An Economical Solution for Strengthening Concrete Columns

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Reinforced concrete columns in many older buildings may require strengthening. This need could arise from a variety of conditions. In warm and humid coastal regions and aggressive environments, the corrosion of reinforcing steel results in loss of capacity of the columns. In other cases, poor quality control during the original construction may result in low compressive strength in the concrete and reduced capacity of the column. The author has been personally involved with the retrofit of two such buildings in Florida, where the concrete compressive strength has been below 1500 psi, only a fraction of the strength specified in the design documents. Some of the investigations following the collapse of the Champlain Tower in Surfside, Florida have also mentioned the weak and “powder-like” concrete in the columns as a potential contributing factor to that failure.

Another situation could be the result of changes in use and/or design philosophies and codes. Before the late 1970s, for example, concrete frames were commonly designed with the beams being stronger than the columns. When such frames are subjected to lateral forces during an earthquake, plastic hinges can form at the ends of the columns. In the worst case of weak columns, flexural yielding can occur at both ends of all columns in a given story, leading to the column sway mechanism and collapse of the building. This is shown with the dashed line in Figure 1. In contrast, when the flexural capacity of the columns exceeds that of the beams, the failure of the frame is more ductile (beam sway mechanism), as shown with the solid line in Figure 1. A large number of plastic hinges that can form at the ends of the beams dissipate significant energy, leading to a more desirable ductile failure. In 1983, in recognition of this behavior, ACI-318 required the ratio of the sum of the flexural capacities of the columns to those of the beams to be larger than 1.2. It is well recognized that keeping this ratio even larger than this specified minimum improves the frame’s overall performance.

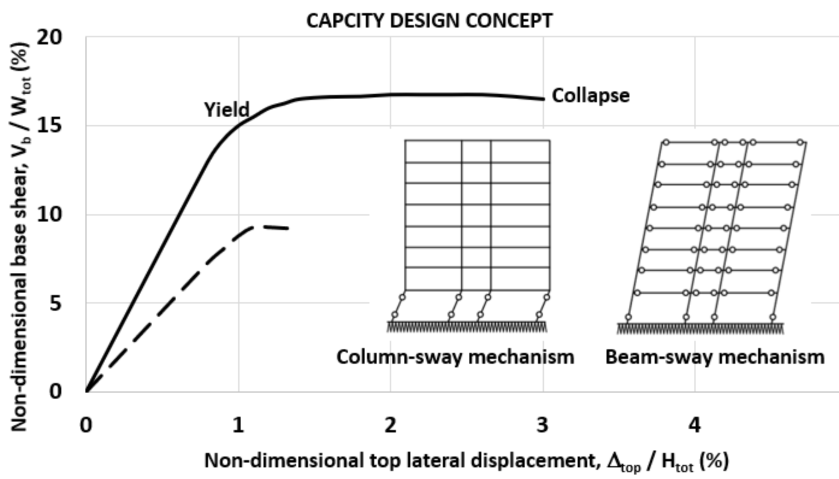

Fig. 1. Capacity design concept

Many older buildings in seismic regions constructed prior to the early 1980s fail this test and have been designated non-ductile structures. For example, in Los Angeles, over 1300 buildings are the subject of an ordinance called *Mandatory Earthquake Hazard Reduction in Existing Non-Ductile*

Concrete Buildings. These building owners must retrofit their structures and address these shortcomings over a 25-year time period that began in 2017.

This article provides a new proprietary solution for enhancing both the axial and flexural capacity of such columns. As detailed below, implementing the technique is relatively easy, leading to a fast and economical solution with minimal disruption to the occupants. An additional feature of the repair is its small footprint, which minimizes floor space loss due to such modifications.

Conventional FRP Solutions

The author introduced the concept of repair and strengthening of structures with Fiber Reinforced Polymer (FRP) products in the late 1980s (Saadatmanesh and Ehsani 1990). In that original approach, known as a wet layup, sheets of carbon or glass fabric are saturated in the field with epoxy. They are bonded to the external surface of the structural element, such as beams, columns, and walls. Within several hours, the materials harden and reach a strength 2 to 3 times that of steel. The FRP serves as additional tension reinforcement that can contribute to the flexural and shear resistance of the host structure. Numerous applications of this system over the past three decades attest to the advantages of these products.

In strengthening columns, the FRP fabrics wrapped around the column, confine the concrete and can increase its compressive strength. This results in an increase in the axial capacity of the column. While the technique is efficient for circular columns, the gain in axial capacity for rectangular columns is limited. For the reasons cited below, the benefits for enhancement in flexural capacity of columns is even more scant.

Applications of wet layup FRP for flexural strengthening of beams are fairly common. In such cases, the maximum moment is typically at midspan, and there is sufficient distance to the end of the span to develop the full capacity of the FRP. On the other hand, applications of wet layup FRP in columns have been chiefly for confinement and shear strengthening. The maximum bending moments in columns occur at the floor levels. Because FRP cannot be easily extended through the floors, it is difficult to achieve significant axial and flexural enhancement of columns with these products. Furthermore, externally bonded FRP does not increase the stiffness of the column that much. This contrasts with the strengthening of beams, where there is appreciable gain in stiffness of the member after FRP is applied. These shortcomings can be overcome using relatively new FRP laminates.

Fig. 2. PileMedic® laminates coiled in 4-foot-wide rolls for shipment.

New PileMedic® FRP Laminates

Over a decade ago, the author introduced a new type of FRP laminate with applications in strengthening columns or piles and pipes (Ehsani 2010). PileMedic® laminates are constructed with specially designed equipment. Sheets of carbon or glass fabric up to 9 feet wide (2.7m) are saturated with resin and passed through a press that applies uniform heat and pressure to produce the laminate (*Figure 2*). The laminates offer several significant advantages compared to the fabrics used in wet layup applications, as listed below:

a) Using a combination of unidirectional and/or biaxial fabrics, the laminates provide strength in both longitudinal and transverse directions; the tensile strength of these laminates can reach 155 ksi (1070 MPa).

b) The laminates can be made as thin as 0.03 inches (0.76 mm); this allows them to be bent around a corner with a radius of 2 inches (50 mm).

c) The laminates are manufactured in plants under high-quality control standards; this improves the quality of the finished construction.

d) The strength of the laminates can be tested *before* installation; this assures the design engineer that the specified strength is met, eliminating delays for corrective actions.

e) The repairs can be completed much faster in the field.

f) The number and pattern of the layers of fabrics in the laminates can be adjusted to produce an endless array of customized products that can significantly save construction time and money.

g) PileMedic® laminates are used to build a structural stay-in-place form around the column, creating an annular space that can be filled with concrete and reinforcing bars.

Since the introduction of this system, many agencies have conducted independent tests to verify the efficacy of these laminates for a range of applications. These include a study funded by NSF and Caltrans for fast repair of earthquake-damaged bridge piers (Yang, et al. 2015), a study funded by the Nebraska Department of Roads for strengthening deteriorated timber bridge piles (Gull, et al. 2015), and another funded by Texas DOT for the repair of corrosion-damaged steel H piles (Dawood, et al. 2015). The most significant investigation was a 3-year study by the U.S. Army Corps of Engineers, which resulted in the military selecting PileMedic® to repair submerged piles worldwide (Hammons, et al. 2018). This article on the U.S. Navy's website shows that PileMedic® was used to repair concrete piles in Ukraine (www.tinyurl.com/PLM-UKR). The U.S. Army Corps of Engineers and the Federal Emergency Management Administration (FEMA) have also singled out PileMedic® as the selected product for repairing columns and piles that may be damaged in a disaster, including hurricane, earthquake, terrorism, and more in their 2013 *Field Operations Guide*.

A proprietary system has been developed to use PileMedic® laminates to construct a shell around the column to create a small annular distance. Reinforcing bars can be placed within this cavity before filling with concrete or grout (Ehsani 2018). The jacket serves as a stay-in-place form that facilitates the construction process and provides significant shear reinforcement and confinement for the column.

Design Example

The following example is provided to illustrate the application of this technique for retrofit of non-ductile frames or columns with low axial capacity. The existing frame (*Figure 3*) consists of an 18x18 inch (457x457 mm) square column, reinforced with eight No. 8 (25 mm) bars. Lateral reinforcement is No. 4 (12 mm) at a 12-inch. (300 mm) spacing along the column height. For simplicity, it is assumed that beams in both directions are 14 inches wide x 26 inches high (355 x 660 mm), and they are reinforced with a pair of #10 (32 mm) bars at the top and bottom. Concrete compressive strength is 4000 psi (27.6 MPa), and steel reinforcement is Grade 60 (414 MPa).

The nominal moment capacity of the column is M_{col} = 219 k-ft (297 kNm), and for the beams is

M_{beam} = 276 k-ft (374 kNm). Therefore, the flexural strength ratio, M_R, can be checked as:

$$M_R = \frac{2M_{col}}{2M_{beam}} = 0.79 < 1.2$$

This ratio does not meet the minimum value of 1.2 set by today’s standards and requires flexural strengthening of the column. Two retrofit alternatives are presented here. In both cases, the corners of the column that do not include any reinforcing steel can be easily cut and removed to minimize the enlargement of the column and loss of floor space. Two new No. 8 (25 mm) bars can be placed at each corner, and these bars extend to the floor above through the slab. Plastic spacers are attached on the column to define the annular space.

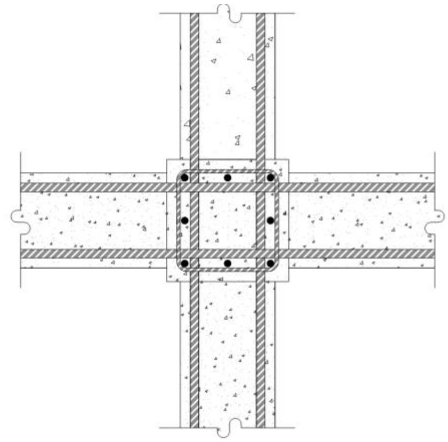

Fig. 3. Original column and beams

PileMedic® laminates are typically supplied in 4-foot-wide (1.2 m) rolls to any desired length (*Figure 2*). Wider rolls are also available. These laminates are 2 to 3 times stronger than steel. Typical detail requires the laminate to be wrapped two complete turns plus an 8-inch (200 mm) overlap around the column (Figure 4). The laminate is cut to the desired length, and an epoxy paste is applied; the laminate is wrapped around the column and bonded to itself to create a 2-ply shell at a distance of 1 to 2 inches (25 to 50 mm) from the face of the column (Figure 4). Additional 4-foot laminates are similarly installed and overlap the previous shell by 3 to 4 inches (75 to 100 mm) to cover the full height of the column (Figure 5). Finally, the annular space between the column and the PileMedic® jacket is filled with concrete or grout using a pump or the tremie method. As shown below, not only PileMedic® laminates expedite the construction as stay-in-place forms, they provide significant strength and ductility for the retrofitted column.

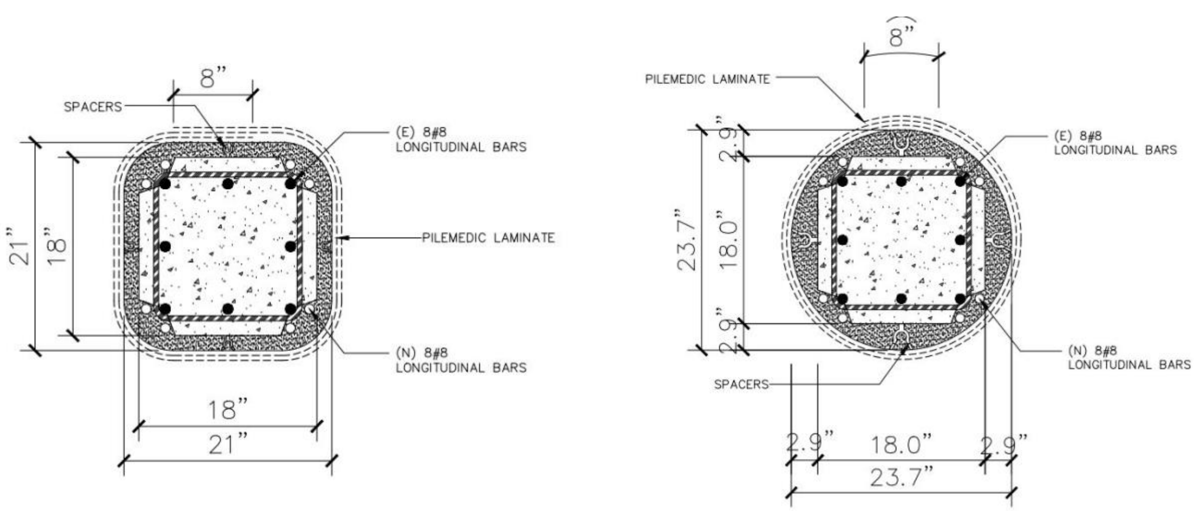

Fig. 4. Retrofit options 1 and 2.

Retrofit Option 1 - In this case, the 18x18 in. (460x460 mm) column is enlarged to a 21x21 in. (533x533 mm) square column. A biaxial glass FRP laminate is used to create a 2-ply shell around the column.

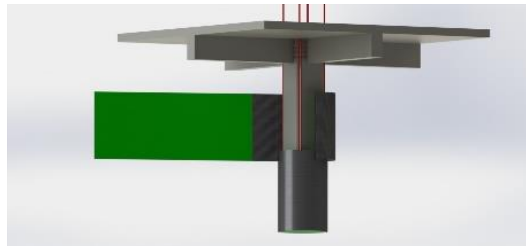

Fig. 5. Installation of laminates around the column to create a shell

Due to the inefficiency caused by corners and flat sides, confinement of rectangular columns to increase the compressive strength of the concrete is hard to achieve. For this reason, in this first option, we will keep the rectangular geometry of the original column since our focus is to primarily increase the column's *flexural* capacity. The shell around the column is made with two plies of PileMedic® glass laminate which represents the minimum number of layers for such applications.

The interaction diagram for the retrofitted column has been calculated and is shown in solid red line in *Figure 6*, assuming the grout strength is also 4000 psi (27 MPa). The axial capacity of the column has increased by 51% from 1460 kips (6500 kN) to 2215 kips (9850 kN). The flexural capacity has also been increased by 220% from 215 k-ft (291 kNm) to 485 k-ft (657 kNm). Therefore, the flexural strength ratio for the retrofitted frame is:

$$M_R = \frac{2M_{col}}{2M_{beam}} = 1.76 > 1.2$$

This is significantly larger than the minimum value of 1.2 and ensures that any plastic deformations are concentrated at the beam ends.

Retrofit Option 2 - If in addition to flexural capacity enhancement, a significantly higher increase in the *axial* capacity of the column is also desired, it is best to alter the column into a circular section. Since confinement is a function of the stiffness of the jacket, we can use a carbon laminate instead of the glass laminate used previously. A circle with a diameter of 21.7 in. (550 mm) has the same area as the 21x21 in. (533x533 mm) square column used in Option 1, i.e. the footprint of the repair for both options is the same. However, the combination of circular geometry and wrapping with the stiffer and stronger carbon laminate results in significant increase in the compressive strength of the *original concrete* and the *newly placed concrete* in the annular space. ACI 440 provides guidelines for quantifying this gain and for this example, the confined concrete reaches a compressive strength of 5150 psi (35.5 MPa).

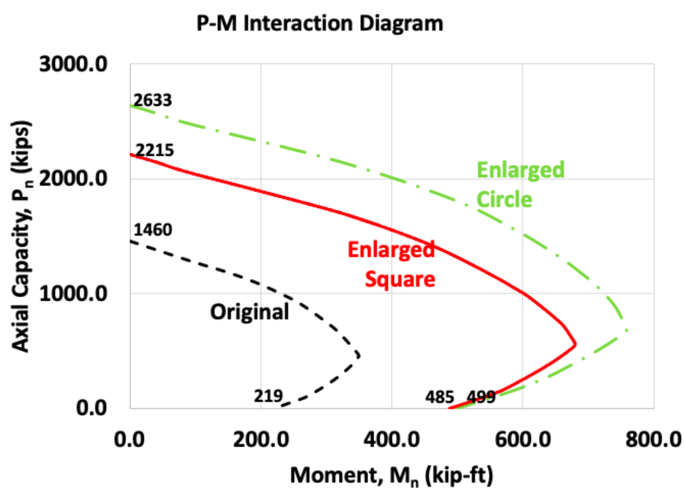

Fig. 6. Interaction diagram for the original and retrofitted columns.

Compressive strength of concrete does not affect the flexural strength of the column significantly. In this case, the retrofitted column has a flexural capacity of M_n = 499 k-ft (676 kNm), which is slightly higher than the first retrofit option. However, as shown in the interaction diagram (Fig. 6), the axial capacity of the confined column increases greatly. In this case, an 80% increase from the original column, and a 19% increase when compared to the retrofit using a square shell of the same size with glass laminate is achieved. Clearly, this option is preferred when the gain in axial capacity of the column is also desired. For example, this could be the preferred retrofit method when due to construction errors the compressive strength in the column is lower than the specified value. A summary of these retrofit alternatives is presented in Table 1.

Spacers - For creating the shell around the column, spacers have been developed that ensure the proper width of the annular space. These can also hold the longitudinal column bars in the desired location (Figure 7).

Table 1. Comparison of the two retrofit options.

	Retrofit Option 1	*Retrofit Option 2*
Laminate type	*PLG14.13*	*PLC150.10*
Laminate construction	*Biaxial Glass*	*Unidirectional Carbon*
Tensile Strength (ksi)	*28.7*	*156*
Tensile Modulus (ksi)	*2,840*	*13,800*
# of plies in wrap	*2*	*2*
Equivalent lateral tie	*#4 Gr. 40 @3.7 in.*	*#4 Gr. 40 @1.0 in.*
Original column f'c (psi)	*4,000*	*4,000*
Enlarged Shape	*21"x21" Square*	*23.7" Round*
Enlarged Area (in.^{2})	*441*	*441*
Confined f'cc (psi)	*4,000*	*5,150*
P_n (kips)	*2,215*	*2,633*
M_n (k-ft)	*485*	*499*

Lateral Ties - The jackets also act as supplementary steel ties, which is a shortcoming in many older or corrosion-damaged columns. Eliminating the need for ties around the longitudinal bars is a great advantage of the proposed solution that results in significant ease of construction. ACI 440 provides environmental reduction factors for FRP based on the use conditions, such as exterior vs. interior installation and the type of fibers used, carbon vs. glass, etc. Including these reduction factors, the equivalency of these laminates as ties is listed in Table 1. The glass laminate is equivalent to providing No. 4 (12 mm) Grade 40 (275 MPa) ties at a spacing of 3.7 in. (94 mm) while the carbon laminate is equivalent to No. 4 ties at a spacing of 1.0 in. (25 mm). In both cases, these values exceed what the current codes require.

Fig. 7. Samples of spacers that can be used to form the shell and position the longitudinal bars

Corrosion Protection - Corrosion of reinforcing bars is a major concern in aggressive environments such as wastewater facilities, mines, coastal regions, etc. The system presented here provides an impervious jacket around the column that prevents ingress of moisture and oxygen. Oxygen is the fuel to the corrosion process. By depriving the column from exposure to moisture, the corrosion rate is drastically reduced, resulting in a long service life for the repaired column.

Joint Region – The retrofit of the frame, in particular in seismic regions, requires attention to the beam-column joint region as well. One option is to epoxy anchor steel ties into the core of the column to provide support against buckling for the newly installed longitudinal column bars (Figure 8). This region can subsequently be encased in concrete with additional reinforcement. Such enlargements are typically within the depth of the beam and can remain invisible above the ceiling. An earlier study by the author has demonstrated that as the flexural strength ratio increases, the required lateral ties in the joint region may be relaxed (Ehsani and Wight 1990). Thus, the flexural strengthening of the column may result in easier retrofit for the joint.

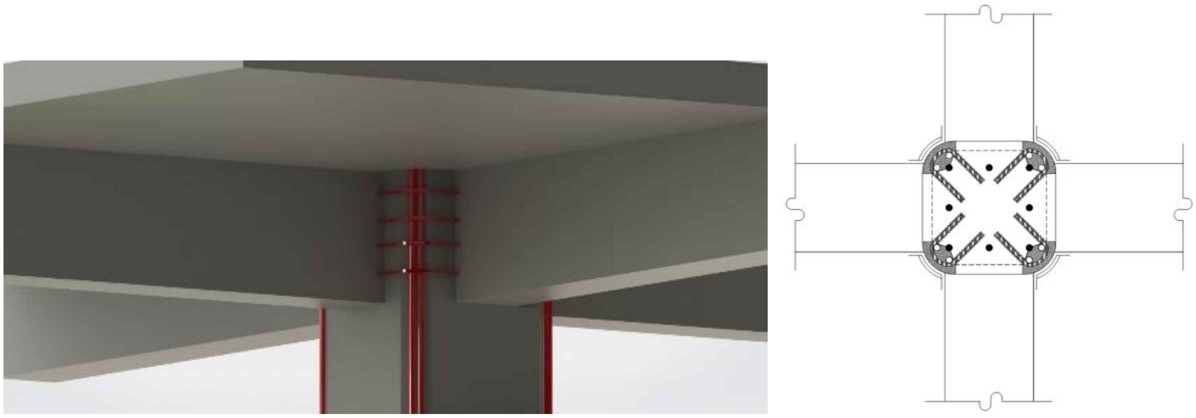

Figure 8. Details of lateral ties for the longitudinal bars within the depth of the beam

Footprint - The footprint of the proposed retrofit is very small. In this example, the column cross sectional area was increased by 36% for both the square and circular alternatives, while the flexural capacity of the column was more than doubled.

Lower Construction Cost - The PileMedic® retrofit solution presented here has many inherent advantages compared to conventional repairs that lead to significant cost savings. For example, the entire system is comprised of lightweight materials that can be taken to any floor of the building using passenger elevators. Handling of the laminates to wrap them around the column requires no heavy lifting equipment either. The adjustability of the jacket size in the field leads to a smaller footprint and eliminates construction delays due to shipping the wrong size formwork to the site. The strength of the laminate that eliminates steel ties results in faster and less costly repairs. Lastly, the impervious shells will permanently protect the host column from corrosion and chemical attack. The estimated cost to retrofit a typical column is well below $10,000.

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