STRENGTHENING OF CONCRETE SLAB, BEAM AND COLUMN

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Abstract

Strengthening and retrofitting of structures may be required due to several reasons, such as design deficiency, usage change, compliance with new design standards, damage due to fire, deterioration, need to support additional loads, extension etc. Most of the times, however strengthening and retrofitting may be needed for better seismic performance. Considerable literature is available on strengthening and retrofitting of structures. This paper presents specific concepts, innovative ideas, techniques and tools to design the strengthening and retrofitting systems for concrete slabs, beams and columns. The paper discusses the determination of capacity of existing members, identification of weakness, specific needs for strengthening, comparing alternative strengthening techniques, design of the strengthening elements, computing the capacity of strengthened system and the detailing considerations. The strengthening for flexure, shear, torsion, axial forces, stiffness, ductility, and flexibility are considered separately. The strengthening systems described in this paper include jacketing, post-tensioning, encasing, bracing, jacking and anchoring. Emphasis is placed on 'lateral thinking' and "out-of-the-box" ideas and solutions. The paper also presents a few case studies of actual projects where some of the techniques proposed in the paper have been used effectively.

Keywords: Strengthening, Retrofit, Composite section, Capacity curve, Jacketing, Encasing

1. INTRODUCTION

The need for strengthening and retrofitting of existing members may arise due to several reasons. The most common objectives of retrofitting are to overcome the design, construction or material deficiency; recover lost load carrying capacity caused by major damages and to efficiently carry additional loads that may be applied as a result of the change in the usage of the structure. *Retrofitting* or *Strengthening* is used when the strength and performance of a member is to be increased. The process of retrofitting involves the identification of the existing and new demands for the structure and the recognition of the member or system to be strengthened. Techniques used to regain the original strength and performance are referred to as *Rehabilitation*, *Repair* or *Restoration*, while *Preservation* and *Conservation* are terms used for procedures that ensure that the original performance of the structure is maintained.

Repair, strengthening and retrofit of reinforced and prestressed concrete members have become increasingly important issues as the World's infrastructure deteriorates with time. Buildings and bridges are often in need of repair or strengthening to accommodate larger live loads as traffic and building occupancies change. In addition, inadequate design and detailing for seismic and other severe natural events has resulted in considerable structural damage and loss of life, particularly in reinforced concrete buildings.

Strength evaluation may be required if there is evidence indicating faulty construction, a structure is deteriorated, a structure will be used for a new function, a structure or a portion does not satisfy the requirements of the code. The strength evaluation can be done analytically or experimentally. The analytical evaluation is carried out if strength deficiency is well understood, material properties and dimensions required for analysis can be obtained. If these parameters are not feasible to establish then load test may need to be carried out.

Once the strength evaluation has been carried out and the needs for retrofitting are established, the designer needs to ensure that some or all of the following criteria are met after retrofitting:

- New performance needs imposed on the members are satisfied
- New loads are transferred to the new system and/or existing members are relieved from existing loads as the case may be
- The old and new system act together or the old and new systems do not act together, as the case may be.

The type and extension of ant repair or strengthening work can be decided after both origin and amount of structural inadequacy have been ascertained. The selected technique must enhance the performance of members under the most probable failure mode. Material aging, loading history, modified stress strain properties and phenomenon such as creep and shrinkage should also be considered.

2. STRENGTHENING PROCESS

The process of strengthening involves the identification of the existing and new demands for the structure and the recognition of the members or system to be strengthened. A systems and materials study then needs to be carried out to identify viable alternatives. From among the alternatives the most efficient, effective and suitable system is selected. This strengthening system is then designed and the entire structure is re-evaluated for performance under new demands and loads. The most important part in the strengthening process is the identification of weakness in the overall system and specific members.

The identification of weakness includes the recognition of the areas of the structure not performing as desired. The first step involves the identification of weak members or subsystems followed by the detection of specific weakness within the members and systems. The weakness may be in strength, serviceability, stability, durability, seismic performance, ductility or other special performance needs. Different approaches need to be adopted to overcome various types of shortcomings; therefore a careful study needs to be conducted for the identification of these deficiencies.

Secondly, the designer needs to identify all the failure modes possible for the system/member under consideration and ensure that failure and performance needs are met.

These failure modes may be divided into two categories: Material Failures and Stability Failures, which are listed in Table 1.

Table 1: Possible failure modes in system/member

Material Failures	**Stability Failures**
Direct Tension Failure Direct Compression Failure Direct Flexure Failure Direct Shear Failure Failure in Shear due to Tension Failure Failure in Shear due to Compression Failure	Axial-Flexural Buckling Lateral Buckling Lateral Torsional Buckling Local Buckling Crippling

Once the failure modes as listed above have been identified, the designer must ensure that these are prevented. The basic methods adopted to prevent failure are:

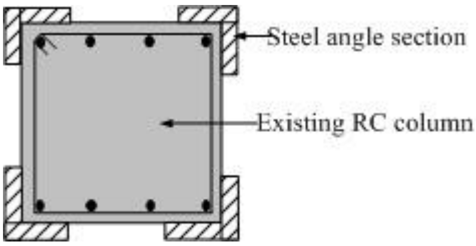
(a) Limit the Modes of Failure (Prevent buckling etc.)
(b) Limit Allowable Stresses (Adequate strength design)
(c) Limit Combined Stresses and Ratios (Consider interaction of actions)

3. BASIC STRENGTHENING METHODS

There are a wide variety of methods available for strengthening of members and systems and the choice of the new system will differ from case to case depending on various factors. The following are some basic methods that may be adopted individually or in combination:

3.1 Jacketing and Encasing

The covering of a lower strength material with a higher strength material is referred to as jacketing. Usually steel plates or sections are jacketed over concrete sections for additional strength. Encasing is the covering of a material with another material of equal or lower strength. Examples of encasing are concrete over concrete or steel sections (Figure 1).



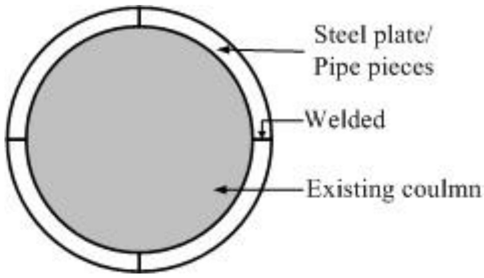


Figure 1a: Jacketing of existing members

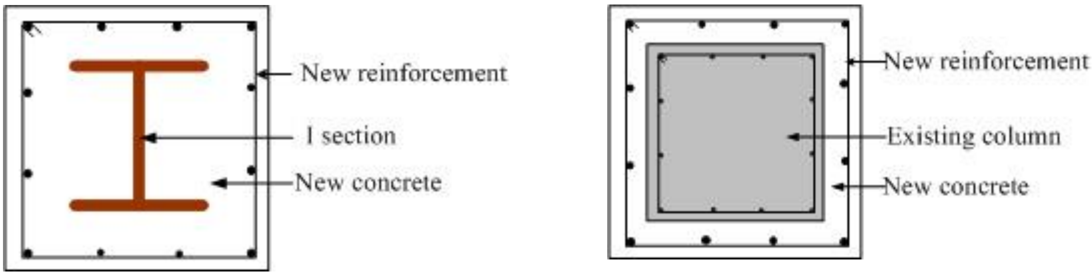


Figure 1b: Encasing of existing members

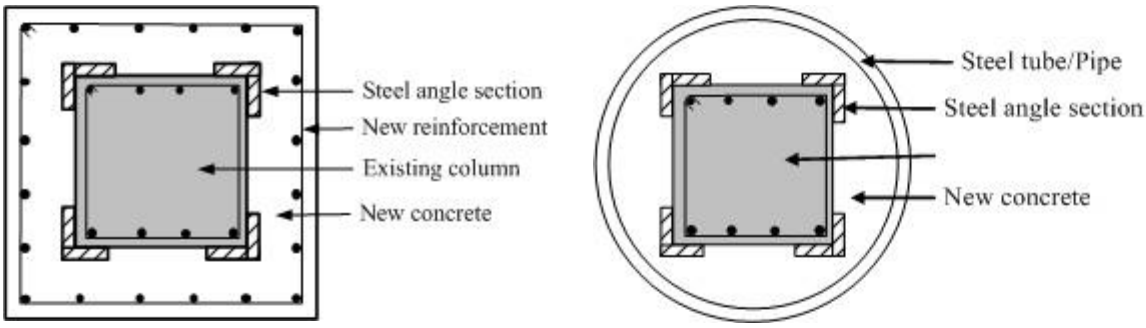


Figure1c: Combined Jacketing and Encasing

3.2 Post-Tensioning

The basic concept of post tensioning is to induce 'Reverse Bending' so that final stresses and deflection can be reduced. High-strength steel wires, prestressing strands, and high-strength bolts or rods, are used for post tensioning (Figure 2).

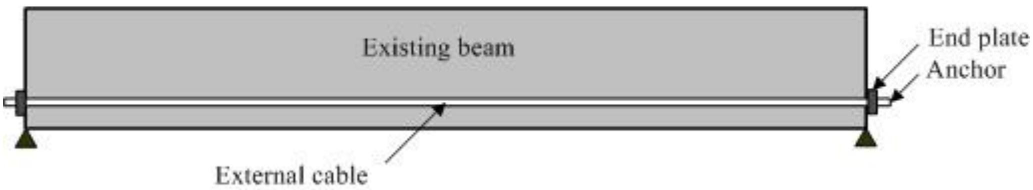


Figure 2: Post tensioning a weak beam by external cable

3.3 Replacing, By-Passing, Relieving and Bridging

These are closely related procedures/techniques with the basic idea of finding or providing an alternate load path. The alternate load path may be provided for existing loads, new loads or a combination of two. The procedure includes the removal, relocation and addition of structural members as shown in Figure 3.

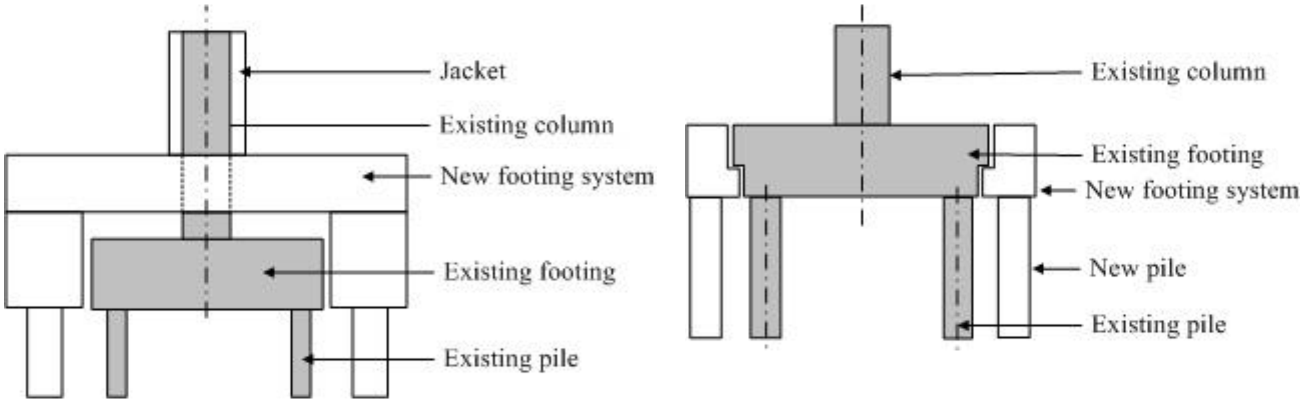


Figure 3: Strengthening of existing foundation (a) Bridging (b) Additions

3.4 Jacking, Lifting, Hanging and Underpinning

The fundamental idea of these procedures/techniques is to reverse the deflection in a member by lifting and replacing existing member. This can be achieved by providing support either from the top or the bottom of the member in question, as shown in Figure 4.

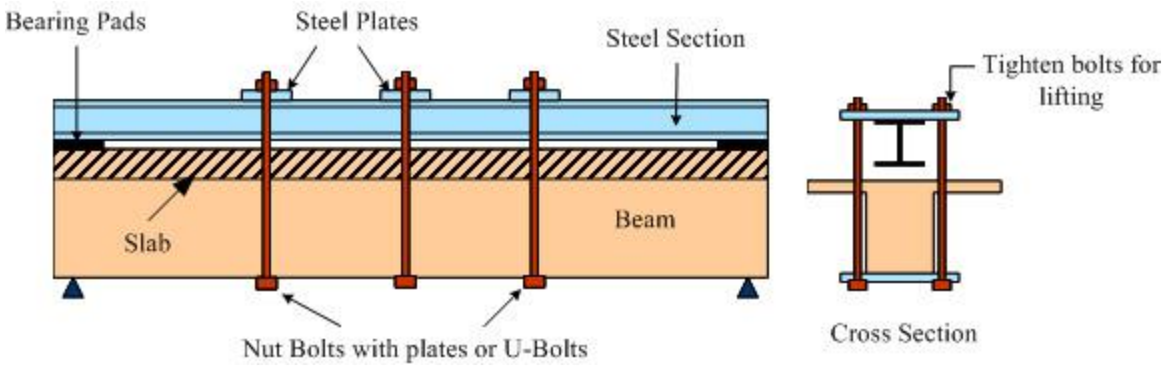


Figure 4: Overall Strengthening of beam by hanging

3.5 Addition of External Members

External truss can be added to support the existing members and carry additional loads. Additional bracings provides alternate load path for load transfer (Figure 5).

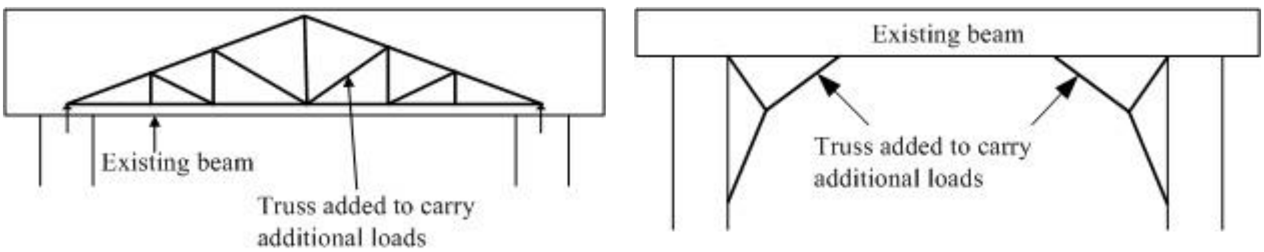


Figure 5: Strengthening by adding external truss

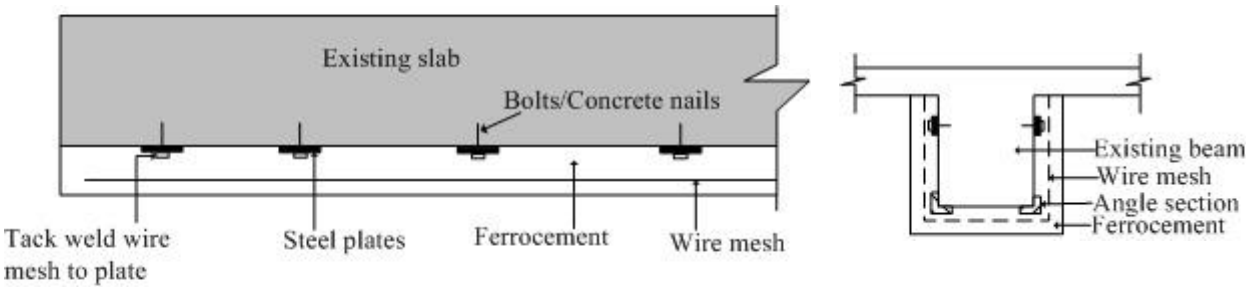
3.6 Strengthening Using Fiber Strips

Plastic or steel fiber is used to add tensile strength and toughness existing material. Fiber reinforcement provides control of shrinkage cracking. Steel and plastic fiber enhances toughness to impact and abrasion [1]. Carbon fiber reinforced polymers (CFRP) are widely used in strengthening and retrofitting purposes [2] because of its excellent mechanical properties such as lightness, high strength, toughness and convenient implementation [3].

4. STRENGTHENING OF CONCRETE MEMBERS

4.1 Strengthening of Beams and Slabs in Flexure

Two basic areas of concern for beams and slabs in flexure are excessive deflection and flexural strength. Flexural strength for beams/slab may be increased by providing steel plate or steel section on the tension side of the beam as shown in Figure 6. The newly added steel section or plates may be protected by encasing the cross-section with ferrocement or mortar. Wire mesh may be added to hold the new material in place. Providing post-tensioning in beams is another effective way to increase the flexural performance of the member. Post-tensioning reduces bending moment, increases the strength of the system, reduces cracking and tension related problems and provides direct uplift forces to balance the loads as shown in Figure 6.



(a) (b)

Figure 6: Strengthening of (a) slab (b) beam using steel plates and ferrocement

Hanging is another suitable method to reduce deflection and to increase the flexural capacity of beams. In this method an I-beam (steel) is provided over the beam in question and is supported at the ends (over the support of the beam) on bearing pads (Figure 4). U bolts or a set of bolts with a steel plates are passed under the beam (to be strengthened) and is supported on the I-beam. This is done on several locations along the beam. The bolts are tightened producing an uplift effect on the beam.

Jacking of excessively deflected beams is another effective way of retrofitting. A Pre-Cambered steel section is placed under the deflected beam and is supported on the ends. The steel section is then jacked up at the supports lifting the beam with it, to which it is then bolted as shown in Figure 7.

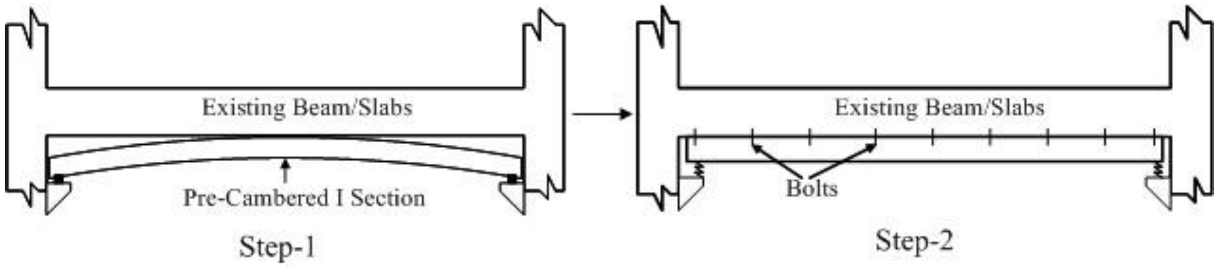
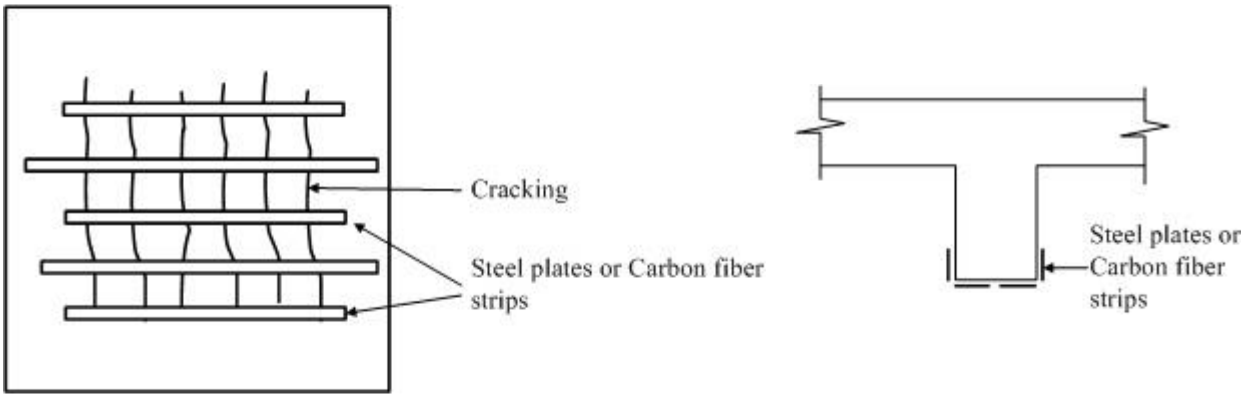


Figure 7: Jacking an excessive deflected beam by pre-cambering

Carbon fiber reinforced polymer (CFRP) strips may be used at the bottom side of the slab and beams for reinforcement as shown in Figure 8. This technique is effective in reducing deflection and crack width [4] and providing additional reinforcement. The plates or strips are glued or anchored to the slab and are covered with a layer of ferrocement increasing the flexural strength of the slab [5].

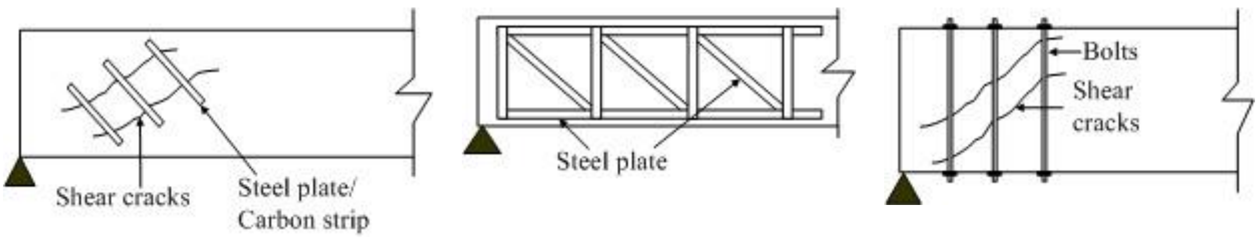


(a) (b)

Figure 8: Strengthening of slab using steel plates and or carbon fiber strips

4.2 Strengthening of Beams in Shear

Steel plates may be bolted to the beam with shear cracks, or shear deficiency. Carbon fiber strips may also be used instead of steel plates. Another method is to provide extra external strips on form of U bolts that will uplift the portion in shear (Figure 9).



(a) (b) (c)

Figure 9: Strengthening of beams in shear (a) Minor deficiency (b) Major deficiency (c) Using transverse post tensioning

4.3 Strengthening of Columns

Encasing and Jacketing are the two most simple and widely used methods for increasing the axial and moment capacity of columns. Concrete column section may be simply jacketed with steel plates or channel sections, which will increase the load carrying capacity of the section significantly. Another effective way of strengthening concrete columns is to provide angle sections and steel strips [6] at the corners and then encase the new section with reinforced concrete. Concrete columns may also be encased by new reinforced concrete to account for the new loads. In case of deficiency in the moment carrying capacity of columns it may be best to provide extra reinforcement in the column as well (Figure 10).

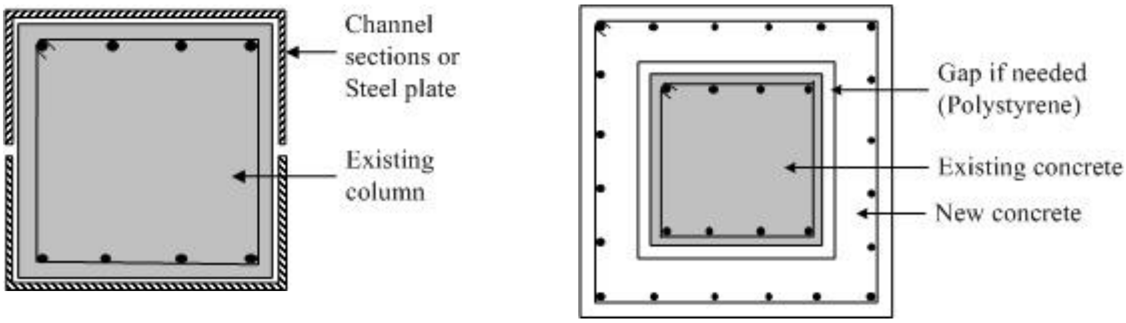


Figure 10: Strengthening of columns for axial loads

4.4 Strengthening of Foundations

The stability of foundation of a construction may be affected by alterations rising either in the soil (such as settlement in soil, earthquake) or in the construction (variation in external actions) [7]. Strengthening of foundation is one of the most difficult task, both from construction aspects and reliability and effectiveness of such strengthening. Bridging, addition and underpinning are the most effective and widely used methods for retrofitting foundations. Bridging consists of transfer of new loads to a new system of foundation, or relieving the old system and transferring the existing loads to the new system (Figure 3). The addition may be a girder supported on piles, which in turn supports the existing foundation. Underpinning may be done using a tension pile or by a cross beam supporting the old system, which in turn is supported in girders on piles at each end (Figure 11).

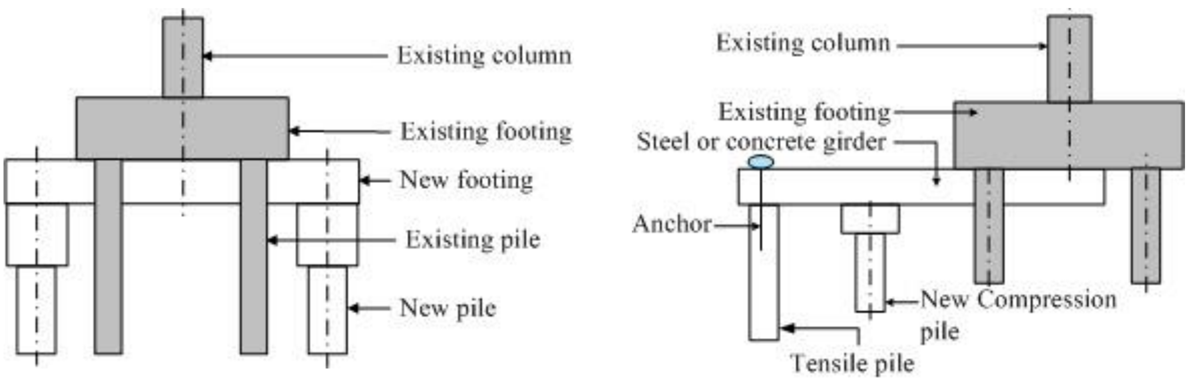


Figure 11: Strengthening of foundation by underpinning

4.5 Strengthening of Joints

Beam-column connection strength and ductility is the main factor influencing frame structure behavior. The beam column joints can be strengthened by use of steel plates and angle section. Steel plates and angle sections may be bolted to the joints (Figure 12). Alternatively it can also be strengthened by use of ferrocement jacketing.

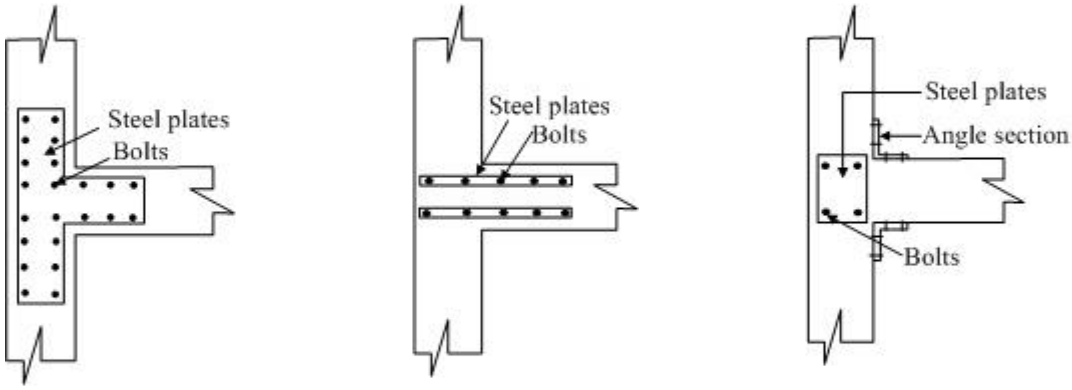


Figure 12: Strengthening of weak joints with steel plates and angle sections

5. DETERMINATION OF AXIAL-FLEXURAL CAPACITY

In light of the above discussion we realize that a section that has been strengthened consists of a variety of material processing their unique characteristics. Analysis of such a cross-section for capacity determination requires a general equation, capable of computing stress resultants for a variety of materials, of different strengths, stress strain relations, configurations, and shape. The following general equation is capable of determining the stress resultant (P, Mx, My) of a cross-section of arbitrary shape and material properties, for a given strain distribution. The capacity reduction factors may be adopted as specified by the code of practice.

A software CSI Section Builder has been developed using this equation by the author in collaboration with Computers and Structures Inc., California [8]. This software is capable of computing section properties, capacity curves and load deformation curves for complex cross-sections as those mentioned earlier. This software can be used effectively to design and analyze retrofitted section using equation 1.

$$N_z = \phi_1 \left[\frac{1}{\gamma_1} \int_x \int_y \sigma(x,y)\, dx\, dy + \frac{1}{\gamma_2} \sum_{i=1}^{n} A_i \sigma_i (x,y) \right] \quad (1a)$$

$$M_x = \phi_2 \left[\frac{1}{\gamma_1} \int_x \int_y \sigma(x,y)\, dx\, dy . \bar{y} + \frac{1}{\gamma_2} \sum_{i=1}^{n} A_i \sigma_i (x,y)\ y_i \right] \quad (1b)$$

$$M_y = \phi_3 \left[\frac{1}{\gamma_1} \int_x \int_y \sigma(x,y)\, dx\, dy . \bar{x} + \frac{1}{\gamma_2} \sum_{i=1}^{n} A_i \sigma_i (x,y)\ x_i \right] \quad (1c)$$

6. LATERAL THINKING APPROACH

In formulating the strengthening or retrofitting solution, it often helps to consider unusual ideas or approaches by concentrating on the source of the problem rather than the problem itself. Some of the examples are:

a) Rather than strengthening a weak member which may be difficult due to construction, operational constraints, alternate load paths may be provided to reduce the action on the members, or strengthen/stiffenening nearby members to redistribute the loads.

b) Avoid strengthening methods that increase dead load. For example, if a flat slab is weak in punching shear, consider adding column capitals rather than an attempt to increase thickness.

c) For continuous and indeterminate members strengthen location that are easily accessible even if it is not at weak location as the new loads will be redistributed to section of higher stiffness and old loads can be resisted in case of plastic deformations.

d) If many members in a structure are found to be defective or need strengthening, consider modifying the basic structural system. For example, a moment resisting frame may be converted to braced frame by adding external/internal bracing.

e) Utilize non-structural components as structural components. For example, the partition walls, door and window frames, floor finishes etc., can be modified to assist in carrying loads.

f) In case of foundation strengthening, consider re-evaluating or investigating the soil by re-testing. Often modifying the factor of safety from 3 to 2.5 or by computing the allowable bearing capacity for each footing individually can eliminate the need to strengthen the footing.

7. CASE STUDIES

A strengthening of a preheater tower of a cement plant was carried out for new loads to meet safety and performance requirement [9]. Due to expansion of the capacity of the plant, cyclones (vertical conical silos) at the top of Pre-heater tower were added. A detailed structural analysis and design review and strengthening of the pre-heater tower was carried out to accommodate the significant extra load at that floor level. The Pre-heater tower was modeled in three dimension using appropriate beam and plate elements and analysis was carried out in ETABS software [10]. The analysis result showed that the some of beam members were critical in flexural and shear failure criteria. It was proposed that the beam be strengthened by steel plates bolted to beam to carry additional flexural and shear loads (Figure 13). The steel plates have been used to strengthen beam which act like external shear stirrup. Spacing and size of steel plates were calculated based on the differential shear forces which is equal to the design shear force in excess of the existing shear capacity of the beam. Similarly for flexural strengthening of beams extra plates were added on the tension side of the beam. These plates act like an externally flexural reinforcement.

Similarly the column were found to be critical under axial load and hence was strengthened by attaching steel plates at sides of existing composite column and filling the free space with new concrete (Figure 14). The floor system was supported additionally by diagonal supports resting on the existing RC walls and columns (Figure 15). These diagonal supports would reduce the bending and shear in most of the critical beams.

Figure 13: Strengthening of beam (a) Slot in beams (b) Beam after strengthened

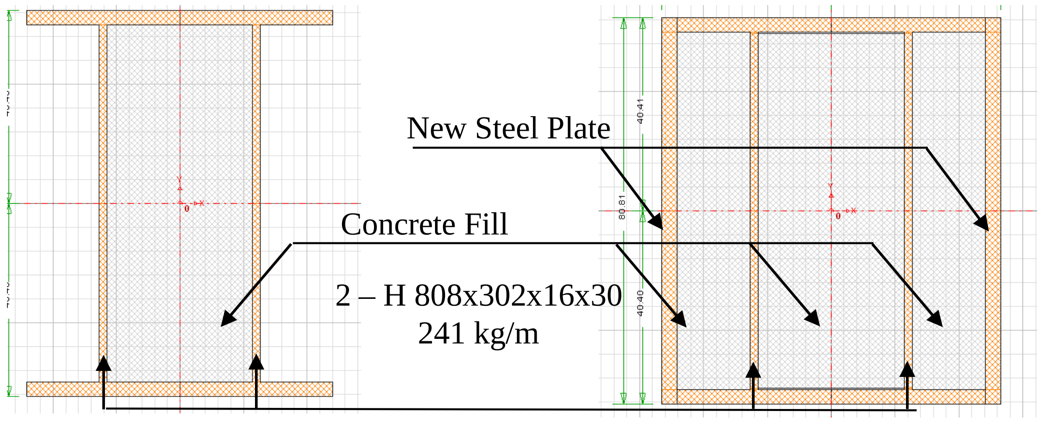


Figure 14: Strengthening Composite Column (a) Existing column (b) Column after strengthening

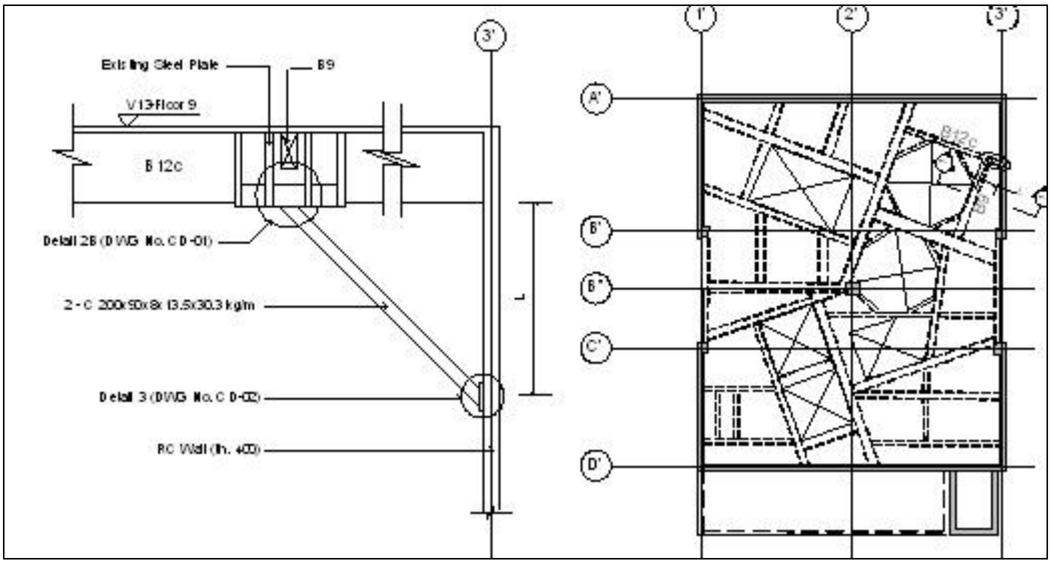


Figure 15: Strengthening of floor system by external bracing

8. CONCLUSIONS

Thus the concrete section can be strengthened in various ways to increase its capacity to withstand new loads, to overcome design deficiency as discussed in the paper. The RC members can be strengthened for flexure, shear, torsion, axial forces, stiffness, ductility, and flexibility using different strengthening techniques such as jacketing, post-tensioning, encasing, bracing, jacking and anchoring. However, the retrofitted cross sections add the complexity of shape, geometry and material to a general cross section. Hence, a comparative analysis of the cross section capacity needs to be made before and after retrofitting. It may also be required to make a strength/capacity comparison between two or more alternate retrofitting option for the same section.

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