# INSIGHTS OF FPLM FOR LONG-VIADUCT CONSTRUCTION IN TAIWAN HIGH-SPEED RAILWAY PROJECT: OVERCOMING THE INTERFACES

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Abstract: The FPLM, Full-span Precast and Launching Method, is selected as the main construction method for the long viaducts in the Taiwan High-Speed Railway (THSR) project. In order to maximize the advantage of this method, "design for construction" should be emphasized. It means that construction knowledge and experience should be taken into consideration among all interfaces and details in preplanning stage. In this paper, the authors identified the key factors affecting the time and cost effectiveness of FPLM construction, including production management, equipment selection and structural requirements. Discovering these facts, several important constructability ideas that should be implemented in planning, design and construction stages respectively are proposed. With continuously discovering and resolving the interfaces in construction, the authors believe that "one girder per day with one set of equipment" is an achievable goal for FPLM construction in THSR project.

Keywords: FPLM, viaduct, high-speed railway, interface, time and cost effectiveness, constructability, box-girder, precast, MSS.

## 1. BACKGROUND

In the past, the alignment and construction planning of transportation infrastructure were based on the concept, "earthwork cut-and-fill balance." As a result, the environment was polluted and destroyed. Nowadays, technological innovation in bridge construction and the utilization of automated equipments not only reduce the construction cost but also shorten the project duration tremendously and develop various kinds of bridge lengths, heights, and types. Therefore, incorporating the idea of long span and viaduct styles into bridge design is of great advantage to the project itself and the neighborhood. First, adopting long-distance design for bridges can avoid not only destroying the landscape but also dividing the two areas beside the highway or railway and reduce the land the embankment built on obviously. While highway and railway on the plains adopt the design of viaducts, the space under the viaducts can be utilized as the temporary roads during construction stage and thus become permanent roads after renovation and improvement. Since these under-viaduct roads can be incorporated into the local highway network, and the local economy will be stimulated gradually.

Undoubtedly, the Taiwan High-Speed Railway (THSR) project is one of the key transportation components of the economic future of Taiwan in recent years. As a Build-Operate-Transfer (BOT) project, the content of THSR includes the construction and operation of the high-speed rail system, management of business development zones, and development of station areas, etc. On the THSR system, the 345km civil works between Taipei and Kaoshiung consists of cut and fill (40km, 11.6%), tunnels (48km, 13.9%), and bridges and viaducts (257km, 74.5%). This is shown that the importance of bridge and viaduct construction in the THSR project, especially the long viaducts on the Chia-Nan Plains in the southern Taiwan. Achieving the goals of high quality, shortest time and least cost in construction, the Full-span Precast and Launching Method (FPLM) is selected as the main construction method for the long viaducts shown in the Figure 1. In order to maximize the advantage of this method, "design for construction" should be emphasized. In this paper, the key time and cost effectiveness factors of FPLM construction are identified, and several important constructability ideas are proposed for achieving the goal, "one girder per day with one set of equipment," in the forthcoming THSR project.

## 2. FPLM

FPLM is a construction method for bridge superstructure with aim of achieving the construction efficiency. This method utilizes heavy-duty carrier and launching equipment to launch the precast box-girder regularly onto the piers. The length of the precast box-girder is usually between 25m and 40m, and different girder lengths are usually allocated carefully together to avoid the conflicts of the pier locations against exist roads and ditches. Also, the settlement of reinforcement cage prefabrication yards and precast production plants can facilitate better control of quality and schedule easily.

### *2.1 Procedures of FPLM construction*

Chiu [1] pointed out that the critical point of this method is to streamline the whole box-girder production process, including the operations of reinforcement cage prefabrication and precast box-girder production and erection. Therefore, the procedures of FPLM construction, including the production process of box-girder, are illustrated as follows [2-3]:

(1) Reinforcement cage prefabrication operation. The non-prestressed reinforcements, such as web, deck slab, and bottom slab reinforcing bars, are assembled and spot-welded first. Therefore, the full-span reinforcement cage is placed into the stationary outer form in the precast plant by two overhead gantry cranes with lattice girder. The diameters, shapes and design of reinforcing bars should be simplified and standardized in order to reduce the manpower requirement and thus efficiently shorten the operation time.

(2) Precast plant operation. After cleaning the outer form, the stranded strands are allocated in the settled reinforcement cage and thus pulled through the pull-head. Next, the strands are prestressed by pre-tension method, which is particularly economical among prestressing methods. This is because the standardized design of pretension method permits reusable strands by using strands' mono-coupler and the synchronized prestressing of various components results in great saving of labor. In addition, expensive anchorage hardware, sheath and its grouting can be eliminated [4]. However, girder with larger span, both pre- and post-tensioning may be required to keep the space for concrete placing. Consequently, the inner mould is installed through the cage, which has been positioned. To shorten the installation time, the synchronized hydraulic mechanism can be utilized on the design of inner mould pull-and-push equipment. Then the High Performance Concrete (HPC) is placing onto the casting bed. The utilization of form vibrators must be very careful in order to avoid separation of aggregates during placing. After initial setting of the concrete, steam curing on concrete is proceeded. To ensure the quality of concrete, the arrangement of steam pipes and scheme of curing temperature should be given serious attention.

(3) Precast box-girder carrying and erection. After the inner mould slips out of the box-girder and the stripping hang-beam is installed, the prestressed strands outside both ends of the girder are relaxed and cut consequently. Next, the carrier, propeller type or gantry type, transports the precast box-girder from precast plant to the field. While the girder is erected from the casting bed to the carrier or lifted by the gantry carrier, working loads on the hanging points on the deck slab of box-girder should be concerned in order to avoid unpleasant effects. Then the carrier moves along the installed viaduct deck and thus erects the full-span box-girder onto the bridge piers by the gantry launcher or gantry carrier as shown in Figure 2. Finally, the carrier moves back to the precast plant and thus the gantry launcher proceeds to the next span, and one precast production "cycle of erection" is completed.

### *2.2 Key factors to success of FPLM*

To achieve the cost feasibility within limited schedule, the authors expect that FPLM in THSR project can be performed as one box-girder production within twenty-four hours with one set of mould. Therefore, the authors identify the following key factors, affecting time and cost effectiveness, by analyzing the procedures of FPLM construction:

(1) Production management. It is very important to reduce waste in prefabrication and includes layout of production lines and sequencing and scheduling of operations.

(2) Equipment selection. Design and selection of girder lifting and erecting equipments and transportation carrier can affect the possibility of rapid installation later.

(3) Structural requirements. Construction activities, such as prestressing, concrete placing and steam curing, should be incorporated with structural designs.

## 3. CONSTRUCTABILITY SUGGESTIONS FOR FPLM IN THSR PROJECT

Constructability is the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objective [5]. Because of early construction involvement in project primary study phase, the performance of whole project can be improved. In this case, project schedules are construction sensitive and basic design approaches consider major construction methods, say "design for construction," through using preassembly, prefabrication and modularization. Therefore, we adopt this concept with invulnerable analysis and insightful suggestions, which will be implemented in planning, design and construction stages respectively, to the FPLM construction in THSR project as shown in Table 1.

Table 1. Constructability Suggestions For FPLM

| | |
|---|---|
| Production management | (1) Site layout of the precast yard |
| | (2) Design of inner mould |
| | (3) Design and pre-fabrication of reinforcement cage |
| Equipment selection | (1) Precast girder transportation |
| | (2) Site erecting |
| | (3) Launching equipment |
| Structural requirements | (1) Use of pre-tension method |
| | (2) Concrete and steam curing |
| | (3) Metal bearing |
| | (4) Continuous beam design |
| | (5) Optimal girder length and pier allocation |

## 4. CONSTRUCTABILITY IN PRODUCTION MANAGEMENT

### *4.1 Site layout of the precast yard*

Precast yard production is the core of FPLM construction and its site layout, especially the operating path planning, is very important. It analyzes the locations of precast and reinforcement fabrication yards, the yard layout of production lines and other temporary facilities, path planning for equipments and logistics, and general condition requirements for the project.

The location of the precast plant is highly related to the distance for box-girder transportation and daily supply access route for materials. Similar to cases in Korea and Italy, it is recommended to locate the precast yard at the back of the bridge abutment, and in THSR project to locate the precast yard at both sides to the viaduct. Because of the non-abutment design of the 158km super long viaduct section at southern Taiwan, the site planning of precast plants in THSR project is much different from the design in Korea and Italy, in which the yards are located behind the abutment. The problem is, how to lift the girder upward to deck?

Moreover, planning of production line is also an important part in the site layout of precast yard. It should take the space demand for production and supportive works, such as reinforcement prefabrication, inner mould stocking, concrete premixing, precast plant, steam curing and prestressing, box-girder transportation, into consideration system-widely and concurrently.

### *4.2 Design of the inner mould*

The design of inner mould is equivalent to the design of the box-girder's interior cross section. Considering shear flow in box-shape structure, the conventional end-diaphragm beam is replaced by closed-ring beam. Similarly, the web at the end section of girder thickens inwardly or outwardly depending on different structural and construction requirements.

To shorten the installation time, the synchronized hydraulic mechanism can be utilized on the design of inner mould pull-and-push equipment. However, its range of deformation is limited and the pull-and-push mechanism of inner mould is affected by the lateral design of the top of bottom slab. To increase advantages of this prefabrication method, one set of inner mould should be enable to produce precast box-girders with different lengths and even continuous girders. Moreover, the interfaces between the bottom face of bottom slab and metal bearings also need to be concerned in details.

### *4.3 Design and prefabrication of reinforcement cage*

The design and prefabrication of reinforcement cage consider about not only the functional requirements but also the fabricating and moving conditions. Low-carbon rebars, e.g. ASTM A706, are usually employed here and $CO_2$ welding is utilized on them. Usually, design of reinforcement cage is also highly related to moving methods that utilized in transportation from preassembly yard to precast plant and application of lattice girder can prevent decomposition of rebars effectively while moving.

While assembling the reinforcement bars, their diameters, bent shapes and designs should be simplified and standardized in order to reduce the manpower requirement and efficiently shorten the operation time. Moreover, the bending platform is utilized with various mechanical designs to improve the efficiency and productivity of the works.

## 5. CONSTRUCTABILITY FOR EQUIPMENT SELECTION

### *5.1 Precast girder transportation*

For girder transportation, the carrier's speed is related to the location of precast yard and the distance to transport. The difference of consequences resulted from moving along the deck of erected existing viaduct by the carrier that should be analyzed carefully. For rubber tire carrier, moreover, the tire width, pressure and allocation will relate to the design work of the transverse reinforcement in the deck slab; for carrier on rail, the interaction among carrier, rail and existing viaduct should be concerned.

During the new girder is transporting, the existing erected girder is under the influence of the tension in the deck slab and the braking force of carrier. In order to satisfy the needs of rapid erecting, innovative carrier that can transport girder with various lengths and three-dimensional intersection among equipments should be invented and utilized.

### *5.2 Site erecting*

In practice, the single-girder launching equipment and twin-girder launching equipment are alternatives in application. In the other hand, the assembly details and the test running circumstance of the launching equipment should be considered, too. Moreover, it needs to be noticed that the launching equipment cannot be conflicted spatially with the existing high-voltage electric cable and lightning protectors.

### *5.3 Launching equipment*

In the case of single-girder launching equipment, the position of front supporting frame (leg) on the pier cap top is related to the size of the pier cap and the design of metal bearing. Moreover, it should be concerned with the problem of punching holes by the rear-supporting frame on the deck slab.

The twin-girder launching equipment can be divided into two types, which the upper and lower guide girders are connected or non-connected. The authors regard that the twin girder with connected upper one and lower one is not suitable for FPLM in THSR project. The twin-girder system, with non-connected upper and lower guide girders, should be able to skip over the deck of cast-in-situ bridge, whose length of span is longer than the precast girder. Moreover, the position and stability of bracing frame of lower guide girder are also important.

## 6. CONSTRUCTABILITY WITH STRUCTURAL REQUIREMENTS

### *6.1 Use of pre-tension method*

The difference between the pre-tension method and conventional post-tension method are on their cost and cycle time. Preventing the strays current resulted from power system is one of the most important issues in pre-tension method. Moreover, simplifying the installation of high-tension strands through the pull-head can save the manpower employed, and using the mono-coupler at the outside of the end form can reduce waste of the high-tension strands after cutting, too.

### *6.2 Concrete and steam curing*

Quality control of concrete is another important issue in FPLM, and concrete it and steam curing usually play critical roles. First, stable quality control and storage of cement and aggregates are essential requirements. Shrinkage and creep potential of newly placed concrete should be monitored carefully. To obtain better performance, application of admixtures, e.g. supper plasticizer, granulated blast-furnace slag powder and fly ash, is permitted in most circumstance and in recent years HPC becomes popular gradually. But the initial setting time and the slump of HPC should be controlled well. However, only innovative material and careful placement are not enough, casting and curing methods usually affect the final quality of concrete and cycle time significantly.

After initial setting, concrete is heating gradually by prearranged steam pipes with temperature sensors to perform curing works. In practice, quality of water for steam-curing system cannot be ignored and the completeness of steam curing mask is beneficial to prevent steam escaping. According to the experience of Kaoshiung Ring Route C393Z in Southern Second Freeway project in Taiwan, transverse pre-tension method for pre-cast segments had been adopted in viaduct construction and the pre-stressing strands were cut after 12-hour steam curing. Can the contractors in THSR project shorten the steam-curing time to not more than 10 hours?

### *6.3 Metal bearing*

The special requirement of longitudinal force transmission mechanism should be considered while metal bearing is used on the long viaduct in the high-speed railway project. Moreover, the structural reinforcements and the shear studs on the top masonry plate are allocated in three dimensions and the interface of the top masonry plate and bottom slab will influence the design of rebars and bottom formwork. Also, the adjusting block for slope should be concerned. The bottom plate and the pier top are connected, too. Moreover, the installation of the metal bearings and fabrication of the rebar cages should be concerned of and prevent from the happening of stray current.

During erecting, the position of the metal bearing on pier top cannot be conflicted with the front leg of the launching equipment or bracing frame. While earthquake or typhoon is happening, it needs to prevent the erected existing girders falling. To maintain or replace the metal bearing, in the other hand, the regular operation of train on the viaduct cannot be interrupted.

*6.4 Continuous girder design*

For highway bridges, which require smooth surface of deck with limited expansion joints, the continuous beams are selected at most time. For railway bridges, in the other hand, the deck expansion joints are related to the interaction with track. The track expansion joints should not be above the deck expansion joints. For this reason, the continuous structural beam may require for the track expansion joint or switch. Therefore, the location of the temporary bearings and the details of protruded rebars need to be planned carefully. While erecting, the erected existing girders in simple support condition should be able to bear the live load of transporting the new girders. Then non-shrinkage concrete is poured into the joint for closing adjacent girders in situ. Consequently, post-tension method is utilized as secondary prestressing. It should be noticed that transportation and erecting for new girders have to be interrupted while continuous structure is under construction. This is the disadvantage of FPLM construction.

*6.5 Optimal girder length and pier allocation*

The length of typical precast girders, which are used on land as well as across the rivers, is evaluated generally. It is necessary to estimate the weight and cost of carriers and launching equipments precisely in order to be the basis for evaluation. The layout of piers not only takes the production plan of precast box-girders into account but also will not be conflicted with existing roads and channels because of utilization of two different lengths of girders.

If the extra high-tension strands are unnecessary totally during new girder transportation, it is recommended to use longer precast box-girder if possible. Moreover, a longer precast box-girder may reduce the number of bottlenecks caused by three-span continuous support, cast-in-situ bridges in FPLM construction.

## 7. CONCLUSION

In recent years, construction firms in Taiwan recognize the importance of FPLM to THSR project. Some engineers of them have already visited the KHSR construction sites, such as Lot 2-2 by Hyundai Construction Co., Lot 3 by Dong-Bu Construction Co. and Lot 8-2 by DaeWoo Construction Co., in which they all adopt FPLM, named PSM in Korea, as their viaduct construction method.

According to these engineers' surveys [6-9], precast plants in both Hyundai and Dong-Bu produce one girder every two days on a set of form bed only. Moreover, the time required in FPLM is only 80% of the cost and 1/6 of the time required by Moving Scaffold System (MSS) method to produce girder with the same length. It is not strange that contractors in Korea gave up the familiar MSS method and adopted FPLM, a comparatively unfamiliar method, to the viaduct construction in KHSR project.

Mr. J.E. Park, the former site manager for DongBu Construction Co. in KHSR Lot 3 who is one of the pioneers of FPLM in Korea, mentioned the followings in his personal advice letter to Taiwanese contractor, which he had seriously experienced. There are very important to the successful execution of FPLM which should be keep in mind always [10]:

(1) Introducing general concepts of FPLM into the design.
(2) Setting up detailed unit procedures to execute easily and timely.
(3) Considering scope of works and functional requirements for equipments in details.
(4) Consideration of utilization and weather in erection of the prefabrication yards and precast plants.
(5) Constructability represented in the detailed designs and shop drawings.

In the forthcoming THSR project, it is believed that if the 250-km viaduct construction will be completed in time within budgeted capitals, the key to turn on these achievements is undoubtedly implementing FPLM under excellent quality management. It should be kept in mind that various and evolutionary interfaces during planning, design and construction phases should be taken into consideration system-widely, concurrently and even in advance. To accomplish this, the following concepts are highly recommended by the authors:

(1) During the initial period of planning stage, the engineers should Keep thinking Integrated, Systematically and Scientifically ($KISS^1$) and Keep the Interface becoming Systematically and Scientifically ($KISS^2$). In short, this is "Design for Construction" and even can be expanded to "Design for Operation."
(2) Also, the engineers should incorporate the requirements for related and additive facilities into the consideration of structural behavior of bridges or viaducts adequately and completely in advance.
(3) Discovering the blind spots of FPLM continuously, the engineers have to prevent these in advance, too.
(4) The engineers should be familiar with the application of machinery in construction, especially highly automated viaduct construction.
(5) Besides these, the engineers must recognize that good and regular maintenance for machinery

during construction period will promote the performance of overall project.

(6) The engineers should devote their efforts to resolve the bottlenecks caused by the inevitable cast-in-situ bridge of FPLM construction before the transportation and erection of new girders. In order to facilitate the crossing of new girder during transportation, the engineers should try to streamline the workflow of every FPLM operation as possible as they could.

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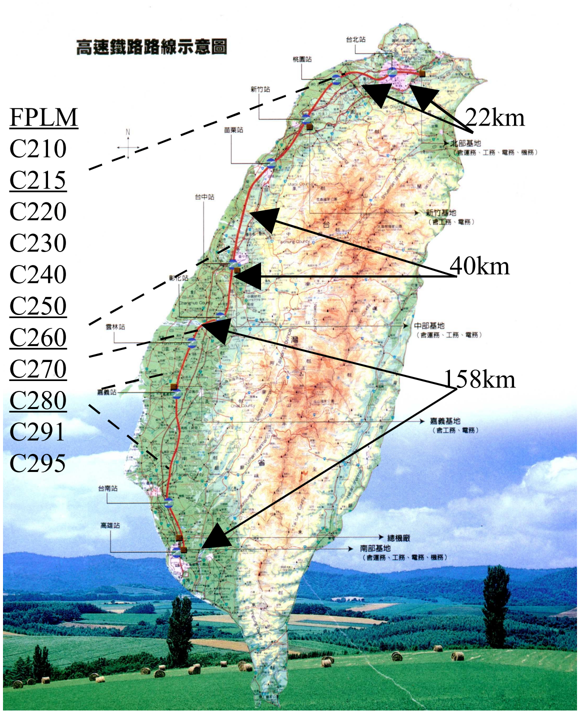


Figure 1. The long viaduct may employ with FPLM in the route of Taiwan HSR

Figure 2. The girder forwarding by gantry Launcher operate in Pyung-Taeck, Korea HSR Lot 3