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Non-laminated FRP Strap Elements for Reinforced Concrete, Timber and Masonry Applications

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ABSTRACT

Advances in material technology allow for the exploration of new structural forms and systems. In recent years, fibre reinforced polymers (FRPs) have emerged as candidate materials for civil engineering applications and the use of FRPs in construction has been an area of growing interest. Unidirectional high strength FRPs are well-suited for use as tensioning elements but anchorage details present a challenge. An alternative is to self-anchor the FRP tensioning element by winding thin layers of material around supports and then laminating all the layers together (a laminated strap) or by securing only the outermost layer to form a closed outer loop while the inner layers remain non-laminated (a non-laminated strap). Non-laminated FRP straps have been found to have higher efficiencies than equivalent laminated straps which is advantageous in high tension applications. The suitability of non-laminated FRP straps for use as unbonded tension elements provides scope for usage in new construction and for the strengthening of existing structures. A review of non-laminated carbon FRP strap system properties and applications in the context of reinforced concrete, timber and masonry structures is presented.

Keywords: fibre reinforced polymers, reinforced concrete, timber, masonry, prestressing

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Introduction

The structural requirements for many civil engineering applications are stringent. In-service conditions can be associated with aggressive exposure conditions and/or high stresses in the structural components. Furthermore, civil engineering applications are often designed with lifetimes of 50-100 years which can only be achieved with, amongst other things, good quality control and durable materials. Over the years, extensive experience has been gained with the use of conventional materials such as concrete, masonry, timber and steel. More recently lightweight, durable, fibre reinforced polymers (FRPs) have emerged as candidate materials either for use in isolation as a structural component, or in conjunction with conventional materials.

Of particular interest in the current work are FRP elements designed to carry significant axial tension. In evaluating FRP materials and systems for high stress applications, a number of characteristics and requirements become evident. Firstly, to achieve a high longitudinal strength and stiffness, a large fibre volume fraction with all, or most, of the fibres running in the longitudinal direction is required. Thus, unidirectional pultrusions with fibre volume fractions exceeding 50-60% are desirable. It is also important to use fibres that have sufficient tensile capacity, have a high resistance to creep rupture and can maintain the required level of stresses over the longer-term without excessive deformation. Secondly, in order to induce the necessary stresses, a means of transferring the force into, and out of, the FRP element is essential. When tensioning prestressed elements, one option is to grip individual FRP rods or laminates using clamping, wedge (see Fig. 1(a)), potted or expansive cement anchorages. The development of reliable long-term gripping systems has been, and continues to be, an area of active research e.g. (Nanni *et al* 1996) but it is a challenge to avoid premature failures in the anchorages. For flat laminates, bolts or pins can be inserted through the holes drilled into the ends of the laminate but the presence of the holes reduces the effective FRP cross-section resulting in a significant loss of strength (Mottram and Turvey 2003).

To avoid many of the problems associated with gripping or drilled anchorage systems, an alternative is to self-anchor the FRP tension element by forming a closed loop or strap. The strap can be produced by winding uni-directional material around two pins and then laminating the strap component (see Fig. 1(b)). The resulting strap represents a versatile component and carbon FRP (CFRP) and glass FRP (GFRP) laminated straps have been successfully used for temporary bridge applications (Bauersfeld 1984) and cryogenic applications (Niemann *et al* 1980). However, one issue is that to form a loop, the fibres need to be curved in some way. As a consequence, in a laminated FRP cross-section with a reasonable thickness, bends introduce undesirable stress concentrations in the FRP when tensioned and lead to a reduction in capacity.

A more efficient self-anchoring tension element can be achieved if the strap layers are non-laminated in the curved regions. Such an element can be manufactured by wrapping layers of thin, flexible, uni-directional FRP tape around supports and anchoring the outermost tape layer to form a closed loop (see Fig. 1(c)). This is the basis for what is described in a 1996 patent application by Meier and Winistörfer as "*a multilayer traction element in the form of a loop to anchor, shear-strengthen, affix and/or keep together construction and machine parts, structural parts, structures and the like, and/or to apply at least one tensile force component, comprising a looping anchor or retaining element*" (Meier and Winistörfer 2001).

In the following, features of non-laminated carbon FRP strap systems are reviewed and the potential for the use of these self-anchored FRP tension elements with a variety of civil engineering materials is discussed.

Laminated and non-laminated strap systems

To highlight the differences in the performance of laminated and non-laminated FRP straps, the influence of lamination will be compared in the context of pin-loaded elements. In a pin-loaded strap, two circular, often steel, pins at either end of the strap are pulled apart to induce tension in the FRP (see Fig. 1(b,c)). However, depending on the application, different support geometries and support materials may be desirable and these aspects will also be considered. It is important to note that it is the combination of the characteristics of the strap and the support that dictate the overall strap system performance.

Performance of laminated straps

In a curved *laminated* strap section, there is a loss of efficiency with increasing thickness due to through-thickness transverse stresses. Based on work on GFRP loops, Conen (1966) combines a plane strain assumption with a thick-walled cylinder analysis to calculate the tensile capacity σ_c of a strap as :

$$\sigma_c = \frac{\varepsilon_{11}\left(\frac{r_o}{r_i}+1\right)}{\left[\left(\frac{r_o}{r_i}\right)^2+1\right]\left(\frac{1-\nu_{13}\cdot\nu_{31}}{E_{11}}\right)+\left[\left(\frac{r_o}{r_i}\right)^2-1\right]\left(\frac{\nu_{31}\cdot\nu_{23}+\nu_{21}}{E_{22}}\right)} \qquad (1)$$

where ε_{11} = the ultimate strain in the fibre direction in the straight legs

r_o = the outer loop radius

r_i = the inner loop radius

$\nu_{13}, \nu_{21}, \nu_{23}, \nu_{31}$ = Poisson's ratios where the first index is associated with the direction of loading and the second denotes the direction of the dimensional change

E_{11}, E_{22} = the Young's modulus of elasticity in the fibre direction, and transverse direction, respectively

If the maximum capacity, $\sigma_{\max}$, is defined as the tensile capacity of a straight section with an equivalent cross-sectional (the area of two loop legs) then for given material properties, the relative efficiency $\sigma_c / \sigma_{\max}$ can be plotted as a function of r_o / r_i where r_i is taken as the pin radius and r_o is then the pin radius plus the laminate thickness. Using the expression in eqn 1, the predicted relationship for a typical carbon fibre material with $E_{11} =$ 121 GPa, $E_{22} =$4.8 GPa, $\nu_{13} =$0.34, $\nu_{21} = \nu_{31}$= 0.014, and $\nu_{23} =$ 0.4 is indicated in Fig. 2(a) where a reduction in efficiency occurs with an increasing r_o / r_i . However, as also shown in Fig. 2(a), Winistörfer (1999) has found that the calculated efficiencies were unconservative when compared with his experimental results on laminated carbon straps. The trend in terms of the reduction in strength with increasing thickness of laminated strap is supported in a review of fibre reinforced composite straps for cryogenic applications. Reed and Golda (1997) make reference to results from a report by Golda, Tannenbaum and Reed where tests were conducted on filament wound straps with either carbon T-700 or T-1000 fibres in an epoxy matrix. The strap thickness, t , was kept constant at 1.9 mm but the spool (pin) diameter, d, was varied to evaluate the dependency on d/t. The results have been replotted in terms of r_o / r_i in Fig. 2 (b) but, as the value for the baseline tensile stress was unclear, the y-axis has not been non-dimensionalised. Depending on the type of fibre, a loss of strength between 25-35% would be expected by increasing r_o / r_i from 1.05 to 1.15.

Performance of non-laminated straps

The issue with laminated straps is the transition from a straight region with an infinite radius of curvature to a profile with a defined curvature. As a result, large stress concentrations are generated. In a *non-laminated* tape system, layers of FRP tape are wrapped around supports. The FRP tape is thin (0.12-0.18mm) and therefore flexible. Tape widths of 5 mm, 12 mm, 30 mm and 50 mm have been used. The tape is supplied as a continuous reel and the number of layers of tape can be tailored to suit particular design requirements. To form a closed strap, the outermost tape layer must either be secured using a clamping system or, in the case of a thermoplastic matrix system, fusion bonded to the next outermost layer. Unless indicated otherwise, all the straps described in the current work were made using thermoplastic tape systems and fusion bonding was selected as the preferred securing method for the outer loop. In the resulting non-laminated strap, the inner layers of tape are not bonded together which allows some relative slip to take place between the layers thereby relieving excessive stresses. However, frictional forces must develop between the layers as otherwise the whole strap would unravel.

To investigate the relative efficiency of non-laminated straps, experiments were conducted on 12 mm wide carbon fibre (Toray T700) tape with a thermoplastic Nylon (PA12) matrix where the number of tape layers were varied (Winistörfer *et al* 2001). A single layer of tape had a thickness of 0.13 mm. The tape layers were wrapped around two circular steel pins and the outer two layers fusion bonded. For the 1, 10, 20 and 30 layer tests, the pin diameter was 30 mm. The pin diameter for the 40, 50, 60 and 70 layer tests was increased to 50 mm in order to sustain the higher forces. In all cases shown, the specimen length was fixed at 700 mm and, with the exception of the 60 and 70 layer tests, where 4 and 2 specimens were tested respectively, 6 or 7 specimens were tested to failure. Taking the baseline efficiency as the failure load of the one layer strap multiplied by the number of layers, an experimental plot of the relative efficiency with increasing r_o / r_i is shown in Fig. 3. While a certain reduction in efficiency was noted with an increasing number of layers, these were less than would be expected in an equivalent laminated loop. In particular, straps with 10, 20, 30 or 40 layers achieved similar efficiencies of approximately 80% that of a single layer strap demonstrating the potential for sustaining high tensile forces in such loop elements.

Further tests have provided insight into the load sharing between the various tape layers where strain gauges were attached to each layer of a 5 or 10-layer CFRP pin-loaded strap (Winistörfer 1999). Although a slightly higher strain (approx. 9%) was noted in the innermost layer of the 10 layer strap, in all other cases, it was found that the strain in each layer was similar suggesting the total load is shared fairly evenly throughout the straight legs of the strap. This also has ramifications in terms of anchoring the outer loop since the clamp or fusion-bond needs only sustain the equivalent of the force carried in one loop.

Although the aligned uni-directional CFRP tape is very strong axially, the material is relatively weak transversely. Tension across the width of the tape in a direction perpendicular to the fibres is sustained primarily by the matrix. This means that care must be taken to ensure any stresses are carried by the fibres in the longitudinal direction.

Supports

The flexible nature of the thin CFRP tape means that it can easily be wound around supports. As will be described in the following, the support systems considered have included circular pins, circular/elliptical support pads and profiles formed in concrete. The required support system will depend on the application. For example, an individually stressed tendon element works well with pin supports but a pad support may be required to encase a structure with a certain width. The main considerations in the selection and design of a support system include the support geometry, the material properties of the support and, although not discussed here, the frictional characteristics of the face in contact with the strap.

Support Geometry

One critical feature of any support system is that there is a minimum radius through which the tape can be curved. Winistörfer (1999) tested the strength of single layer straps with a thickness of 0.18 mm with circular pins of different radii. In Fig. 4, the resulting mean stresses (where each data point is based on 10 tests) on a nylon (PA 12) CFRP tape have been normalized using the average experimental capacity obtained with a pin radius of 75 mm. It appears that, provided the pin has a radius of greater than around 20 mm i.e. $r_i/t \approx 110$, the radius has a relatively minor influence on the strength of the single layer strap. This recommendation has also been supported by non-linear finite element modelling (Winistörfer and Mottram 2001).

This insight has been used in the design of pad supports for straps to enclose the web of reinforced concrete beams (see Fig. 5). To date, steel pads have been successfully used as top and bottom supports for beams ranging from a web width of 105 mm (Kesse and Lees 2007) (see Fig. 5(a)) to 150 mm (Stenger 2003). One approach for the design of these supports has been to fix a circular radius at the end of the pad at 20 mm (in line with Winistörfer's pin-loaded recommendations). The required web width plus a small clearance at each end e.g. 5-7 mm gives the overall pad base dimension and the height of the pad can be selected as appropriate e.g. 40 mm balancing the need to transfer vertical load and any minimum clearance requirements. An ellipse is then fitted to this height and the intersection of the circular and elliptical shapes is calculated to be the point where both the geometric co-ordinates and the tangents to the circle and the ellipse are the same. An example for a beam width of 260 mm is shown in Fig. 5(b). The force transfer from the strap to the pad is greatest in the regions of highest curvatures such as the circular area of the pads. This means that the bearing stress under a pad will not be uniformly distributed. The optimization of pad geometries is an area for future work.

It is important that the support is flat across the width of the strap as curvature in the transverse direction has been found to be detrimental to the strap capacity (Hoult 2005).

Support Pad Materials

As discussed, steel has been used in pin-loaded tests and for support pads. However, non-metallic versions of support pads of the type shown in Fig. 5 have also been developed (Nägeli 2006). Straps consisting of 10 layers of 0.13 mm CFRP tape supported on high density polyethylene (HDPE), GFRP or CFRP prestressed concrete pads have been investigated. Short-term tests to failure (see Fig. 6) and also sustained load tests at 50% of the strap breaking load over time-frames of up to 3 days were conducted. The plastic deformation of the HDPE pads was found to be excessive and made these pads unsuitable both in the short and longer term. Although cracks were also noted in the CFRP prestressed pads, these were fairly thin and not believed to be problematic. The GFRP pads showed promise in terms of structural performance and only a minimal change in deflection was noted in the longer-term tests. These initial results suggest either CFRP prestressed concrete or GFRP support pads could be combined with a CFRP strap to provide a non-metallic tensioned strap system. Additional examples where GFRP pins have been used to tension CFRP straps or where the strap has been supported on profiles formed within the base concrete structure will be presented in subsequent sections.

In summary, the main requirements for a support system are that it is flat across the tape width, has a minimum radius of curvature and has sufficient structural integrity over the long-term to sustain the applied strap forces. The support frictional characteristics will be a consideration in terms of the strap behavior and the stressing procedures.

Non-laminated strap system behavior

As the behaviour of the strap will be a function of the strap, the support and the anchorage, it is important to understand the resulting system performance both during short-term static testing and under high sustained loadings.

Static testing to failure

In a static test to failure, the mechanics of the force transfer around a strap support is complex. As discussed, it appears that as the load increases the inner strap layers tighten against the outer closed loop but then lock. Good quality workmanship is required to ensure the tape layers are aligned since an even support for the layers is important. In a strap load-displacement test, the initial behavior will be a function of how well the strap was made as in the early stage of loading any slack in the system will be taken up. This may be observed as an initial region of lower than expected stiffness (see Fig. 7). Thereafter, the tape layers become taught and the overall strap behavior is fairly linear until failure. The force distribution in the tape layers will vary around the curved supports and this will influence the equivalent unbonded length of the strap and the associated displacement. However, for many pin and pad support systems, provided the relative sizes of the curved support regions are small in comparison with the straight lengths, the equivalent unbonded length can be approximated as the distance between the outer support faces. One beneficial observation is that, at higher loads, small slivers of tape fracture and detach from the strap. Yet the strap will continue to sustain load and the ultimate failure of the strap is fairly gradual. This response therefore gives some warning of pending failure. The non-linear contact mechanics of the load sharing in the tape layers around the support regions requires further study but there is some evidence of fusion bonding of the strap layers in the curved regions due to the high contact stresses developed in the thermoplastic matrix during the later stages of loading. This localized fusion bonding helps to maintain the overall strap integrity. Nevertheless the final failure is brittle and there is only a limited amount of pseudo-ductility. The modulus of elasticity of the strap and the strap failure stress and strain will reflect that of the constituent tape material. Typical measured failure stresses range from 1760 MPa (T-700 with PA 12) to 2550 MPa (Tenax IMS with PEI) with associated Young's moduli of around 138 GPa and 171 GPa respectively.

Long-term testing

Long-term testing of non-laminated straps has been undertaken. Early work suggested that one area requiring careful attention is the fusion-bonded welded joint since a creep failure in this region would lead to failure of the strap. This outcome led to further development and sustained loading tests on pin-loaded straps with improved joints were instigated at the Swiss Federal Laboratories for Materials Testing and Research in 2000 (Winistörfer *et al* 2001). Two 27 layer straps were loaded using dead weights at a stress level equivalent to approx. 90% of the average static strength and, after 9 years, these specimens have not failed. These sustained load tests are ongoing.

Applications

Non-laminated, efficient, high tensile FRP elements have the potential to play a role in a wide range of civil, structural and mechanical applications. These elements could be used as individual stand-alone components e.g. as rock anchors or composite connection rods for pumps or combustion engines (Winistörfer and Mottram 1997) or in conjunction with other structural materials and systems. In 1995, Meier and Winistörfer wrote in the context of CFRP bonded plate systems, "*… even in the distant future CFRP will not replace classical materials such as steel, concrete and wood but rather supplement them as called for*." This remains an important observation in that we must look to take advantage of the properties of any given material to develop advanced systems.

So in the same way that a FRP strap needs to be considered in conjunction with its support system, when used with other construction materials, the interactions between the materials and the combined system performance are important. There is also an opportunity to revisit structural forms that could benefit from the utilisation of high tension FRP straps. The use of CFRP strap elements in combination with reinforced concrete, timber and masonry will be reviewed and research needs highlighted.

Reinforced concrete

The ability to sustain a high tensile stress is a requirement for prestressed concrete applications and a non-laminated CFRP strap is well suited for use as an unbonded tendon. The self-anchoring nature of the strap is an advantage as it avoids the need for a gripping system and, if required, the strap can enclose a cross-section. However, due attention must be paid to both the strap support and tensioning system.

The Young's modulus of elasticity of a typical CFRP non-laminated strap is lower than that of steel which means that, relative to steel tendons, the extensions during stressing will be higher. However, the smaller Young's modulus means that any losses due to concrete creep or shrinkage will be lower. When an unbonded strap encloses a reinforced concrete specimen there will be a 'size' effect since the stress in the strap is a combination of the initial prestress plus an additional strain due to tensile strains, crack opening, or expansion within the base structure that the strap surrounds. This means that for a given crack opening the strain induced in a shorter strap will be higher than in a longer strap. There is also a trade-off between the initial prestress level and the required residual strain capacity. Depending on the application, a lower prestress may result in a lower overall strength enhancement. But then equally too high an initial prestress will leave a smaller reserve strain capacity to accommodate subsequent crack opening or expansion which may result in a premature strap failure. A prestressed strap will act to confine the concrete and provide restoring forces across cracks.

There is potential for the use of non-laminated FRP post-tensioned elements in new construction, but much of the work in the reinforced concrete field has focused on repair and strengthening. Meier (2000) envisaged the use of prestressed FRP straps in bridge repair for '*active shear strengthening, for end anchorage systems of tensioned CFRP strips, for flexural strengthening and for external post-tensioning*'.

Flexure

To date, the research effort devoted to incorporating CFRP strap tensile elements in flexural applications for new and existing concrete structures has been rather limited. However, a recent innovation by Schlaich and Bleicher has been to use non-laminated CFRP straps in the development of a prototype for a stress-ribbon bridge (Schlaich and Bleicher 2007). The 13 m bridge (see Fig. 8) consists of a series 1.53 m × 0.6 m × 0.10 m concrete panels supported on 50 mm wide, 10 layer straps anchored around pin supports at either end of the bridge. The straps were prestressed and the concrete panels were secured to the tendons using flat, glass FRP (GFRP) laminates bolted into the panels. The advantages of using CFRP straps rather than normal structural steel were the high tensile strength and low specific weight which facilitate more elegant and efficient structural forms.

Shear strengthening

Some of the earliest work investigating the use of flexible fibre reinforced materials for reinforced concrete was related to shear strengthening. Meier, Deuring and Meier's 1993 patent application on a "*Method and Apparatus for Increasing the Shear Strength of a Construction Structure*" suggested a system for providing shear strengthening or as an end anchorage system for bonded CFRP flexural plates. The example used was that of a U-system consisting of a resin anchored aramid fabric tube. The strengthening element was formed by threading the fabric tube through slots and around a support on the base of the beam (see Fig. 9). The tube was splayed in conical anchorage regions in the compression zone and was prestressed. Resin adhesive was injected in the conical regions and the stressing system was kept in place until the adhesive hardened. The recognition of the advantages of a flexible system and the benefit of providing a prestressed shear element were critical observations that informed many future studies.

Investigations of non-laminated CFRP strap systems to enhance the strength of reinforced concrete beams have been conducted where the straps were supported on steel pad supports placed on the top and bottom of the beam (for example, Fig. 5(a)). The installation process is shown schematically in Fig. 10. In these studies, layers of tape were wrapped around a reinforced concrete beam to form discrete shear strap elements. The tensioning process consisted of lifting a steel support to induce a prestress in the strap and inserting shims underneath the support to transfer the force to the concrete. In this process it can be difficult to control the prestress in the strap and research on alternative tensioning methods is an area of interest. Although the top pad was placed on the beam surface, in practice, where there is top surface access, a groove could be formed in the cover concrete so the top pad becomes either flush or lower than the concrete surface. A protective topping layer would then be added.

It has been found that an appropriately designed prestressed CFRP strap strengthening system can successfully increase the shear capacity of an existing reinforced concrete structure. The effect of the CFRP strap spacing (Yapa and Lees 2009) and the influence of the strap stiffness, spacing and prestress (Kesse and Lees 2007) on the strengthened behavior of rectangular reinforced concrete beams have been investigated. The strength enhancement of T-beams with top and bottom support pads have also been considered (Lees *et al* 2002). Work by Meier, Marti and Stenger at ETH (Stenger 2000) has demonstrated that for CFRP strap strengthened deep beams, the initial strap prestress force plays a critical role in the level of strength enhancement as a strengthened deep beam with a low prestress had a strength similar to that of an unstrengthened control beam. Of interest, work on smaller scale beams has not shown the initial prestress to be as influential (Kesse and Lees 2007) which demonstrates that there is a size effect associated with the unbonded prestressed system.

Further investigations on reinforced concrete T-beams have been used to assess the potential for using non-laminated CFRP strap systems in slab-on-beam structures without the need for top slab access (Hoult and Lees 2009). In this system, holes were drilled from underneath the flange of the T-beam and a curved slot was grouted in to the hole. The CFRP tape was threaded through this slot and around a support pad on the base of the beam thereby encasing the beam web. The main variables in this study were the influence of the installation technique and the depth of strap penetration into the flange. If the straps did not penetrate sufficiently into the flange, shear cracks propagated above the straps and the level of strength enhancement was compromised. However, if the straps extended well into the compression zone, the strengthening technique was found to be effective.

An alternative shear strengthening system that is being considered for a concrete box girder bridge in Switzerland uses a non-laminated CFRP pin-loaded strap supported on concrete saddles (Czaderski *et al* 2008). One advantage is that the tendons can be prefabricated and brought to site. Tensioning is achieved by pulling the pins together (see Fig. 11). Work to investigate frictional losses around the concrete saddles during stressing has been carried out and the resulting stress distribution was deemed to be acceptable.

Many of the CFRP shear strengthening tests undertaken have been static tests to failure. While this provides very valuable information about the concrete/CFRP strap system performance it is necessary to also consider the behaviour over the longer-term. Initial longer-term sustained load and cyclic tests (Hoult and Lees 2005) have suggested that the strap strain will increase with time due to the creep of the concrete. Thus, it is important to take into account the longer term behavior when selecting the level of design prestress and to make due allowance for the interactions between the CFRP strap and the base structure.

In general, more practical and efficient strap tensioning and installation methods are required for certain applications. There is also further scope for profiling the base concrete structure to support the straps and/or the development of completely non-metallic pad support systems. These features, when combined with the CFRP straps, will result in a durable strengthening alternative to steel.

Column strengthening

In the shear strengthening applications described in the previous section, the non-laminated straps have been considered as discrete elements located at set spacings. However, the straps can also be considered in the context of a more ‘continuous’ system, albeit they may not be self-anchored.

Non-laminated CFRP tapes have also been used to strengthen square 400 mm × 400 mm reinforced concrete columns (Pfyl-Lang *et al* 2008). Two hoses that ran vertically from the base to the top were placed on the sides of the column. Two wraps of 30 mm wide layers of CFRP tape with an overlap of 20 mm were then wound around the perimeter encasing the column and the hoses. The tape was fixed to the concrete at either end of the column using an epoxy resin. Pressurised mortar was injected into the hoses causing expansion and inducing prestress in the straps (see Fig. 12). When compared to either an unstrengthened control column or an equivalent column with non-prestressed straps, the increase in ultimate axial load capacity was fairly modest. However, unlike the control specimen that failed after reaching the peak compressive strength, significant post-peak deformations were noted in the two columns strengthened with CFRP, indicating an improved deformation capacity. The final failure of the column with prestressed CFRP straps was associated with a lower deformation than the non-prestressed case, which further demonstrates the connection between the initial prestress level and the residual strain capacity. This interaction has also been observed in uni-axial compression tests on 150 mm × 600 mm concrete cylinders wrapped with either unstressed or prestressed non-laminated CFRP tape (Janke *et al* 2009).

One challenge with any concrete application is that many characteristics of conventional reinforced concrete behaviour are still not fully understood and the inclusion of prestressed FRP elements introduces an additional complication. Initial predictive models have been proposed for aspects of the strengthened behavior but in general further work is required to extend and validate analytical and design approaches for shear, axial and flexural cases.

Timber

Timber is an anisotropic composite material with a relatively low Young's modulus of elasticity, *E,* so is often stiffness dominated. The use on an unbonded strap in conjunction with timber therefore has the advantage that the CFRP can be prestressed to provide additional stiffness. Furthermore, since the number of tape layers can be varied, the strap area *A* can be readily adjusted and the axial strap stiffness *EA* can be selected to meet a variety of requirements. Another feature of timber is that it is hygroscopic and so will expand or contract in response to the equilibrium temperature and humidity of the surroundings. So the ability of an unbonded strap to accommodate dimensional changes without inducing significant changes of stress in either the CFRP strap or timber is also beneficial. The bearing strength of timber is relatively low and the strength of a dowel or bolt connection will depend on the grain direction. Care must be taken in the load transfer regions between the CFRP strap and the timber to avoid local failures in the timber.

In new construction, the availability of high strength durable FRP tension elements has provided an opportunity to revisit structural forms that incorporate stressed tension elements. One such example is the bowstring arch where the CFRP strap can be used as the tension tie. Based on the conceptual vision of U. Meier, a 12 m long, 3 m wide bridge with a glulam timber deck and longitudinal CFRP tension ties (see Fig. 13) was constructed in Dubendorf, Switzerland in 2007 (Brönnimann and Widmann 2009). The main CFRP tensioning elements were secured to the deck using GFRP pins and provide stiffness to the structure. The resulting form is very slender as the deck thickness is only 160 mm. The deck was also stressed transversely using tensioned CFRP straps.

CFRP straps have also been used to strengthen historic timber roof structures. For such applications, the aesthetic, low impact and reversible nature of the CFRP strap system are particularly desirable. The light weight and ease of installation are further benefits. *Laminated* CFRP straps were used to provide bracing to strengthen Frauenkirche Meissen in Germany (Meier 2001) but more recently *non-laminated* straps have been used as additional stiffening elements in St Marien’s Church in Germany (Huster *et al* 2008). Although stainless steel was considered for St Marien’s, the higher thermal expansion and relative stiffness would attract significantly higher loads than the CFRP strap solution and these forces would have been in turn transferred to the timber resulting in a less desirable strengthening system.

Masonry

Masonry structures consist of individual block or brick units with defined joints. Prestressing can therefore be used either to delay or prevent cracking and/or to increase the stability of the masonry structure either in new construction or in strengthening applications. The strengthening of historical masonry structures is an area with potential for post-tensioned FRPs more generally. The drivers are similar to those associated with historical timber structures; durability, limited visual impact, low thermal stresses and the fact that the intervention can be reversible (Triantafillou and Fardis 1997). Seismic upgrading is another field where unbonded post-tensioning can play a role and post-tensioned non-laminated CFRP straps have been used for the seismic strengthening of a brickwork wall (see Fig. 14). In this application, each strap was secured at the dead end using a pin support that was bolted to the concrete foundation as shown in Fig. 14(c). A strap was tensioned with a hydraulic jack that lifted a link plate (see Fig. 14(b)) which was attached to the live end strap pin support (not shown). Shims were then inserted underneath bearing plates to transfer the strap prestress to the structure.

General and further considerations

There are a number of considerations that are common across applications. The CFRP straps have a high strength to weight ratio which results in fairly thin structural elements. As a consequence the system is aesthetically pleasing when compared to bulkier metallic solutions. In addition, the fatigue performance of CFRP is generally very good which presents an advantage over steel in high stress applications. In many of the applications presented, the CFRP tension elements are potentially exposed to external environments where excellent durability characteristics are paramount.

The CFRP straps are unbonded, which means that in most cases they can be fairly easily inspected, and provision can be made for future replacement. However, the drawback is that they can be susceptible to vandalism and due care needs to be made to protect and/or limit access to the tension elements.

The fire resistance of any FRP system is an important consideration and of particular concern in building applications. For strengthening applications, a core principle posited by Meier (1995) is that the design strengthened capacity should not exceed 50% that of the unstrengthened and that should the strengthening system fail, the base structure should retain a residual safety factor of 1.2. This may have parallels in fire design where the reliance on the FRP should take into account conditions where the capacity of the strengthening system is reduced due to fire. Related aspects such as the spread of fumes also need to be considered. An alternative is to provide fire protection. The area of the fire resistance of FRP structural systems requires further research.

Non-laminated thermoplastic straps rely on the integrity of the fusion bonded joint. The lamination of the straight legs of the strap while leaving the curved support regions non-laminated would reduce reliance on the joint region.

Conclusions

A CFRP strap represents a versatile, durable, lightweight, self-anchoring tension element. When the strap is non-laminated, higher efficiencies can be achieved due to a reduction in the stress concentrations in bend regions. Non-laminated prestressed CFRP strap elements have a wide range of uses in combination with reinforced concrete, timber and masonry structures. As noted in an article on bridge engineering, "*Modern materials will not only increase in significance as a result of the requirements of innovative bridge construction; they will also themselves become a catalyst for innovation*." (Meier 1992). This has already proved to be the case with the development of slender CFRP/concrete stressed ribbon and CFRP/timber bowstring arch bridges as new structural systems. It is expected that future strengthening applications will encompass historical structures and also more modern structures required to sustain increased loading. However, with any application it is important to understand the fundamental behaviour of both the conventional and the FRP elements in order to develop innovative systems which take full advantage of the potential synergies between the component materials.

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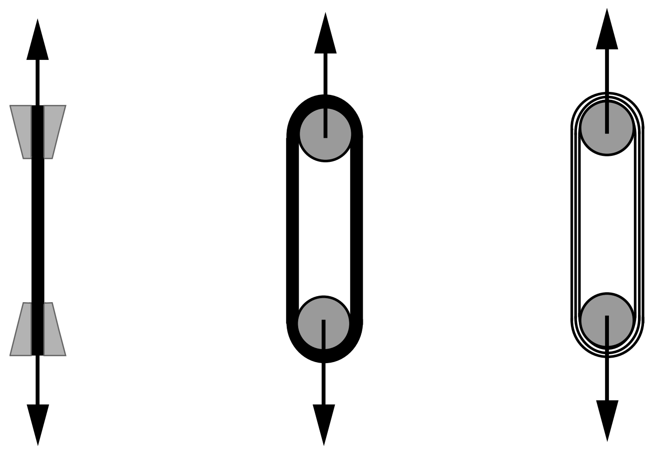
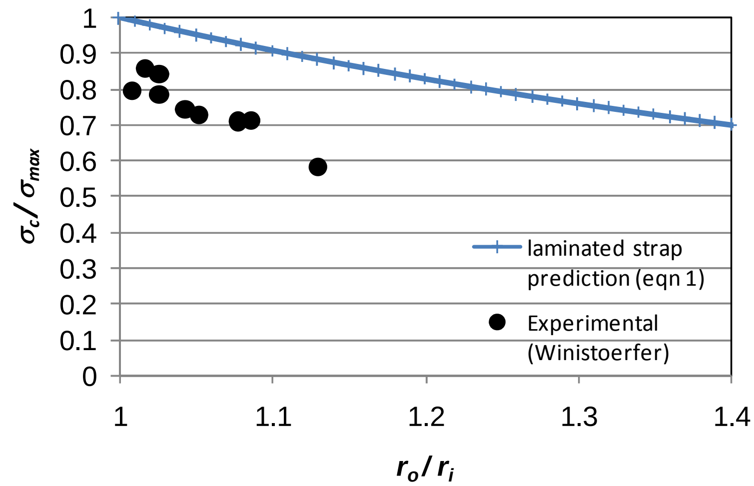
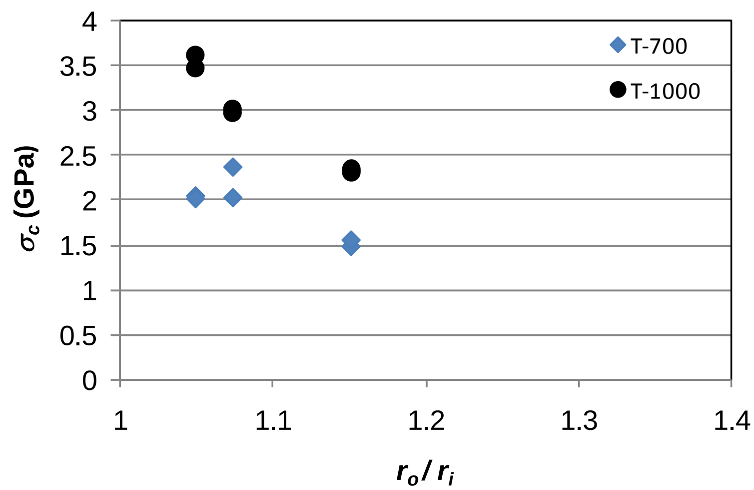


(a) (b) (c)

Figure 1. Schematic diagram of (a) straight rod or laminate (b) pin-loaded laminated loop and (c) fusion-bonded pin-loaded non-laminated loop



(a)



(b)

Figure 2. Comparison of thickness effects for laminated straps (a) theoretical prediction using eqn 1 and experimental results from Winistörfer 1999 and (b) experimental results reported in Reed and Golda, 1997.

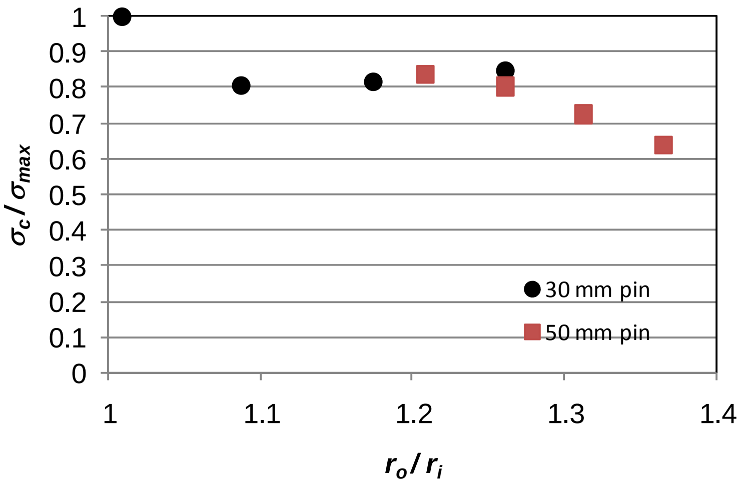


Figure 3. Non-laminated pin-loaded strap experimental results (Winistörfer *et al* 2001)

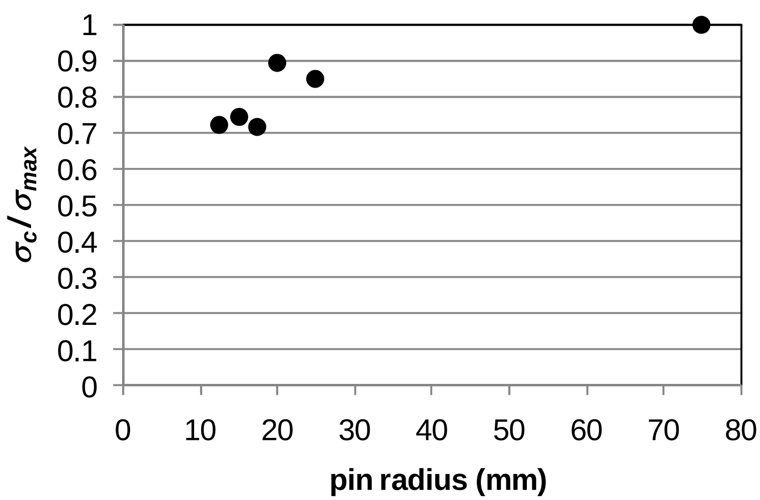
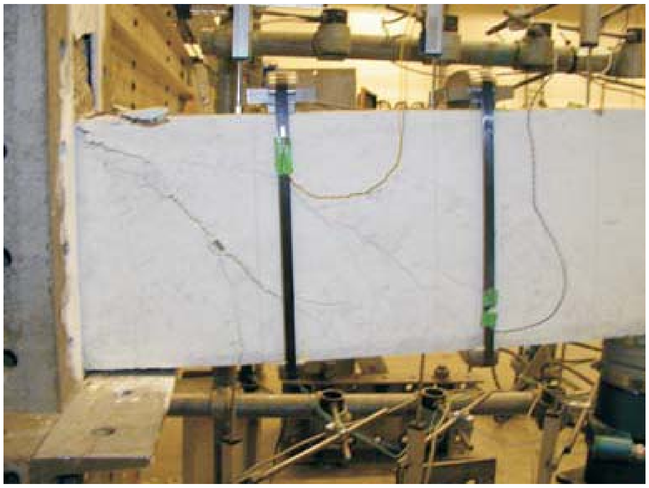
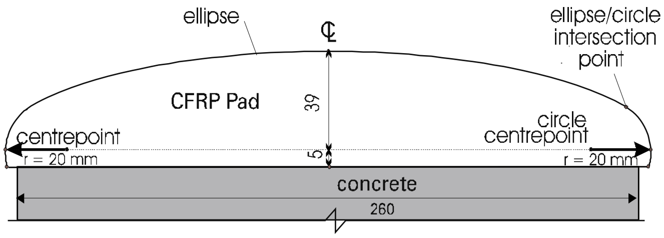


Figure 4. Comparison of strength of single layer strap relative to pin radius (Winistörfer 1999)



(a)



(b)

Figure 5. (a) Photo of 150 mm wide concrete beam with top and bottom steel support pads and (b) possible support pad geometry for 260 mm wide beam

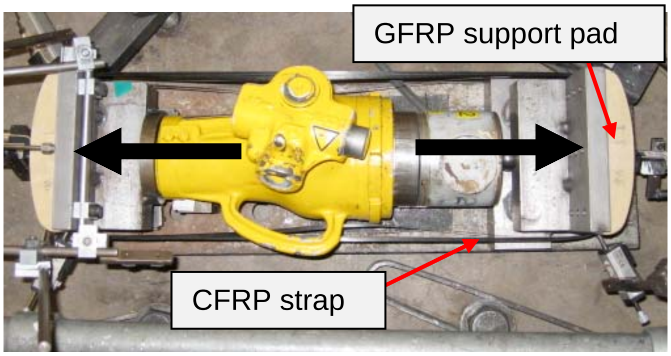


Figure 6. Testing of strap and GFRP pad support system

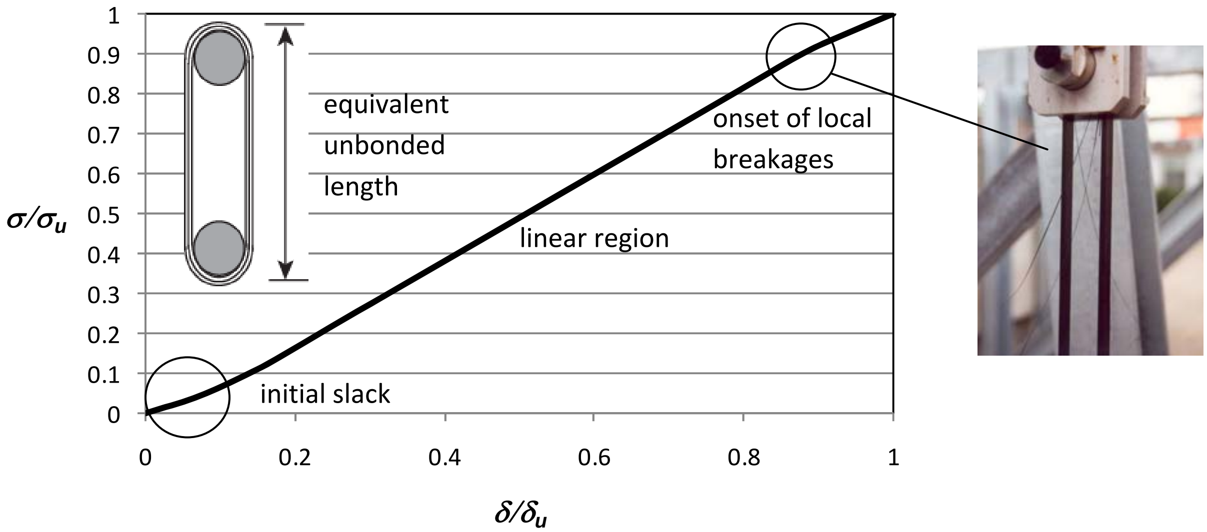


Figure 7. – Schematic strap load-displacement behaviour

(a) (b)

Figure 8. Stressed ribbon bridge (a) view from underneath the bridge (b) anchorage detail

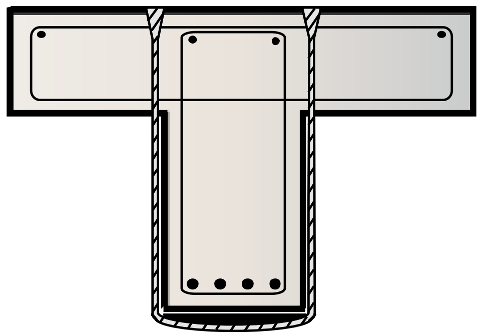


Figure 9. Shear strengthened T-beam (*after* Meier *et al*, 1997)

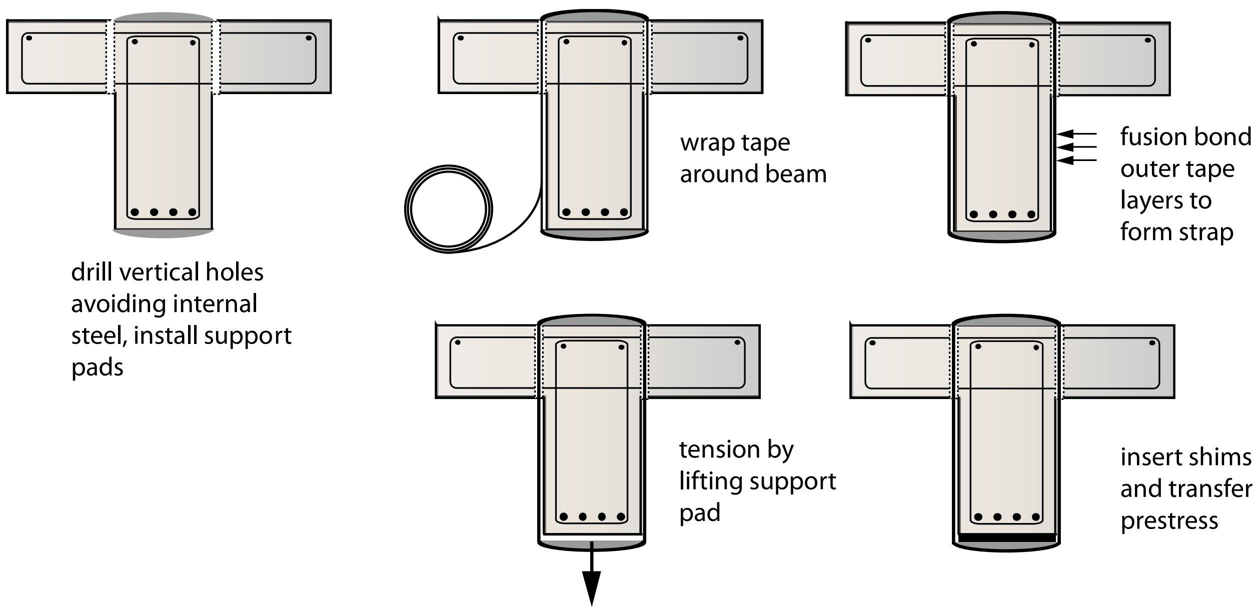


Figure 10. Schematic diagram of reinforced concrete web prestressing

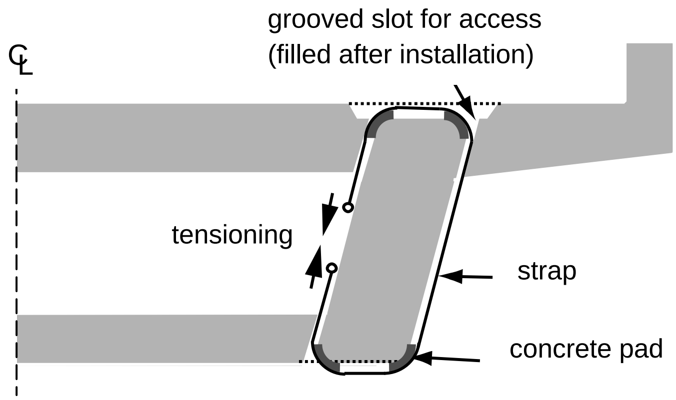


Figure 11. Strengthened box girder section *after* (Czaderski *et al* 2008)

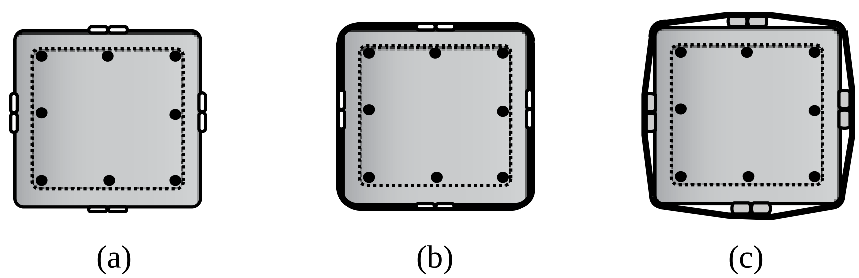
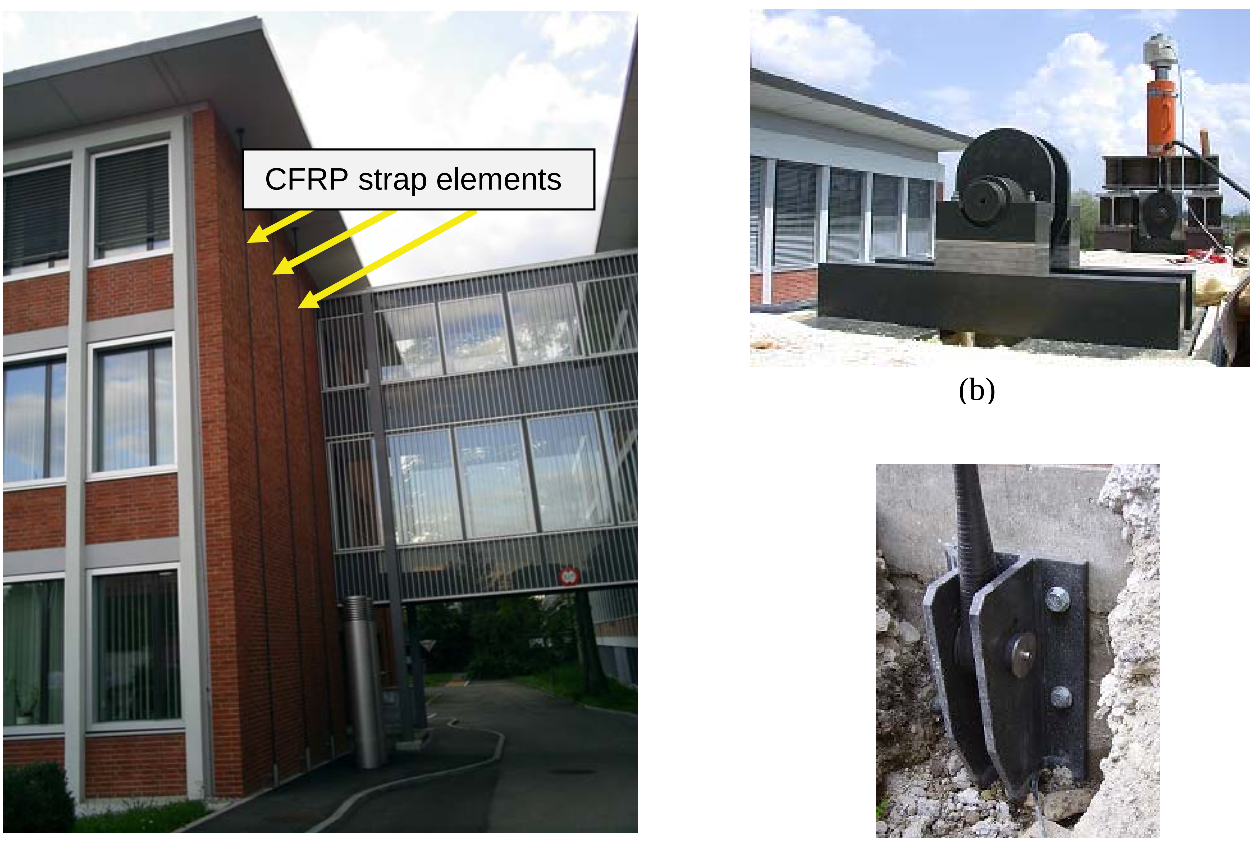


Figure 12. Schematic sequence for installation of continuous strap column strengthening system (a) base column with hoses on surface (b) section wrapped with CFRP straps and (c) prestressing of strap by injecting mortar into hoses

(a) (b)

Figure 13. CFRP/Glulam bowstring arch bridge (a) elevation and (b) tension tie anchorage detail



(a) (b) (c)

Figure 14. (a) CFRP strengthened masonry wall (b) tensioning system (c) dead end anchorage