is also necessary to check the corresponding strain in the wrap. The strain in the wrap fibres $\varepsilon_f$ is calculated as follows:

$\varepsilon_f = T/(A_f E_f)$ or $\varepsilon_f = (F_l . R) / (A_f E_f)$
We can also write this as:
$F_1 = A_f \varepsilon_f E_f / R$, …(3)

where $A_f$ is the fibre cross sectional area per mm height of column and $E_f$ is elastic modules of the fibres.

$A_f = n\, t_f$,

where $t_f$ is thickness of each fibre wrap and n is the number of layers

If $\zeta_f$ is defined as the volumetric ratio of wrap fibre to column then

$\zeta_f = (A_f .L.1) / (A_C . 1) = (A_f L / A_C)$,

where L is perimeter of fabric or column and Ac is the cross sectional area of concrete. Substituting in eq. (3) above, we get

$F_l = (\zeta_f A_c/L)(\varepsilon_f E_f / R)$ …(4a)

For circular columns, $A_C = \pi R^2$, $L = 2\pi R$. Hence, eq (4a) becomes,

$F_l = \zeta_f \varepsilon_f E_f / 2$ …(4b)

Thus, for the wrap thickness calculated from tensile force from (eq 2), we can check that the strain is within allowable limit. Alternatively, for maximum allowable $\varepsilon_f$ we can calculate $\zeta_f$ and hence wrap thickness directly from eq. (4a) for the required $F_l$ and then check that the corresponding stress in fibre is within limits.
A simple procedure for calculating wrap thickness would be :

1. For required concrete cylinder strength $F_{cc}$ calculate the required lateral pressure $F_l$ from eq. (1).
2. From $F_l$ calculate tension T in wrap from eq. (2).
3. Knowing the allowable stress in the wrap calculate its required thickness from T.
4. For the thickness (and layers) calculated above check that the strain $\varepsilon_f$ is within limit from eq (3) or (4b). If not within limits then revise the thickness.

Typically glass fibres have a tensile strength of 2400-3500 N/Sq mm, $E_f$ = 70,000 – 85,000 N/Sq mm and maximum elongation of 3.5 – 4.7%. Carbon fibres have tensile strength = 4000-5000 N/Sq mm, $\varepsilon_f$ = 2,50,000 N/Sq mm and 2% or less elongation. Thus, carbon fibres have higher strength but are less ductile. Various partial safety factors have been given by U.K. Committee [1] for these fibres. These are based on two factors – type of fibre and its method of manufacture. As per this report, for glass fibres, the combined partial safety factor would be $\gamma_f$ = 3.85 minimum. For carbon fibres it is recommended as 1.54. U.K. Committee also recommends E value to be reduced by division by a factor of safety $\gamma_E$ - since E of FRP may change with time. $\gamma_E$ is given as 1.8 and 1.1 respectively for glass and carbon fibres.

Hence, for design, ultimate tensile force T in a wrap of thickness tf and tensile strength $\sigma_f$ is

$T = (\sigma_f / \gamma_f)\, t_f$
or
$t_f = (T) / (\sigma_f / \gamma_f)$ …(5)

Knowing T from eq. (2), we can calculate $t_f$ from the above equation.

As an example, consider a circular column of 600mm diameter with a concrete grade of $F_{ck}$ = 25 (cube strength) and its strength is to be increased to 35 N/Sq mm. Then from eq. (1) we get $F_l$ = 1.346 N/Sq mm and from eq. (2) T = 403.8 N/mm.

Assuming glass fibre of $E_f$ = 76000 N/Sq mm, tensile strength $\sigma_f$ = 3400 N/Sq mm and $\gamma_f$ = 3.85, we get from eq. (5),

$t_f = (403.8) / (3400/3.85) = 0.457$ mm
and from eq. (3) or (4b),
$\varepsilon_f = (1.346)(300) / ((76000/1.8) * 0.457) = 0.021$

U.K report [2] recommends the strain to be restricted to 60% of the maximum elongation of the fibre. Assuming 4% as maximum elongation of the glass fibre, allowable $\varepsilon_f$ = 0.024. Hence, the strain calculated above is within limits.

In the above example we assumed a glass fibre with $\sigma_f$ = 3400, $E_f$ = 76000 and maximum $\varepsilon_f$ = 4%. For the actual fibre to be used in a project these values are to be obtained from the manufacturer. Values of $\gamma_f$ = 3.85 and $\gamma_E$ = 1.8 assumed above have to be taken by the designer.

**Columns of Noncircular Sections in Compression**

The above derivations are mainly for columns of circular cross section where hoop tension in wrap gives uniform radially inward lateral pressure on the column. For a rectangular section the wrap is straight without any curvature on the long and short sides. Hence, the tension in wrap cannot give any lateral pressure on the column. Only at the corners where the wrap turns through $90^0$, there is a concentrated thrust on the column. Thus, a square column is subjected to inward thrusts from wrap at its four corners. As long as the column size is not large it is reasonable to assume that all areas of concrete of the column will be subjected to triaxial compressive stresses and hence will gain in its axial load carrying capacity. The corners of the column are smoothened in a curve of a small radius upto 30 mm before wrapping is done resulting in the fibres curving smoothly over the corners.

For a square column of cross section b x h, where b = h, we can assume R = radius of an inscribed circle = b/2. Then, $A_f = b^2$, L = 4b. Substituting in equation (4a), we again get same equation (4b) as above.

Thus, for non circular sections also the formula of eq (1) is applied except that the right hand side is multiplied by an efficiency factor $\kappa_a$. Hence, eq. (4b) is written as :

$$F_l = \kappa_a \zeta_f \varepsilon_f E_f / 2 \qquad \ldots(6)$$

This equation is the same as in the ACI report [1]. The value of $\kappa_a$ is obviously 1 for circular sections. For square and rectangular sections, $\kappa_a$ is dependent on the section geometry, aspect ratio (length/width of cross section) and percentage of reinforcement.

The efficiency factor for rectangular sections is given as

$$\kappa_a = 1 - [(b - 2r)^2 + (h - 2r)^2] / [3bh\,(1 - \zeta_g)] \qquad \ldots(7)$$

in which b and h are dimensions of cross section of the column, r = radius of the curves at corners and $\zeta_g$ is ratio of volume of column reinforcement to the volume of concrete.

One can easily see, however, that in rectangular columns with large aspect ratio i.e. b/h greater than 1.5, the concrete of the column in areas away from the four corner will remain unaffected and not gain strength. Even for columns with b/h < 1.5, if the dimension b & h are large then in some central area concrete will remain unaffected.

ACI report [1] clearly states:

"The confining effect of FRP jackets should be assumed to be negligible for rectangular sections with aspect ratios b/h exceeding 1.5, or face dimensions b or h, exceeding 36 in. (900 mm), unless testing demonstrates their effectiveness".

Similarly, the U.K. Committee Report [2] states:

"Wrapping circular columns with FRP increases the axial load capacity as well as the bending and shear capacities (only limited increases are possible with square and rectangular columns)".

and :

"current estimates suggest that the confinement efficiency of square columns may be only 30 – 70% of circular columns. This efficiency is believed to decrease still further with columns of rectangular cross–section and/or, large side dimensions"

and :

"From the information currently available: A significant increase in the axial load capacity of square or rectangular columns by wrapping with FRP may be difficult to achieve in practice".

**Mumbai Scenario**

In spite of the above it is seen that rectangular columns/shear walls with large cross sectional dimensions and/or large aspect ratios are being commonly "strengthened" by FRP wrapping. The designers and vendors executing FRP works are unable to provide satisfactory explanation when asked how FRP can be considered as effective for rectangular wall like columns. The structural consultants should ask for calculations from FRP vendors to check that such conditions are satisfied and then also to check the thickness, layers of FRP proposed by the vendors.

We have received calculations from FRP vendors containing several errors and omissions For example, cube strengths instead of cylinder strengths are used in equation (1), instead of volumetric ratio of FRP and concrete, area ratios are used in eq (6), strains are not checked etc. For shear wall like columns with large aspect ratio eq. (1) was used and increase in strength was justified in a wrong way. For example, for a column of size 230 x 1000, increase in strength was calculated for the end 230 x 230 portions of the column and for the central 230 x 540 portion using equations (1), (7) etc. - as if the column was divided into 3 parts. Fcc, the enhanced strength of the whole column was then calculated by taking an average of the three Fcc values obtained for the three sections. This approach of calculating an average enhanced strength of column has no theoretical or experimental basis. But in their zeal to promote FRP strengthening and to sell their products the vendors seem to make such calculations and assume that column strength is accordingly increased. Hence, it is absolutely necessary that the structural consultant checks and approves the calculations given by FRP vendors.

**Durability of FRP**

FRP has been used widely for strengthening slabs/girders of old bridges in U.K./U.S.A. U.K. Committee Report [2] mentions

"Experience of the long-term durability of fibre composites is not yet available. This may be a disadvantage for structures for which a very long design life is required but can be overcome by appropriate monitoring. A draft Highways Agency Interim Advice Note on strengthening Concrete bridge supports using fibre reinforced plastic uses 30 years for the design life of a fibre composite strengthening system".

and :

"If a mature structure is to be strengthened, a 30 year life for a strengthening system may well be appropriate. However, this may not be the case for structures with long design lives, such as bridges and nuclear structures. Here, it may be necessary to accept a strengthening system with a design life less than the anticipated remaining life of the structure, on the understanding that the life of the strengthening system will be reassessed at a future date".

and :

"Because of the relative lack of long–term experience of the performance of fibre composite strengthening systems, regular inspection and maintenance regimes should be instigated. This is particularly important for buildings, which, unlike bridges, are not generally subjected to any form of routine inspection".

The FRP vendors argue that FRP jacketing is covered by plaster and PoP and hence, is protected from any damage from UV rays of the sun. Of course one advantage is that the reinforcement in such wrapped columns is much better protected against corrosion which is one of the main causes of deterioration in strength of columns (or beams) due to cracks from corrosion as is commonly seen in Mumbai.

**Mumbai Scenario**

Again, inspite of the above limitations, columns, beams and slabs are being routinely strengthened in India in new buildings or buildings under construction to add extra floors. The life of these new buildings is minimum 60 years and there is not enough experience on the life of FRP strengthening after 30 years. Since regular inspection, monitoring behavior and condition of FRP will not be done in residential/office buildings the structural consultant, municipality and other agencies should specify structural audit every five years after installation of FRP strengthening.

Otherwise any "strengthening" done will be only an eye wash and the columns may be resisting any extra load by encroaching on the factors of safety and no one will know what can happen after 30 years or when actual design loading such as from an earthquake occurs. In Ahmedabad several buildings upto 16 storeys also, under use for some years, collapsed when hit by an earthquake for which apparently they were not adequately designed as per requirements of IS Code.

**Alternatives For Wrapping Columns With Large Aspect Ratios**

For columns with long sides, some FRP vendors may suggest finishing the column with a curved surface on the long sides besides rounding at the corners. This will make the profile of the fabric curved along the long side and hence, is expected to give lateral pressure on the column on the long sides. The radius R of this curved surface to generate required pressure $F_l$ can be calculated from equation (2) above. This R will be generally small and hence will give a large bulge at the centre of long side of the column which will increase column size.

In one of the projects the vendor gave a scheme for strengthening by wrapping the columns. This was same even for long shear wall like columns. When questioned about effectiveness of the wrapping for long columns, the vendor then proposed a new scheme wherein fibre anchors to hold the FRP wrap in position at equally spaced locations along the height of the column (Fig 2) were proposed. Each anchor is a bunch of fibres and is placed in a hole drilled in the column. The hole is grouted with epoxy and the fibres of the anchors projecting on both sides of the column are splayed into the horizontal wraps on the two sides of the column.

Under vertical load when the column tries to bulge laterally it will tend to deform as shown in Fig. (3) assuming its deformation is restrained at the anchor point. The tension in the resulting stretched profile of the fibre wrap will exert lateral compressive pressure on the column (and tension in the anchor) even along its long length. No theoretical calculations regarding horizontal spacing of anchors was given by the vendors. Horizontally the anchor spacing proposed seemed to be such that each individual segment of column between two anchors or the column corner and the adjoining anchor, was kept with an aspect ratio of 1:2 (should have been at least 1:1.5). Thus, for a column width of 230mm the anchors were spaced horizontally at 460mm. No theoretical calculations were also given for the vertical spacing proposed for the anchors.

Sufficient number of reports on experimental tests on columns with large aspect ratios with hoop wrap and with hoop wrap plus anchors, are not available, to know the effectiveness of such anchors in "long" columns. Reference [4] mentions about improvement of the confinement effect of transverse fibre sheets due to fibre anchors on long sides based on tests done. But it does not give any quantitative details. Also, the tests with anchors are very limited in numbers and their plots do not seem to show significant increase in strength.

**Mumbai Scenario**

Under the circumstances, mentioned above it is difficult for a structural consultant to accept such strengthening measures for columns with aspect ratios greater than the recommended 1:1.5. But some experts in the field of fibre wrapping [5] express full confidence in the gain in strength of fibre wrapped columns even with large aspect ratios after fibre anchors are also provided. But such shear wall like columns are also being "strengthened" by FRP wraps in Mumbai and elsewhere in India even without any anchors.

**Problem At Top Of Columns**

Hoop wrapping can be provided on a column from top of a floor slab to bottom of upper floor slab if there are no beams framing into the column at the upper floor. But beams are generally present in both directions of the column. Can we assume that the portion of the column from top of slab to bottom of beams is sufficiently confined due to the beams and hence, even if wrap is not possible/effective in this zone, it is O.K? Can we assume that column design moment can be taken at face (bottom) of the beams? Are these assumptions valid when one side of the column is large with only one beam framing into it at its centre (or elsewhere)? These are the questions the structural consultants should consider and discuss with the vendor for every given situation and satisfy himself about the effectiveness of the wrap.

**Members In Bending**

Beams and slabs are strengthened by bonding fibre laminates at their bottom (tensile zone) to make up for the shortfall in reinforcement. In columns horizontal hoop wrap increases its concrete strength. Even with the increased strength if the provided reinforcement is still not sufficient to resist vertical load plus moments due to lateral loads etc, then additional vertical laminates on the two sides of the column are provided to enhance its moment carrying capacity (generally in the weak direction of the column). Commonly carbon fibres are used for such laminates as against glass fibres used for hoop wraps.

The calculation of width and thickness of the laminates is similar to that of reinforcement of a RCC beam in bending except here there are reinforcements of two types : deformed bars provided in the beam and fibre laminates. Equations for FRP area required are then similar to those for reinforcement in RCC beams.

The FRP laminate is bonded to the RCC member by epoxy. It can get debonded from the parent concrete if wide cracks due to flexure and shear develop in concrete above the fibre laminates – since this concrete will be subjected to higher tensile strains after strengthening. Hence, U.K. report [2] recommends:

"to avoid debonding failure the strain in the FRP should not exceed 0.8% when the applied loading is uniformly distributed, and 0.6% if combined high shear forces and bending moments are present, such as where the load is concentrated at a point and at hogging regions close to supports".

Again, these recommendations are for carbon laminates and shall be different if laminates are other than carbon. The structural consultant should ask the vendor to submit calculations of thickness and width provided for the laminates including calculations of strains in the FRP.

Thus, for a carbon fibre laminate with $E_f$ = 250000, $\gamma_f$ = 1.54, $\gamma_E$ = 1.1 and $\sigma_f$ = 4500, we get limit state design stress in laminate = (0.008) (250000/1.1) = 1818 N/sq.mm from consideration of maximum strain which is less than (4500/1.54) = 2922 (based on stress consideration) and hence, will govern. Correspondingly, the design stress in steel reinforcement is taken as (415/1.15) = 361 or (500/1.15) = 435 N/sq.mm for steel with Fy = 415 and 500 respectively. Thus, carbon fibre laminate has much higher ultimate design stress. But this will not be the case with glass fibre laminates (which have a much lower E value and a much higher $\gamma_f$ ). For a glass fibre laminate with $E_f$ =76000, $\gamma_f$ =3.54, $\gamma_E$ =1.8 and $\sigma_f$ = 3400 N/sq.mm, we get the ultimate design stresses as 338 N/sq.mm from strain consideration and 960 N/sq.mm from stress consideration. The governing value = 338 N/sq mm is very low. Hence, carbon fibres are preferred over glass fibres when used as laminates.

It is very important that like steel reinforcement a laminate must be anchored beyond the location where it is not required. Otherwise it will not be effective. U.K. report [2] recommends a minimum anchor length of 500mm. Anchoring laminate can be also done by hoop wrapping at their ends. Such hoop wrapping would be easily possible in a stand alone beam. But where slab is present one can get only a U shaped wrap around the beam. The vendors will propose to anchor this hoop wrap itself in a small groove of 15 – 25 mm depth made at the junction of beam and slab into which the wrap is taken and bonded with epoxy. Sometimes vendors continue the wrap from vertical sides of the beam to some distance at right angles at the bottom of the slab. The efficiency of these anchorage methods are not really known. FIB report [3] suggests providing anchors or wrap going through to top of slab or providing anchors through the beam web or through the slab on the L bent wrap portion below the slab. If the U wrap is provided to enhance the shear capacity of a beam then it is necessary that it is properly anchored at the top of the vertical faces of the beam.

In columns, the design bending moments in the weak direction due to minimum eccentricity and slenderness are constant over their height. Lateral load moments will be maximum at their top and bottom. Hence, vertical laminates in a column have to be effective over their full height. There are problems in providing and anchoring such laminates. If there is no cross beam then laminates can be taken right upto bottom of slab above and bent at right angles. Anchorage here would be provided by hoop wraps or anchors, Fig.5 or by extending the laminate into a groove at slab/column junction as mentioned for beams, if it is effective. If there are cross beams at the center of the long sides of the column then the laminate could be in two parts one on each side of the beam and taken to the soffit of the slab. But there cannot be hoop wrapping at this end of the column although some vendors wrap the column in this zone by horizontal U shaped hoop wraps on each side of the cross beam. But this is also not possible when there is also a beam along major direction of the column. Generally, for columns, hoop wrapping should also be provided over the vertical laminates to prevent their buckling.

## Site Inspection

The structural consultant should evaluate the effectiveness of the vendors' proposal of strengthening for each member – considering the design and anchoring aspects. Each column, beam or slab to be strengthened may need a unique way of strengthening since hoop wrapping, anchoring of laminates etc. will depend on conditions at ends of each such member and will have to be taken into account for the strengthening to be really effective.
Fig.4 shows some typical cases of hoop wrapping at top of a column. Also, Fig. 5 shows typical anchoring of laminates at their ends. Surface preparation, application of epoxy, wrapping of fibers should be done by experienced personnel under supervision of an experienced site supervisor and the structural consultant should see that requirements of effective strengthening are actually achieved at site for each member.

For beams and slabs, few of the strengthened beams and slabs can be easily tested as per IS code to give confidence on the efficiency of the strengthening done.

## Conclusions

Strengthening of columns, beams, slabs by external bonding by FRP fibres by hoop wrapping and/or laminates is lately being used commonly in India not only for old buildings but also for new buildings where floors are to be added.

The structural consultants seem to mainly accept whatever strengthening measures given by the FRP vendors which may be inadequate. It is therefore necessary that the structural consultant, who is responsible for the stability of the structure, understands the principles of FRP strengthening proposed by the FRP vendor, asks for and checks his calculations and details. It is also necessary that the structural consultant checks the conditions at ends of each member to be strengthened and takes measures to ensure that adequate hoop wrapping, end anchoring of hoop wraps and laminates especially at junctions of columns, beams and slabs are achieved at site. Otherwise the structure, in reality, may not get strengthened as desired.

Municipal, Government authorities and ISSE should issue some basic guidelines for design and detailing of such strengthening measures for structural consultants to follow. Standard details for hoop wraps and laminates especially at ends of the members should be also given.

## References


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[3] International Federation for Structural Concrete (Fib), Lausanne, Switzerland, 2001, "Externally Bonded FRP Reinforcement for RC Structures"

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## Author


Dr. Vasant S. Ketkar is a Senior Consulting engineer having more than 50 years of experiences. He is a visiting lecturer at Stenford University USA. E-mail : kcplbom@gmail.com

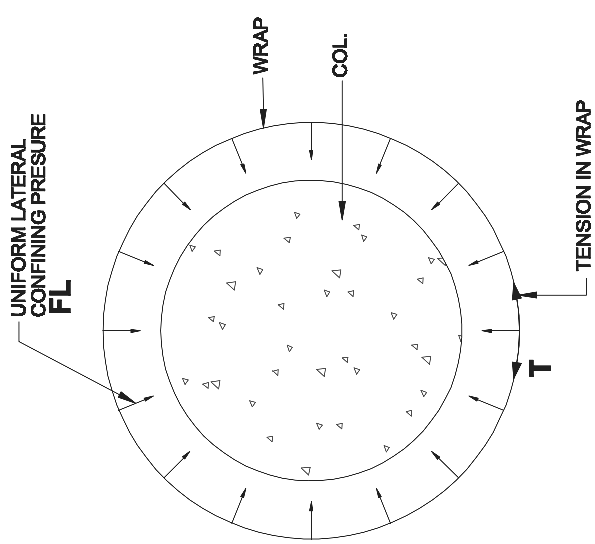



FIG. 1

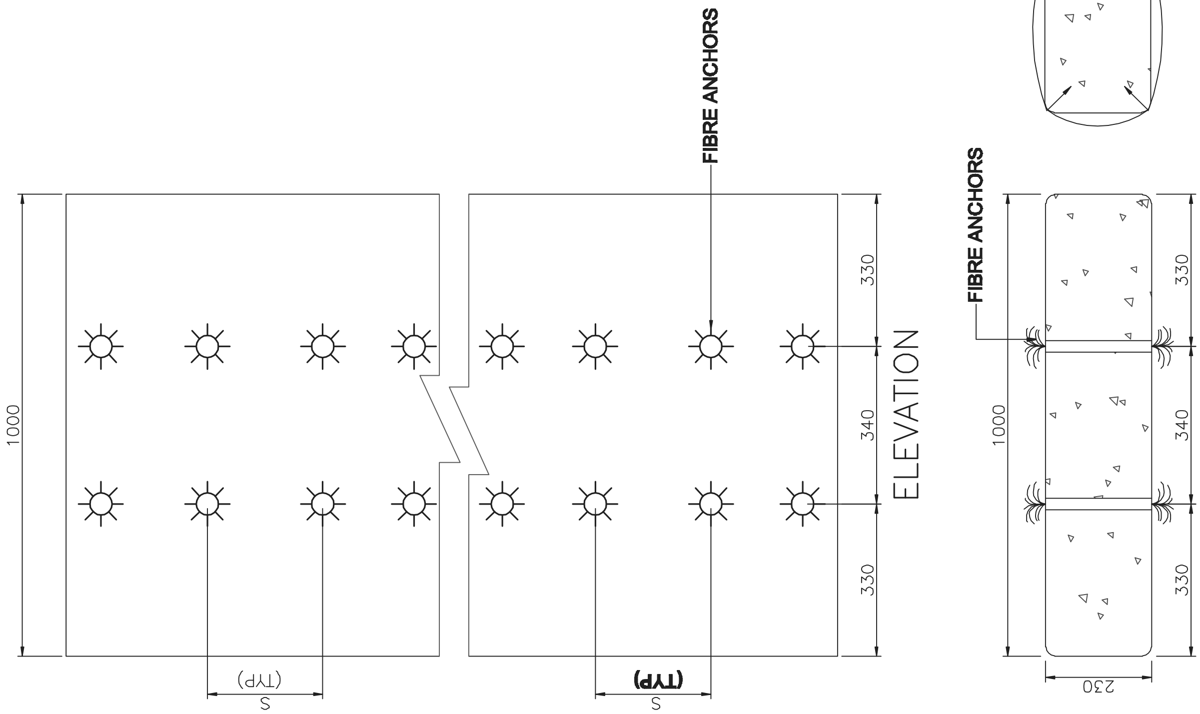



FIG.2

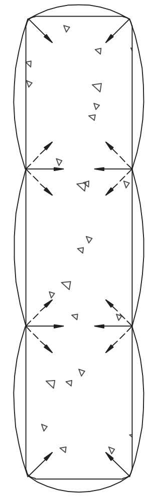


FIG.3

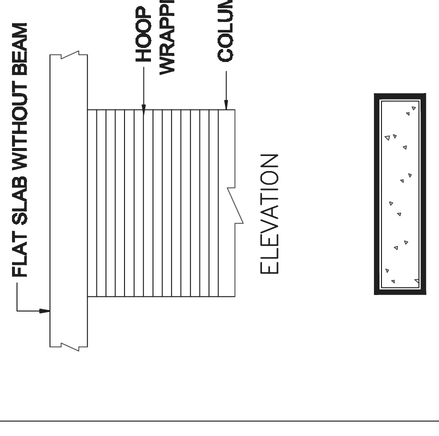



FIG.4a

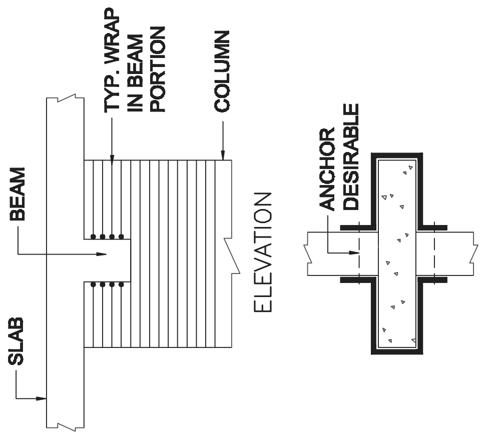



FIG.4b

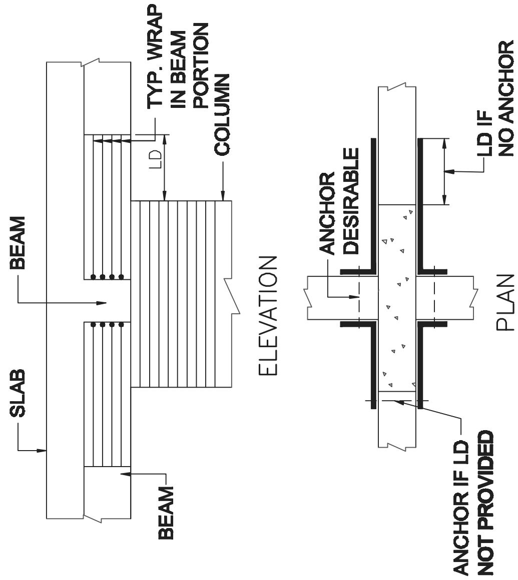



FIG.4c

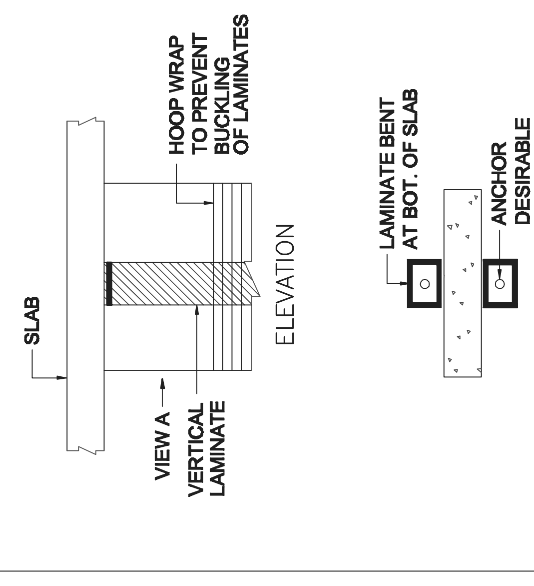
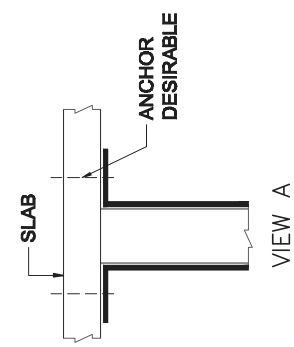



FIG.5a



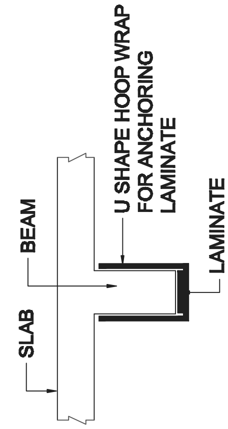




FIG.5b