Performance and Cost Effectiveness Analysis of the Active External Post Tensioning System

Min-Jae Lee¹ and Kangmin Lee*²

¹ Associate Professor, Department of Civil Engineering, Chungnam National University, Korea
² Associate Professor, Department of Architectural Engineering, Chungnam National University, Korea

Abstract

The new active strengthening system is an excellent system to replace previous external post tensioning systems without causing additional structural problems. In this system, the compressive forces due to prestressing are absorbed into the reinforcing system by adding the compressive member and no axial force is transferred to the member. In this study, the constructability and performance of this system were analyzed by applying the proposed technologies to a real construction project. Compared with previous systems that have been effective in new construction, such as beam and slab, the new active system can have a ripple effect on new repair and strengthening technologies by adapting it to repair and retrofitting. This system was proven to be an excellent strengthening system in constructability and structural performance since it is very simple, compared to previous systems. Finally, the new active system was proven to result in more than a 10 percent reduction in construction cost compared to previous systems, and positive economic effects can be expected because construction duration is shorter than other systems, and other floors and adjacent spaces in the building can be used during strengthening works.

Keywords: active post tensioning system; strengthening; performance; cost effectiveness; flexural members

1. Introduction

Many buildings experience structural problems caused by deterioration, overload, and design and construction errors. These structural problems can be linked to fatal accidents and can cause huge damage. To prevent these structural failures, the need for an improved external structural strengthening system was raised.

Structural strengthening with previous passive systems requires additional effort for restoring excessive deformation. Also, strengthening of the continuous beam parts is impossible. However the proposed new method strengthens the mid span of the beam only. The new active structural strengthening system can solve the previous passive system's problems. Transferring prestress into the structural member in an external post tensioning system restores generated deformation of members, as well as the bearing force of the structure. However, the compressive force from prestress might generate deformation in adjacent members or cracks in the slab, so caution is necessary regarding their applications.

Since the previous external post tensioning strengthening system could generate new structural damage to undamaged members while strengthening damaged members, the development of an alternative strengthening system was necessary. To minimize the problem, a new active system using a compression member in which the compressive force generated from prestress will not be delivered to structural members and is absorbed inside the strengthening system was developed. This system does not generate structural problems on structural strengthening members and adjacent members, and shows better performance than earlier external post tensioning systems.

To consider application of the new active system to actual field use, verification of the functions, performance, constructability, and economical efficiency of this system were required. In this study, the strengthening performance of the new active system and its impact on adjacent members was examined through a static bending test and structural analysis, and the constructability and effectiveness of the active system were verified through an experimental field test. In addition, the economic efficiency of the active system was analyzed by using field application case studies.

2. Literature Review

Typical structural strengthening systems currently in use can be classified into passive systems, such as steel...
plate strengthening or carbon fiber sheet strengthening, and active systems, such as external post tension strengthening, as shown in Table 1.

Table 1. Comparison of Conventional Strengthening Systems

| Characteristics | System summary                                                                 | Method                                                                 |
|-----------------|--------------------------------------------------------------------------------|-----------------------------------------------------------------------|
| System          | System of strengthening by attaching a steel plate on a structure's surface   | Uniting the system with the structure by epoxy after fixing the strengthening steel plate with an anchor bolt |
| Summary         | System of strengthening by attaching carbon fiber on a structure's surface     | Uniting a strengthening carbon fiber sheet with the structure by epoxy |
| Construction    | External post tension cable in the opposite direction of the load applying to  | Wet system                                                            |
| Method          | the structure                                                                 | Easy to apply due to light materials                                   |
|                 |                                                                                   | Low reliability by strengthening with epoxy adhesion.                  |
|                 |                                                                                   | Construction only after removing finishing materials                  |
|                 |                                                                                   | Restores original condition only by strengthening after jacking up    |
|                 |                                                                                   | Restores original condition only by strengthening after jacking up    |

The advantages of a strengthening system with external post tension were fully understood, and studies have been conducted in Japan, England, and Korea. However the previous external post tensioning systems have shown many problems such as, structural, economical, environmental, and constructability problems. The new active system could be an effective strengthening method that overcomes these problems and, as a result of testing and analytical study over many years, this system has proven to have a better structural performance than previous systems and is superior technically, environmentally, economically, and in terms of application.

3. The New Active System

External post tensioning systems can reduce the bending moments generated by surface loads since the system generates moments in the opposite direction by transferring prestress. Also, the system restores the deformation generated from surface load to its original state. However, transferring prestress not only creates the results mentioned above, it also creates compressive force inside the supporting location since the supporting location of prestress strengthening is attached to the structural member as a single body as conceptually described in Fig.1. If compressive force is applied to the whole section of the member in a structure where simple strengthening and compressive force is applied to the whole section of the member in a structure, a shrinkage crack will be generated on the whole structure. In a structure with both sides fixed, compressive force is generated inside the supporting point of prestress strengthening, and tensile force is generated between the supporting point of prestress strengthening and the supporting point of the structure. In this case, there is the possibility of a crack in the section where the tensile force is generated.

Since a structural problem occurs when compressive force is generated from prestress to the structure in the previous system, there is a need for a method to prevent
compressive force. The proposed new active system can help counter this problem. The details of the new active system are described in Figure 2 and show that, unlike the previous system, the end anchorage of prestress strengthening is not attached to the structure to prevent the compressive force generated from the transfer of prestress to be delivered to the structure. Steel members that absorb the generated compressive force are added, and angles and structure are attached by a slot to create anchorage slip. The angle is connected by a bolt through the structure and the slot hole. The tensile force of the tendon is delivered to the angle, but the force is not delivered to the structure due to anchorage slip in the slot hole. By strengthening the structure with this method, deformation and cracking of the structure due to the compressive force generated from prestress can be prevented. Fig.3. schematically describes the force transferring mechanism of the new active system. As shown in this figure, both compressive and tensile forces are transferred to the system by two-way pre-stressing devices.

To compare strengthening performance between the previous external post tensioning system and the new active system, the impact of strengthening on adjacent members was examined by Lim and Moon (2008) and Lim et al. (2009). In these researches, an experimental program was designed and conducted with slab, simple beam, and continuous beam specimens and the following are a summary of the numerical and experimental results from these researches.

As a result of examining the condition of the fractures in each test specimen, the main fracture mode in the case of strengthening with the previous external post tensioning system and the new system was a flexural fracture with even and widely-distributed cracks, showing that the shape of the flexural fracture was similar to the previously strengthened concrete structure, regardless of the shape of the test specimen or strengthening system. A problem that could occur in the previous external post tensioning system is the possibility of a crack being generated in the tension section.

A test with long-term loading showed that sagging was increased by approximately 2.3 percent compared to sagging in the initial loading prestress, which was decreased by approximately 2.0 percent compared to the initial transfer prestress. Therefore, it is determined...
that there was no significant structural problem due to long-term loss of sagging and prestress.

Also, an analytical study was conducted using the structural analysis program. According to the results of the test using the external post tensioning system and the new active system, the test specimen strengthened with the new system showed an almost identical performance on the structural bearing force to the previous external post tensioning system, thus confirming that strengthening design by a method presented in the standard of concrete structure design would be possible.

From the experimental and analytical test results, the authors found that the following should be considered for strengthening design and field construction so that the new active system can be more safe and economical:

1) There is a possibility of a flexural fracture occurring at the dead end in slabs strengthened with the new system, so an improved linkage system should be selected.

2) There is a possibility of a collapse of the screw thread at the end anchorage (wedge) according to the transfer of forced prestress and installation of the prestressing device, so the end anchorage (wedge) should be used only once, and selecting a prestressing device for preventing collapse of the screw thread should be selected based on the specification.

3) Cracks can be generated in members, and pull-out of anchors can occur at the same time in the anchorage device (set anchor) of the center saddle supporting tendon, so a method for complementing the anchorage method of the saddle should be selected, so that the set anchor cannot be pulled out even if a crack is generated in the members.

4) Generation of anchorage loss varies depending on the prestressing device and length of the tendon when transferring prestress at the beginning stage, so prestress should be transferred after determining the characteristics of the applied method and determining the anchorage loss according to the prestressing device and length of the tendon. To do this, a preliminary prestressing test should be executed as follows. A preliminary prestressing test is conducted in preparation for confirmation of anchorage loss according to the length of the tendon. Therefore, it is not an essential item that is conducted in the construction field and also is not included in the construction cost. Anchorage loss from prestress varies depending on the type and length of the tendon. That is, when releasing a device for anchorage after transferring prestress, anchorage slip occurs on the tendon until the anchorage wedges. Anchorage loss can be predicted theoretically by the relationship between stress and deformation of the tendon according to the deformed length of the tendon. After calculating and examining anchorage loss theoretically, the characteristics (anchorage loss, anchorage slip) are determined by conducting a preliminary prestressing test for the applicable length of the tendon before conducting fieldwork.

5) An angle converting device in accordance with the field conditions used to transfer prestress in a construction field could make problems described in 2) and 4) above even greater, so it should be used after sufficient examination.

6) When transferring prestress to a tendon from the sides or bottom of concrete members, interference between the form tier and concrete members might be generated that will disable the transfer of prestress. Using an angle converting device could prevent interference between concrete members and the form tier.

4. Performance of the New Active System

The new active system has more advantages than previous strengthening systems such as the external post tensioning system and was proven to be better than other systems regarding construction duration, construction cost, and constructability. The following are advantages of the new active system over the previous external post tensioning system.

a) Concrete surface treatment for attaching a dead end device is not required: The new active system requires only drilling work for anchorage since strengthening is fixed with an anchor bolt only, unlike the previous external post tensioning system.

b) System for reducing construction time: When strengthening a slab, strengthening work is done by simple attachment work since the strengthening systems are processed and assembled in a factory, so construction time is reduced.

c) Application to locations with poor work conditions: The new active system is convenient for application to a location with poor work conditions due to the characteristics of the system and can be applied to all horizontal structural members.

d) Deformation or cracks are not generated during strengthening: Compressive force from prestress is absorbed inside the strengthening system, so there is no deformation of a building or generation of cracks.

e) Space for installing a form tier is not required: Since a two-way prestressing device is used in the beam and the strengthening system produced in a factory is used for the slab, space for installing a form tier is not required.

f) Reduction of anchorage loss from prestress: Space for installing a form tier is required in the previous external post tensioning system, so the length of the prestress strengthening is shortened and anchorage loss is larger. Space for installing a form tier is not required in the new active system, so anchorage loss is smaller and fixed prestress can be assured more easily.

g) Reduction in the number of attachment bolts: An anchor bolt should be designed to sustain horizontal
reaction and vertical reaction generated from prestress in the previous external post tensioning system, however in the new active system, horizontal reaction is sustained by a compressive force absorber and only vertical reaction is generated, so fewer anchor bolts can be used.

The new active system’s technical advantages in advancement, field applicability, and effectiveness compared to the previous external post tension strengthening system can be summarized as follows:

(1) Advanced Technology

The external post tension strengthening system is an active system that increases the allowable load of members effectively by reducing stress from a fixed load and increasing the bearing force of members. The new active system is a system in which additional compressive force generated from the previous external post tensioning system will not be delivered to strengthening members and absorbed inside the strengthening system, so there will be no deformation or cracks generated in a building. In the case of designing a dead end device to support prestress, the previous external post tensioning system should be designed to be safe for both the vertical and horizontal reaction force from post tension. However, the new active system is designed to support the vertical reaction force only, so the number of anchor bolts required for fixing the dead end plate can be reduced.

In the case of strengthening a slab with the new active system, this can reduce prestress length, which affects anchorage loss. When transferring the fixed prestress into the strengthening system, a loss of prestress is generated for various reasons, including elasticity deformation, creep, drying shrinkage, stress relaxation, and anchorage loss. Anchorage loss will be in inverse proportion to the length of the tendon. The length of the tendon should be as large as possible to minimize anchorage loss. If the length of the tendon is very short, anchorage loss becomes too high and the effect of prestress might become 0. Therefore, if the length of members is short at the root or by securing space for using the prestressing device (tensioning system) on the dead end of members, anchorage loss could be very high. A two-way prestressing device is used in the new active system, and prestressing work is conducted on this part, so a section on the dead end of members for installing the prestressing device is not necessary. Therefore, prestress anchorage loss of the new active system applying to a slab might be smaller than prestress anchorage loss of the previous post tensioning system. The convenience of prestressing work is assured because a two-way prestressing device is used.

(2) Quality

In previous external post tensioning systems, the dead end should be installed to maintain prestress, and equal processing of the previous steel plate attaching system, such as removing finishing material, attaching steel plates, and using epoxy, should be executed to install the dead end.

If the dead end is attached to structural members poorly, bond failure could occur before securing the fixed bearing force. The new active system eliminates the possibility of bond failure. Also, compressive force from prestress can be absorbed inside the strengthening system, so cracks and deformation of strengthened members and adjacent members can be prevented and excellent strengthening quality can be expected.

(3) Construction Duration

Previous external post tension strengthening systems require anchor bolt and epoxy adhesion, installing a dead end for prestressing by welding and mounting the tendon on the dead end. The dead end anchorage parts of generalized previous external post tension should receive stress from prestress through anchor bolts and epoxy adhesion. Therefore, a steel plate functioning as an anchorage part and an anchor bolt fixing this steel plate to the building frame are indispensable parts. The total construction duration, from warehousing factory-processed materials in the field to the end of construction, is 2-3 days; the new active system can reduce this by at least 1 day, since it requires only simple fixing of all materials by anchor bolts in the field as all materials are processed and produced in a factory rather than requiring field assembly. Therefore, construction duration can be reduced by approximately 20 percent, and there is no process required to remove the material's surface for cleaning.

(4) Constructability

Constructability can be increased since removal of the finishing material and surface treatment of the concrete are not necessary compared to previous systems, and stressing is done using a two-way prestressing device without removing or transferring electrical equipment. Also, all the systems are produced in a factory and delivered to the field, so only installation of these systems on the target structure for strengthening is required. Constructability of this system is superior to previous systems. Fig.4. shows a comparison of the field construction process between the previous system and proposed active system.

(5) Safety

Compared to previous systems, the complicated field working process can be simplified by dividing the factory production process and the field assembling process of strengthened members; this system is excellent for safety control since maintaining cleanliness of the field is possible. Also, worker safety can be increased since work can be conducted at the safest location using a two-way prestressing device.

(6) Environmental Friendliness

This system can drastically reduce environmental problems such as dust and noise since only field assembly according to factory production is used and
concrete surface treatment is not required.

(7) Ease of Maintenance

In the new active system, all regulations related to quality, process, and installation of material can be controlled by specifications. Materials conforming to standard regulations were used, and process and installation were conducted based on superior production quality. The fixing condition of the saddle fixing anchor bolt, installation of set anchors for installing the compression member, and quality of welded parts were confirmed based on specifications. Securing fixed prestress and decreasing prestress due to sagging were confirmed through an experimental study; definitions of these methods were confirmed after conducting a field installation test.

5. Cost Effectiveness of New Active System

A comparison of strengthening work cost estimates between the previous system and the new active system on the same building is shown in Tables 2. to 4. Strengthening plans were designed for three similar projects with equal conditions. Since data for proving the economic efficiency of the previous post tensioning system are not reflected in the current standard of construction estimates, economic efficiency was compared based on design costs submitted for a field designed using the previous post tensioning system. The most generalized post tensioning system was applied, which consists of attaching a steel plate to a beam with surface treatment through anchor bolts and epoxy grouting and installing a dead end for tension by welding and mounting a tendon. In this study, two case studies were performed (Case study 1: Table 3.), (Case study 2: Table 4.).

As seen in Table 2., the new active system can reduce 10 percent of the total construction cost compared to previous strengthening methods. In addition, the reduction in construction cost is expected

| Table 2. Cost Breakdown for New Active System |
|------------------------------------------------|
| New Active Type (ℓ ≒ 6000, Φ 15.2 Low)          |
|                                                                 |
| Per Section                                      |
| Code    | Item                  | Unit | Quantity | Material | Labor | Equipment | Total |
|---------|-----------------------|------|----------|----------|-------|-----------|-------|
| Bt-G-100| EA                    | 2    | 96,000   | 192,000  | -     | -         | 96,000 |
| Bt-G-200| EA                    | 4.0  | 100,000  | 400,000  | -     | -         | 100,000 |
| Bt-G-300| H Type                | 4.0  | 90,000   | 304,000  | -     | -         | 90,000 |
| Bt-G-400| Saddle                | 2.0  | 115,000  | 230,000  | -     | -         | 115,000 |
| Bt-W-100| T Type                | 13.2 | 3,700    | 48,840   | -     | -         | 3,700  |
| Bt-WC   | Φ 15.2                | 8.0  | 4,200    | 33,600   | -     | -         | 4,200  |
| L-75X7  | EA                    | 164.0| 700      | 114,800  | -     | -         | 700    |
| Anchor  | Man                   | 5.1  | 90,908   | 463,630  | -     | -         | 90,908 |
| Welder  | Man                   | 0.65 | 3,400    | 37,320   | -     | -         | 3,400  |
| Special  | Man                   | 5.1  | 66,051   | 136,860  | -     | -         | 66,051 |
| Carpenter| Man                   | 2.7  | 32,374   | 141,409  | -     | -         | 32,374 |
| Labor   | Man                   | 1    | 19,560   | -        | -     | -         | 19,560 |
| Material | Cost                  | 1,632,197 | -       | -       | -     | -         | 1,632,197 |
| Labor   | Cost                  | 979,019     | -       | -       | -     | -         | 979,019 |
| Total   | Cost                  | 2,611,216   | -       | -       | -     | -         | 2,611,216 |

Fig.4. Comparison of Field Construction Process
Table 3. Cost Breakdown for Previous Post Tensioning System (Case Study 1)

| Post tension Type | Unit Cost | Labor Cost | Equipment Cost | Total Cost |
|-------------------|-----------|------------|----------------|------------|
| Code | Item | Unit Cost | Unit Cost | Unit Cost | Unit Cost |
| Wire Reinforcement | Anchor Plate | 4.00 | 160,000 | 55,000 | 80,000 |
| SADILE 18,814 | PC WIRE MAN | 3.20 | 174,000 | 58,500 | 82,500 |
| Wedge | 4.00 | 6,500 | 26,000 | 55,000 |
| Plate M | 39,22 kg | 750 | 44,415 | 70,000 |
| Anchor (high Loading) | 24.00 | 33,000 | 811,200 | 82,490 |
| NPT Anchor | 6.00 | 1,800 | 10,000 | 10,000 |
| Other Material | 1.00 | 1,832 | 91,642 | 10,928 |
| Equipment set up engineer | 3.60 | 69,484 | 250,142 | 90,908 |
| Steel bender | 2.50 | 62,101 | 233,963 | 84,415 |
| Water Proofer | 1 | 79,788 | 10,928 | 84,415 |
| Special worker | 2 | 66,051 | 10,928 | 77,000 |
| Tensioning system | 1 | 52,000 | 10,928 | 62,928 |
| Hires of machines and tools | 5% Labor cost | 1 | 940,720 | 252,000 | 1,192,720 |
| Total | 233,963 | 252,000 | 33,800 | 507,923 |

6. Conclusion and Suggestions

When transferring prestress using the previous external post tensioning system, compressive force is generated on strengthening members, and deformation might be generated on adjacent members or cracks might be generated in the slab, so care should be taken. The new active system can address this problem by using compression members so that compressive force generated from prestress will not be delivered to strengthening members and is instead absorbed inside the strengthening system. The strengthening effect of the new active system can replace previous external post tensioning systems, and additional structural problems are not generated to strengthened structure members and adjacent members.

The new active system was developed by analyzing problems associated with previous external post tensioning strengthening systems. The effects of the new active system were verified through tests and analysis to confirm structural performance; constructability and efficiency were analyzed by applying this developed technology to field construction.

The new active system is effective for strengthening in aged structures, structures with less bearing force, renovation and remodeling, and especially for strengthening in underground parking lots. This system can be used for the beam and slab strengthening of reinforced concrete structures, column strengthening, beam and slab strengthening of steel-frame structures, and strengthening of composite concrete structures.

The new active system was found to have many advantages, including convenience of installation, reduction of construction duration, and building use during strengthening work. Quality improvement of previous structural conditions can be expected after conducting strengthening work. Previous prestress systems have been used as effective methods for new buildings such as beam and slab; the new active system can have a high ripple effect on new repair and strengthening technology by adapting it to the repair and retrofit fields. In addition, this system was proven to be an excellent strengthening system in terms of constructability since it is very simple compared to previous repair and strengthening systems but shows excellent structural effects. The system was proven to have excellent substitutability since a strengthening structure for additional load can be created by replacing only a few members. Therefore, the new active system can be considered to have excellent economic efficiency concerning strengthening.

The new active system was proven to result in more than a 10 percent reduction in construction cost compared to previous systems, and savings can be expected since the construction duration of this system is shorter than other systems. Also, other floors and adjacent spaces can be used while conducting the strengthening work, resulting in even larger savings.

Table 4. Cost Breakdown for Previous Post Tensioning System (Case Study 2)

| Post tension Type | Unit Cost | Labor Cost | Equipment Cost | Total Cost |
|-------------------|-----------|------------|----------------|------------|
| Code | Item | Unit Cost | Unit Cost | Unit Cost | Unit Cost |
| Steel plate reinforcement | PLATE 4.5T | 82.00 | 180,000 | 50,000 | 230,000 |
| Anchor | 39,22 kg | 750 | 44,415 | 70,000 |
| Air Outlet | 3.00 | 800 | 2,400 | 3,000 |
| Epoxy Salding | 2.50 | 9,000 | 22,500 | 31,500 |
| Epoxy Grount | 6.00 | 16,000 | 96,000 | 112,000 |
| Other Material | 5% material cost | 1 | 115,828 | 115,828 | 115,828 |
| Steel Plate | Anchor | 0.95 | 90,908 | 86,363 | 177,271 |
| Water Proofer | 0.50 | 70,786 | 35,394 | 106,180 |
| Special worker | 0.85 | 65,051 | 55,293 | 120,344 |
| Hires of machines and tools | 2% Labor cost | 1 | 4,588 | 4,588 | 4,588 |
| Total | 2,432 | 233,963 | 2,466 |

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This technology has not been used in overseas construction, but it is expected to contribute to the international structure repair and strengthening market, especially in the repair and strengthening market when remodeling and renovating buildings. The possibility of this technology expanding overseas is expected to be high and continuous studies on this technology are necessary.

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