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# Cost Comparison of Inverted Tee Girder with I-Girder: A Case Study of Shalimar Flyover

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## Abstract

*A study is conducted to compare cost, construction time frame and safety of the inverted-T Girder design concept used in the design of Shalimar Flyover with conventional I-girder. First, the superstructures with NHA (National Highway Authority) 'Type H' I-girder at five different centre to centre spacing are designed and the one at 2.75m is found to be the most economical for the span used at Shalimar Flyover. Secondly the economical I-girder superstructure is compared with the Inverted-T girder superstructure used at Shalimar Flyover at 1m centre to centre spacing and it is observed that the inverted-T girder at 1m c/c spacing is 22.64 % more expensive than the I-girder super structure at 2.75m c/c spacing. However, the Inverted-T girder super structure is lesser in depth and requires lesser number of spans for the same reach than the I-girders. This reduces land acquisition cost which in turn affects the total cost of the project. The Inverted-T girders are also checked at different spacing and it is found that the same girder section at 1.3m centre to centre spacing is 9.06 % economical than the adopted 1m c/c spacing of the girders at Shalimar Flyover.*

**Key Words:** Reinforced Concrete Bridge, Inverted T Girder, I- Girder, Cost comparison

## 1. Introduction

Bridges are one of the key elements in the transportation system and play a vital role in the economy of a country. Economic and time constraints are studied before such facilities are provided at important road junctions. Due to current economic situation of Pakistan, the facility should be provided within the available funds and a balance must be achieved between the cost and construction time frame without compromising the safety of the structure. One kilometer long Shalimar Flyover connecting Shalimar link road to the main cantonment over the railway crossing is one step towards the speedy flow of about 35000 vehicles that move across the canal daily. The current design practice in Pakistan is to design the bridges by providing simply supported I-girders over piers and using in situ deck slab over these girders. However, the designers are willing to adopt modern concepts developed in other part of the world. One such concept is the Nebraska Inverted Tee (IT) system used in the design of Shalimar Flyover. The precast post-stressed inverted–T bridge system was developed at University of Nebraska, Lincoln [1]. The system consists of inverted–T shaped cross section as longitudinal post-stressed concrete members. This system comprises of stay-in-place (SIP) formwork for the cast-in situ slab. This results in reducing the labor and construction time and also reduces shuttering required for the deck slab. The members in inverted-T are light weight, which facilitates the handling and placement of the inverted-T system. Through analytical and experimental testing, researchers have shown that the system can span up to 25.9 m (85 ft) with a total structural depth of 725 mm (28.5 in) [1,2].. Ambare and Peterman [2] suggested some modifications in the inverted-T system at Kansas State University. According to them the inverted-T should have curved edges instead of knife edges to eliminate bug pores during the process of casting. The approximate equations given in AASHTO LRFD cannot be used for determining the load distribution factors in the IT system because the required girder spacing conditions are not met. Therefore, there was a need for refined methods of analysis. Ambare and Peterman [2] carried out their research work for the live load distribution factors for inverted–T girder and they found that the AASHTO LRFD approximate equation gives slightly higher values for live load distribution factors than were derived by refined methods. The distribution factors for shear loads are slightly conservative but may become unsafe for large skew angles.

The researchers suggested that the available design procedures for the prestressed concrete I-girder bridges may be used for the design of this new system because the guidelines for the design of new IT girder system are still being developed. [2,3]. Therefore, attention is required during the design of the post tensioned inverted-T system.

The key objectives of the study includes (i) cost comparison of inverted-T girder superstructure to alternative design option of NHA I-girder (ii) Investigation of the adopted Inverted-T girder spacing at the Shalimar Flyover from the economic point of view.

## 2. Bridge Description

The Shalimar Flyover has 31 spans of an average length of 30m each. The Flyover total width is 19.4m dual carriage way with 160mm thick cast in situ deck slab over inverter-T girders and with end NJ barriers and a median at the centre of flyover. The cross section of the bridge is shown in the Fig. 1 and the cross section of the IT girder is shown in Fig. 2. In order to make the comparison, the equivalent alternate design with NHA 'Type H' I-girder is carried out. Width of the Flyover is kept same as in the original bridge, i.e., 19.4m. The cross section of the bridge is shown in the Fig. 3 and the cross section of the NHA 'Type H' I-girder is shown in Fig. 4.

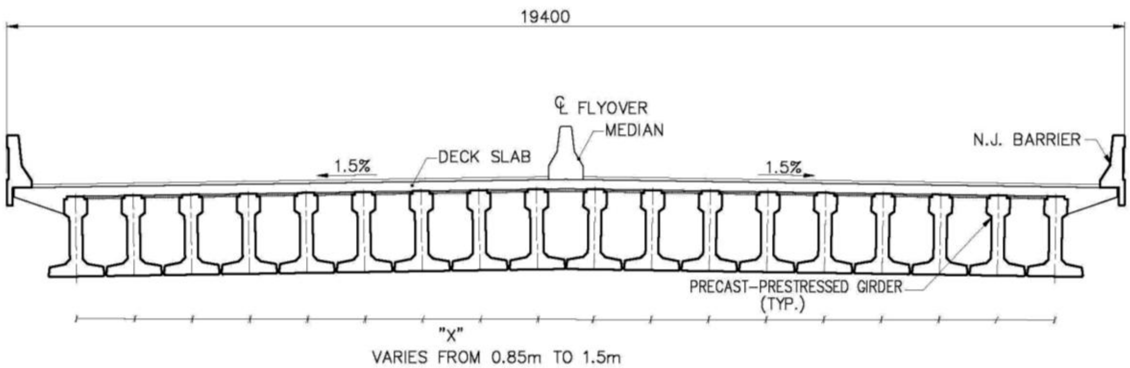



**Fig. 1** Bridge Cross Section for Inverted T Girder Super Structure

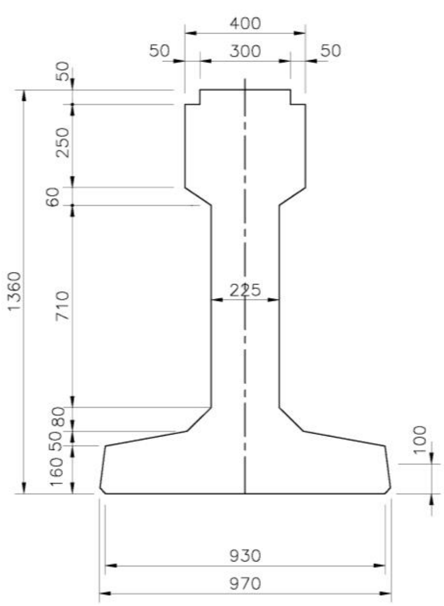



**Fig.2** Cross Section of Inverted T (IT) Girder

| Girder Cross Sectional Properties | | |
|---|---|---|
| Area | 558775 | $mm^2$ |
| M.O.I (Ix) | 1.449E+11 | $mm^4$ |
| M.O.I (Iy) | 3.04E+10 | $mm^4$ |
| Location of N.A from bottom | 520.525 | mm |

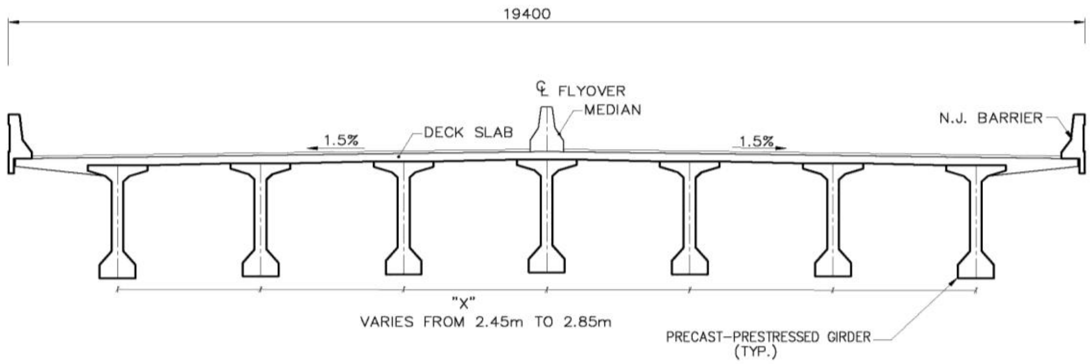
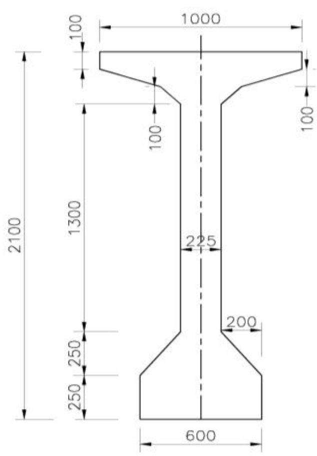



**Fig.3** Bridge Cross Section for NHA 'Type H' I-girder Super Structure




| I Girder Cross Sectional Properties | | |
|---|---|---|
| Area | 692000 | $mm^2$ |
| M.O.I (Ix) | 3.811E+11 | $mm^4$ |
| M.O.I (Iy) | 1.795E+10 | $mm^4$ |
| Location of N.A from bottom | 1035.453 | mm |

**Fig.4** Cross Section of NHA 'Type H' I-girder

One of the major factors effecting cost of system is the number of girders which directly depends on centre to centre spacing between the girders. Therefore the main focus of the study was the effect of centre to centre spacing of the girders on the overall cost. Accordingly, both types of superstructures are studied under varying centre to centre spacing. Five cases with different girder spacing are carried out for each type of superstructure to find out the most economical solution as shown in Table 1.

Grillage analysis technique is used for the analysis of system. In this method the real structure is idealized as rigidly connected skeletal members at nodes. The load deformation relationship at ends of skeletal elements is expressed in term of stiffness property with due consideration to member axis. Loadings are converted into nodal loads by calculating the fixed end forces and then transferring to global axis. The resulting system of simultaneous equations is solved to find the nodal displacement in the structure. The forces in the member are found by back substitutions of the nodal displacements in the system of equations. The bridge super-structure is stiff in the horizontal plane due to the presence of deck slab. The displacements along two horizontal axis (parallel and perpendicular to road way) and rotation about vertical axis is not considered in analysis as the structure is very stiff against these deformations. Analysis of the structure is carried out for the dead loads including self weight of girder, deck slab, wearing surface and barriers loads. Live load is considered as per West Pakistan code of practice for highway Bridges [4]. After carrying out the analysis the stresses for three stages i.e., at yard, intermediate loads and service loads are evaluated for each case. The pre-stressing force is kept constant in all the cases and the effect of change in centre to centre spacing of girder is focused. Full pre-stressing is done and only the minimum amount of mild reinforcement is provided in girders. Stresses at the extreme fiber are checked at three different stages and compared with the allowable limits by AASHTO

[5]. It was found that the stresses in all the cases except IT-5 were within the allowable limits.

| Girder Allowable stresses | Top fiber ($KN/m^2$) | Bottom fiber ($KN/m^2$) |
|---|---|---|
| At Yard | -3 √fci’ | 0.55 fci’ |
| Intermediate Condition | 0.55 fci | -3√fci |
| At service load | 0.6 fc’ | -6 √ fc’ |

Minus sign indicates tension.

The ultimate moment and ultimate moment capacity comparison for different cases is given in the Table 2. The ultimate moment capacity of the same girder sections is different because of varying composite section properties i.e. effective flange width and number of tendons required is not same for all the cases. The IT at 1.5m centre to centre is over stressed because the numbers of strands required are not adjustable in the section and the section crosses the allowable deflection under live load.

**Table-1** Analysis and Design Models

| Bridge Superstructure | Girder Spacing c/c (m) | No. of Girder (Nos.) | Deck Slab Thickness (m) | Cantilever (m) |
|---|---|---|---|---|
| Bridge Superstructure with NHA ‘Type H’ Girders | | | | |
| I-1 | 2.45 | 8 | 0.225 | 1.125 |
| I-2 | 2.55 | 7 | 0.225 | 2.05 |
| I-3 | 2.65 | 7 | 0.225 | 1.75 |
| I-4 | 2.75 | 7 | 0.225 | 1.45 |
| I-5 | 2.85 | 7 | 0.225 | 1.15 |
| Bridge Superstructure with IT Girders | | | | |
| IT-1 | 0.85 | 22 | 0.160 | 0.775 |
| IT-2 | 1 | 18 | 0.160 | 1.20 |
| IT-3 | 1.15 | 16 | 0.160 | 1.075 |
| IT-4 | 1.3 | 14 | 0.160 | 1.25 |
| IT-5 | 1.5 | 12 | 0.160 | 1.45 |

**Table-2** Ultimate Moment and Ultimate Capacity Comparison

| Bridge Superstructure | Girder Spacing c/c (m) | Ultimate Moment (T-m) | Number of Tendons (Nos.) | Moment Capacity (T-m) |
|---|---|---|---|---|
| Bridge Superstructure with NHA ‘Type H’ Girders | | | | |
| I-1 | 2.45 | 1066 | 4-(7/0.5) | 1170 |
| I-2 | 2.55 | 1197 | 5-(8/0.5) | 1343 |
| I-3 | 2.65 | 1199 | 5-(8/0.5) | 1343 |
| I-4 | 2.75 | 1177 | 5-(7/0.5) | 1195 |
| I-5 | 2.85 | 1163 | 5-(7/0.5) | 1195 |
| Bridge Superstructure with IT Girders | | | | |
| IT-1 | 0.85 | 525 | 3-(9/0.5) | 540 |
| IT-2 | 1.00 | 643 | 3-(12/0.5) | 686 |
| IT-3 | 1.15 | 672 | 3-(12/0.5) | 686 |
| IT-4 | 1.30 | 748 | 3-(14/0.5) | 752 |
| IT-5 | 1.50 | 1479 | | Over Stressed (O/S) |

**Table 3** Bill of Quantities for Girders at 2.75m centre to centre (I-4 Case)

| DESCRIPTION | | L | W | H | Nos. | Qty. |
|---|---|---|---|---|---|---|
| | | m | m | m | | |
| Deck Slab Concrete ($m^3$) | | 30 | 19.4 | 0.225 | 1 | 130.9 |
| Deck diaphragm Concrete ($m^3$) | | 15.1 | 0.2 | 1.85 | 2 | 11.17 |
| | | 15.1 | 0.2 | 1.25 | 2 | 7.55 |
| Prestress -I Girders 30m span Concrete ($m^3$) | | 30 | Cross sectional area of girder 0.692 | | 7 | 145 |
| Launching of Precast Girders (Ton) | | @ 2.4 x Qty. in CM | | | | 349 |
| Reinforcement in Deck slab (Ton) | # 6 | 19.25 | | | 265 | 11.4 |
| | # 4 | 30 | | | 172 | 5.13 |
| Reinforcement in Diaphragm (Ton) | # 8 | 15.9 | | | 14 | 0.88 |
| | # 6 | 15.9 | | | 18 | 0.3 |
| Tendons (0.5 "dia.) Prestressed steel Wires (Ton) | | | | | | 1.64 |
| Non prestressing reinforcement in Girder (Ton) | Shear Stirrup | | | | | 2.58 |
| Non prestressing reinforcement in Diaphragm (Ton) | | | | | | 1.18 |

**Table 4**. Cost Estimate for Girders at 2.75m centre to centre (I-4 Case)

| Per Girder Cost Estimate | | | | | |
|---|---|---|---|---|---|
| Description | UNIT | QTY | RATE | Amount | |
| | | | Rs. | Rs. | Million Rs. |
| Reinforcement as per AASHTO M-31 Grade-60 | Ton | 2.6 | 108830 | 282958 | 0.283 |
| Prestressing Steel (Pre- cast prestressed girder) | Ton | 1.64 | 260529 | 427267 | 0.427 |
| Precast Prestressed Girders, Concrete (5000 psi) | CM | 20.7 | 7785 | 161150 | 0.161 |
| Launching of Precast Prestressed Girders | Ton | 50 | 602 | 30100 | 0.030 |
| | | | | 901475 | 0.901 |
| Total Number Of Girders = | 7 | Nos. | | | |
| Total Cost Of Girders = | 6310325 | Rs. | | | |
| Deck Slab Estimate | | | | | |
| Description | UNIT | QTY | RATE | Amount | |
| | | | Rs. | Rs. | Million Rs. |
| Deck Slab Concrete (4000 psi) | CM | 131 | 7618 | 997958 | 0.998 |
| Reinforcement as per AASHTO M-31 Grade-60 Deck Slab | Ton | 16.53 | 108830 | 1798959 | 1.799 |
| Diaphragm Concrete (4000 psi) | CM | 18.75 | 7618 | 142838 | 0.143 |
| Reinforcement as per AASHTO M-31 Grade-60 Diaphragm | Ton | 2.39 | 108830 | 260104 | 0.260 |

The bridges were designed for all the cases given in Table 1. For brevity the only final results are discussed here. The complete analysis and design results can be found in some other reference [7]. After designing the super structure, the bills of quantities are prepared and then the cost of the superstructure for 30m span length is calculated. The unit rates are taken from composite schedule of rates for Punjab province as published by National Highway Authority [8]. Bill of quantities and detailed cost analysis of the superstructure for case I-4 are given in Table 3 and 4. Separate cost for each girder and deck slab is calculated to show the variation in cost as the spacing of girder is changed. Table 5 shows the cost comparison of superstructure of all the cases for 30m span length. The cost for IT-5 is not calculated because it is overstressed. From the above cost analysis it is clear that the super structure with girder at 2.75m centre to centre spacing (Case I-4) is most economical design and is used for comparison with the inverted-T girder system at 1m centre to centre used in Shalimar Flyover. From the rate analysis we can see that the number of girders matters a lot as the cost of single girder at 0.85m centre to centre spacing is the most economical one but as at this spacing number of girders required are more than other options which makes this solution uneconomical. As the girders have been placed side by side, the thickness of deck slab has been reduced from 225 mm to 160 mm which gives cost saving as well as time saving as lesser volume of concrete is casted. No shuttering and scaffolding is involved in casting of the deck slab in case of IT girders. This results in saving of time (at least 31 weeks for 31 spans). As no scaffolding is required for the support of deck slab formwork, therefore there is no hindrance to the movement of traffic underneath the Flyover during construction. A smooth bottom finish is obtained in case of inverted-T girder due to negligible gaps between the girders. However, there may be ugly mud and strains at the joint between the bottom flanges with the passage of time. Moreover, it is impossible to visually inspect the condition of the girders after an overload or breakage of tendon.

**Table 5** Total Cost of Super Structure for one Span

| Bridge Superstructure | Spacing | No. of Girders | Per girder Cost | Total cost of girders | Deck Slab Cost | Diaphragm Cost | Total Cost |
|---|---|---|---|---|---|---|---|
| | m | Nos. | Million Rs. | Million Rs. | Million Rs. | Million Rs. | Million Rs. |
| I-1 | 2.45 | 8 | 0.920 | 7.363 | 2.492 | 0.382 | 10.237 |
| I-2 | 2.55 | 7 | 0.870 | 6.092 | 3.145 | 0.382 | 9.619 |
| I-3 | 2.65 | 7 | 0.871 | 6.094 | 3.164 | 0.398 | 9.656 |
| I-4 | 2.75 | 7 | 0.901 | 6.310 | 2.797 | 0.408 | 9.516 |
| I-5 | 2.85 | 7 | 0.899 | 6.295 | 3.164 | 0.421 | 9.879 |
| IT-1 | 0.85 | 22 | 0.557 | 12.260 | 1.853 | 0.356 | 14.470 |
| IT-2 | 1.00 | 18 | 0.613 | 11.031 | 2.120 | 0.345 | 13.495 |
| IT-3 | 1.15 | 16 | 0.629 | 10.059 | 2.130 | 0.334 | 12.524 |
| IT-4 | 1.3 | 14 | 0.694 | 9.712 | 2.221 | 0.335 | 12.268 |
| IT-5 | Girders are over stressed, Cost is not Estimated | | | | | | |

**Table 6** Total Cost of Super Structure

| Bridge Superstructure | Spacing | No. of Girders | Per girder Cost | Total cost of girders | Deck Slab Cost | Diaphragm Cost | Total Cost |
|---|---|---|---|---|---|---|---|
| | m | Nos. | Million Rs. | Million Rs. | Million Rs. | Million Rs. | Million Rs. |
| I-1 | 2.45 | 8 | 0.920 | 7.363 | 2.492 | 0.382 | 10.237 |
| I-2 | 2.55 | 7 | 0.870 | 6.092 | 3.145 | 0.382 | 9.619 |
| I-3 | 2.65 | 7 | 0.871 | 6.094 | 3.164 | 0.398 | 9.656 |
| I-4 | 2.75 | 7 | 0.901 | 6.310 | 2.797 | 0.408 | 9.516 |
| I-5 | 2.85 | 7 | 0.899 | 6.295 | 3.164 | 0.421 | 9.879 |
| IT-1 | 0.85 | 22 | 0.557 | 12.260 | 1.853 | 0.356 | 14.470 |
| IT-2 | 1.00 | 18 | 0.613 | 11.031 | 2.120 | 0.345 | 13.495 |
| IT-3 | 1.15 | 16 | 0.629 | 10.059 | 2.130 | 0.334 | 12.524 |
| IT-4 | 1.3 | 14 | 0.694 | 9.712 | 2.221 | 0.335 | 12.268 |
| IT-5 | Girders are over stressed, Cost is not Estimated | | | | | | |

Table 6 shows that inverted-T system has 31 number of spans and I-girder superstructure for the same length of the bridge has 34 spans. Three spans of bridge were reduced (3x30=90 m) due to reduction in depth of girders thus giving a saving in cost due to lesser land acquisition. Depth in elevation of superstructure at Shalimar Flyover has been reduced by 800 mm which gives an elegant grace to the bridge super/sub structure.

Total depth of girder including slab using conventional girders (I-type) = 2.325 m.

Total depth of girder including slab using new design girders (inverted t-type) = 1.520 m.

Reduction in depth of girder = 0.805 m

Due to reduced depth of girders the weight of girder was reduced (36 tons vs 50 tons) which resulted in speedy rate of launching with light weight cranes. (Launching rate of 50 ton I girder is 5 to 6 girder/day while, 17 IT girders were launched per day so earlier launching resulted in early casting of deck and early completion of the project resulting in cost saving. From Table 6 it can be seen that the IT-girder system is 22.64 % expensive as compared to I-girder system, but if land cost is taken in to account this difference can further be reduced.

## 3. Results and Discussion

On the basis of results of the analysis and design the following conclusions are drawn:

- The I-girder superstructure (i.e. NHA 'Type H' I-girder super structure at 2.75m spacing) is compared with the Inverted-T girder superstructure used at Shalimar Flyover at 1m centre to centre spacing and it is observed that the adopted one is 22.64 % more expensive than the I-girder super structure at 2.75m c/c spacing of girders.

- IT-girder at 1.3m is the most economical IT-girder solution and requires fourteen girders instead of eighteen girders of the same cross section for adopted 1m spacing at Shalimar Flyover.

- The Inverted-T girders at 1.3m centre to centre spacing is 9.06 % economical than the adopted 1m c/c spacing of the girders at Shalimar Flyover.

- Reduction in length of bridge has resulted in overall reduction of the cost of the bridge due to reduction in cost of bridge itself and due to cost of lesser acquired land and property.

- As the girders have been placed side by side, the thickness of deck slab has been reduced from

225 mm to 160 mm which gives cost saving as well as time saving as lesser volume of concrete is casted.

- No shuttering and scaffolding is involved in casting of the deck slab. This results in saving of time (at least 31 weeks for 31 spans). As no scaffolding is required for the support of deck slab formwork, therefore there is no hindrance to the movement of traffic underneath the Flyover during construction.

- A smooth bottom finish is obtained in case of inverted-T girder due to negligible gaps between the girders. However, there may be ugly mud and strains at the joint between the bottom flanges with the passage of time. Moreover, it is impossible to visually inspect the condition of the girders after an overload or breakage of tendon.

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