Prestressed Steel Arch Bridge

C P Nazir, *Fellow*

Using arch form to span deep gorges with steep rocky banks is not new. However, in recent times other types of construction due to high costs of formwork and construction time have eclipsed the arch bridge. This has prompted a new bridge system being proposed. Called the 'prestressed steel arch bridge', its main load bearing members are steel arch ribs that are prestressed with high tensile rock anchors embedded in the banks. The prestressing aims to achieve material economy by relieving the arch rib bending moments induced under self-weight and non-uniform load. The principle design criteria are design of arch rib as tensile arch under prestressing load during self-weight condition and as a conventional arch bridge under live load and temperature variation. The key elements of design and construction are discussed. An example illustrates the effectiveness of the new design.

Keywords: Arch bridges; Steel; Prestressed

INTRODUCTION

Bridges have become important elements of infrastructure. From early ages bridge design has been challenging the skills and stretching the talents of bridge designers. Many designs have evolved to suit the different requirements of span, foundations, availability of materials etc. Arch bridges are amongst the oldest man made bridges. It is a most efficient structural form that is both striking in appearance and aesthetic in character. In a bid to further optimize the use of the arch profile, so as to arrive at a more economical arch bridge design, a new type of bridge called the 'prestressed steel arch bridge' has been proposed. This paper discusses its salient features in respect of design and construction.

Developing a bridge of a new type is a creative challenge as well as a technological one. Lin[1] has stated that 'such creativity generally comes about when the planned and synthesized applications of the available materials, equipment, experience and theories of structural behaviour meet the environmental and construction requirements of the particular crossing'.

OVERALL CONCEPT

The arch bridge carries its load by compression and this makes concrete an ideal material of construction. However, high costs of formwork and construction time have restricted their use. Thus, steel has been chosen as the principal construction material. To make the design more cost effective, the main arch ribs are prestressed so that stresses opposite to those originating from its own weight are produced.

However, since rock is weak in tension, it was decided to regulate the prestressing magnitude which would take advantage of the tensile arch action yet load the foundation in an optimal manner in compression for full dead load and live load. Nazir[2] has developed a similar concept for arch dams. Prestressed steel bridges have been built and have been found to be more economical than prestressed concrete structures[3].

C P Nazir resides at 5A Dilkusha Street, Kolkata 700 017.

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THE NEW DESIGN

The new design that emerged (Figure 1) is called the 'prestressed steel arch bridge' and has the following features:

(a) The main arch ribs are box girders fabricated from structural steel and having a parabolic profile with a rise to span ratio of 0.2 to 0.3.

(b) Reinforced concrete foundations are used to transfer the forces from the arch ribs to the abutments.

(c) Prestressing bar anchors are used to prestress the arch ribs and anchor them to the rocky banks.

DESIGN PRINCIPLE

The first approach to a new design was to use a shallower and, therefore, lighter rib for the bridge. This led to the selection of structural steel. The past decade has seen a dramatic change in the perception of structural steel — from practical but uninspiring, to adaptable but stimulating. The introduction of curved structural sections has allowed more creative bridge designs to be built[4].

It was proposed to transfer the dead and live loads by arch action. A parabolic profile of the arch was selected, as this results in an economical structure for loading which is predominantly uniformly distributed. To reduce the maximum stresses on the arch under loading, the arch rib was prestressed in a manner so as to induce predominantly tensile

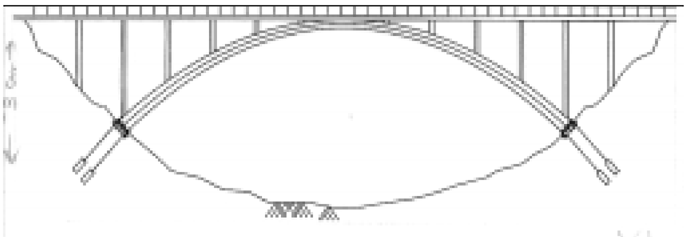

Figure 1 Typical elevation of prestressed steel arch bridge

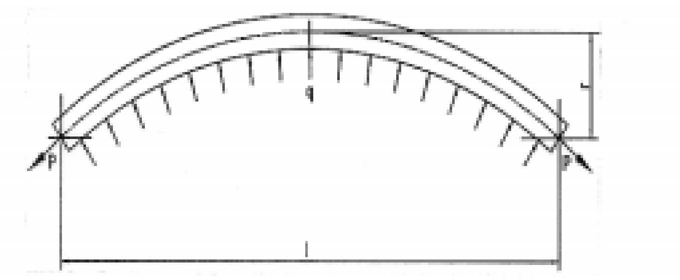

Figure 2 Uniform load due to prestressing

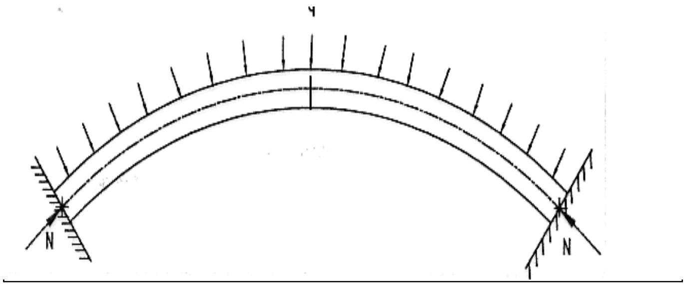

Figure 3 Uniform load due to self weight

stresses throughout the arch section. As seen from Figure 2 the arch rib can be visualized as a tensile arch tensioned by a prestressing force P; which is equivalent to loading the arch by a uniformly distributed load q, having an intensity

$$q = 8\,Pr\,/\,l^2 \qquad (1)$$

where l is the span of arch; and r, the rise of arch. In the final stage when the structure is designed as a conventional arch under uniform dead load and live load, it resists the load predominantly by compression in the member as shown in Figure 3. The stresses in the structure are opposite in nature to those produced by prestress. Thus, at the final stage the structure is effectively designed for only half the dead load and full live load.

PRELIMINARY DESIGN

The more important steps in the design process would comprise: (a) to check if topographical conditions are favourable — an ideal site would be a gorge having steep sides and a relatively short span; (b) to check if geological conditions are favourable — ideally the banks should be composed of strong monolithic rock; (c) selecting a parabolic arch profile for the bridge; (d) selecting a preliminary set of sectional properties; (e) making structural analysis for the various load combinations; (f) results of analysis is used for designing all structural members; (g) making dynamic analysis for wind and earthquake forces; and (h) determining final section properties.

METHOD OF CONSTRUCTION

Briefly the main stages in construction would comprise: (a) laying out the bridge; (b) installing the prestressing bar anchors in position; (c) constructing the concrete foundations; (d) shop fabricating steel arch ribs. The box girder is fabricated in two pieces like a coffin box and lid. The soffit and two side plates, associated internal diaphragms and stiffeners form the box and the independently stiffened top plate becomes the lid, connected to the box with an external longitudinal seam weld on each side; (e) erecting segments of the steel arch with towers as temporary supports. The heavy segments with base plates is erected first and temporarily bolted; (f) after erection is complete the segments are connected by full penetration welds; (g) securing arches to foundations with high tensile prestressing bar anchors; (h) tensioning of the arch rib by Fressi flat jacks placed on the temporary towers and pushing upwards as shown in Figure 4; (i) the space created between the base plate and the concrete foundation by the elongation of the prestressing bars to be grouted with epoxy concrete as shown in Figure 5; (j) erecting bracing between two arch ribs; (k) removing of temporary towers; (l) erecting steel portals on arch ribs to support concrete deck; (m) casting concrete deck and laying finishing surface; (n) installing railings, light fixtures, drainage pipes, etc; and (o) subjecting bridge to static and dynamic load tests.

EXAMPLE

As a practical design application, an analysis is made of a prestressed steel arch bridge having a span of 50 m, a rise of 10 m and a carriageway width of 7.5 m (Figure 6). Loading

Figure 4 Tensioning of arch rib by jacking

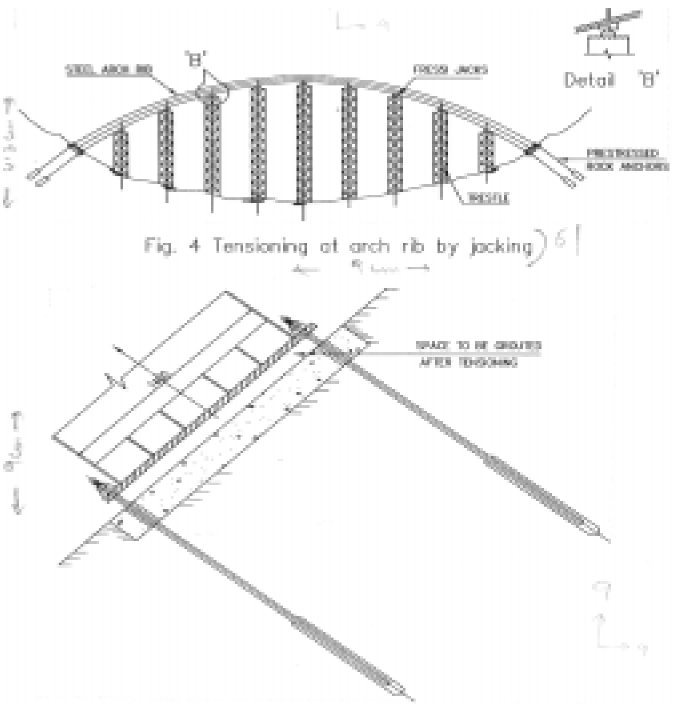

Figure 5 Anchorage cross-section

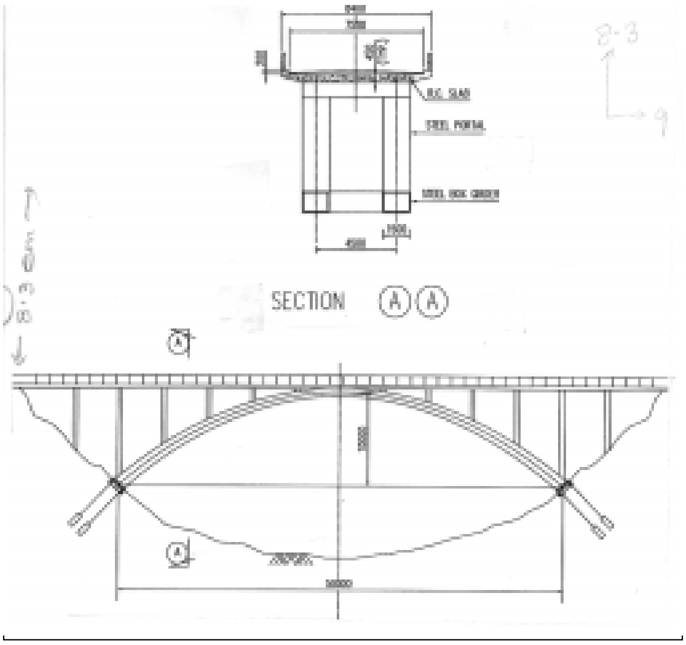

Figure 6 Preliminary dimensions for the example

is as per IRC: 6[5] and the bridge is designed for a Class AA tracked vehicle of 70 t.

For the purpose of this example, the bridge comprises two steel parabolic arches supporting a 450 mm thick concrete deck on steel portals spaced at 5 m centres. The arch is formed by a steel box girder having a constant width of 1.5 m and a depth at crest of 0.8 m gradually increasing to 1.4 m at springing. Plate stiffeners internally stiffen the box. Each end of the box is welded to a steel base plate. The base plates are secured to the concrete foundation by prestressing bar anchors, anchored in rock. The other relevant data used are: mild steel conforming to IS: 2062 grade with minimum yield stress of 230 MN/m^2-250 MN/m^2 depending on thickness of plate and prestressing bar anchors of 26.5 mm diameter having ultimate tensile strength of 1230 MN/m^2 with safe working load of 0.325 MN.

Structural Design

Analysis is carried out for the following four cases:

(a) as tensile arch under prestressing load applied to produce an equivalent uniform load of half the dead load;

(b) as a conventional arch, fixed at supports and with full live load placed at mid-section;

(c) as a conventional arch fixed at supports and with live load placed at supports; and

(d) as a conventional arch fixed at supports under a temperature variation of 10°C.

Loading on One Arch Rib

Dead load: Self weight of slab and portals	=	0.0838 MN/m
Self weight of arch rib and bracings	=	0.0140 MN/m
Total	=	0.0978 MN/m

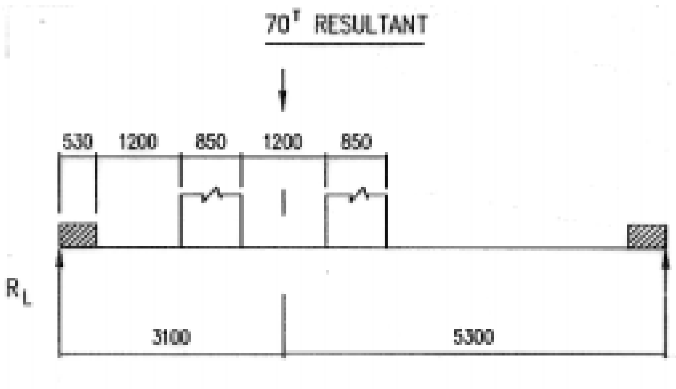

Figure 7 Disposition of Class AA tracked vehicle for maximum load on one rib

LIVE LOAD

For live load, the Class AA tracked loading is arranged as shown in Figure 7 to obtain maximum reaction on one arch rib.

Induced load allowing for impact of 15.4% = 0.7 × 1.154 × 5.38/8.4 = 0.4935 MN.

Length of tracked vehicle is 3.6 m.

Therefore, live load per metre length = 0.4935/3.6 = 0.137 MN.

Structural Analysis

Condition 1: Checking arch rib as tensile arch under a uniform load due to prestress of half the dead load. Based on a STAAD plane analysis of fixed end arch, the moments, thrust and shear are given in Table 1.

Condition 2: Checking arch rib as conventional fixed arch. For maximum moment at crown, the live load is disposed centrally at mid-span over a distance of 3.6 m and full dead load is assumed over the entire span. The moments, shear and thrust are given in Table 1.

Condition 3: This case is similar to Condition 2 except that the live load is placed at the springing to obtain maximum moment at springing. The moments, shear and thrust for this case are indicated in Table 1.

Condition 4: A temperature variation of 10°C is assumed and the moments, shear and thrust are given in Table 1.

Design of Box Girder

The basic elements of the welded steel box girder are shown in Figures 8 and 9.

The section considered has a constant width of 1.5 m, and a varying depth of 1.4 m at springing reducing to 0.8 m at crown. The 12 mm thick arch top and soffit plates and the two side plates are stiffened with 16 mm thick transverse stiffeners at 1.0 m centres and four 16 mm thick longitudinal stiffeners. Stiffened diaphragms are provided at locations of portal legs. To allow for the effect of corrosion of the internal surfaces, a deduction of 0.6 mm to all the plate thicknesses is recommended[6].

Table 1 Results of analysis for different load conditions

Load Cases	Moment, (M), MNm	Thrust, (N), MN	Shear, (V), MN
Condition 1			
Upward load of 0.0465 MN/m			
(a) At springing	– 0.4570	– 1.950	– 0.0930
(b) At crown	0.0340	– 1.470	– 0.0230
Condition 2			
Dead load of 0.0978 MN/m for full span and live load 0.137 MN/m at midspan			
(a) At springing	0.0031	4.790	0.0001
(b) At crown	0.8890	3.780	0.1700
Condition 3			
Dead load of 0.978 MN/m for full span and live load 0.137 MN/m at end			
(a) At springing	2.0630	4.530	0.7200
(b) At crown	0.0530	3.130	0.0500
Condition 4			
Temperature variation of $\pm 10^{\circ}$C			
(a) At springing	± 0.1380	± 0.020	0.0159
(b) At crown	± 0.0650	± 0.029	0.0005

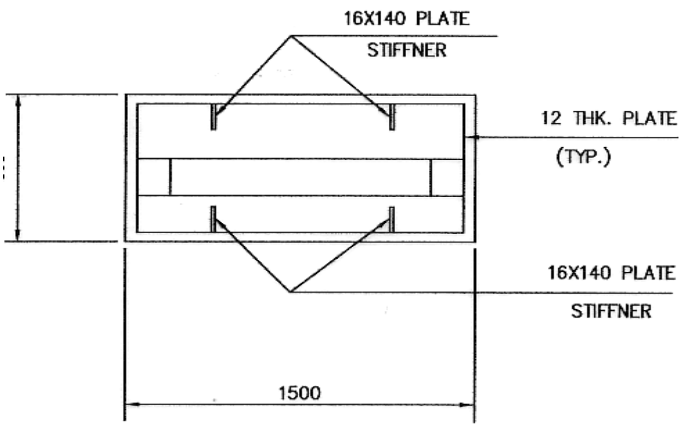

Figure 8 Typical box girder dimensions of example at support

For checking the stresses in the box girder, the allowable stresses as indicated in IRC: 24[7] for steel of grade having yield stress of 236 MN/m^2 have been considered.

SECTION PROPERTIES AT SPRINGING

Area of section, $A_a = 0.0683\,\text{m}^2$, moment of inertia $I_x = 0.0215\,\text{m}^4$, section modulus $Z_x = 0.031\,\text{m}^3$ and radius of gyration, g = 0.56 m.

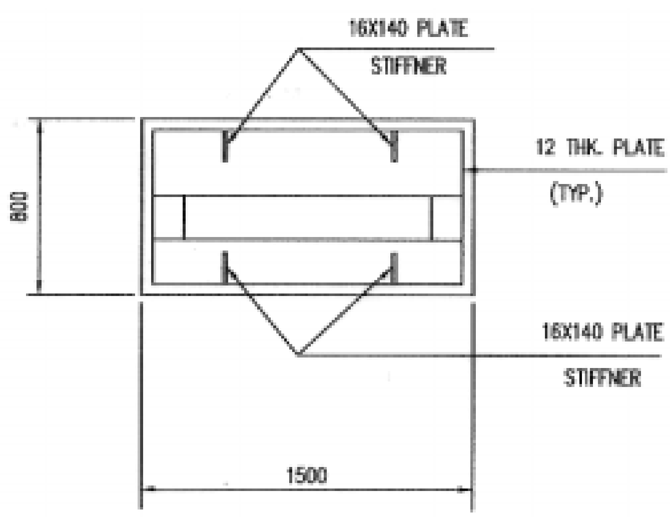

Figure 9 Typical box girder dimensions of example at crown

SECTION PROPERTIES AT CROWN

$A_a = 0.0546\,\text{m}^2$; $I_x = 0.00652\,\text{m}^4$; $Z_x = 0.0163\,\text{m}^3$; and g = 0.345 m.

The relevant stresses for the different load case are shown in Table 2.

Maximum resultant stresses after allowing for prestress:

For springing, Condition 3 is critical;

Direct stress $f_a = -28.67 + 66.62 + 0.29 = 38.24$ MN/m^2

Bending stress $f_b = -15.23 + 68.76 + 4.6 = 58.13$ MN/m^2

For combined bending and direct load:

$$f_a / F_a + f_b / F_b < 1 \qquad (2)$$

Table 2 Summary of stresses for different load cases

Load Cases	Direct Stress, MN/m^2	Bending Stress, MN/m^2
Condition 1		
At springing	– 28.67	– 15.23
At crown	– 26.72	– 2.12
Condition 2		
At springing	70.44	0.10
At crown	68.72	55.56
Condition 3		
At springing	66.62	68.76
At crown	56.91	3.31
Condition 4		
At springing	± 0.29	± 0.52
At crown	± 4.60	± 4.06

where F_a and F_b are the allowable axial compressive stress and allowable compressive stress for bending; respectively, taking into account buckling factor.

Then 38.24/92.5 + 58.13/141 = 0.41 + 0.41 < 1

CHECKING SHEAR STRESS

Average shear stress $f_s = 0.72/2 \times 0.012 \times 1.4 = 21.42$ MN/m². This is less than the permissible shear stress F_s = 85 MN/m².

CHECKING RESULTANT STRESSES AT CROWN

For crown; Condition 2 is critical

Direct stress $f_a = -26.72 + 68.72 + 0.52 = 42.42$ MN/m².

Bending stress $f_b = -2.12 + 55.56 + 4.06 = 57.5$ MN/m².

Then $f_a / F_a + f_b / F_b$ = 42.42/92.5 + 57.5/141 = 0.46 + 0.41 = 0.87 < 1.

Shear stress f_a = 0.17/2 × 0.012 × 0.8 = 8.85 MN/m² < allowable F_s = 85 MN/m².

Design of Bolts

Using 26.5 mm diameter threaded prestressing bar anchor having ultimate tensile strength of 1230 MN/m² and safe load of 0.33 MN

Net tensile force from arch N = – 1.95 MN: Moment M = – 0.457 MN_m.

$$\text{Force } B_b \text{ in bolt} = N/n + My/I \tag{3}$$

where n is number of bolts; I, moment of inertia bolt group; and y, the lever arm.

Providing a total of 10 bolts in 2 layers at 1.6 m centres.

Tensile force in bolt = 1.95/10 + 0.457 × 0.8/6.4 = 0.195 + 0.057 = 0.252 < 0.33 MN.

The example was not intended to show a final solution, but rather to express how the design could be evolved further to achieve a complex bridge which might reflect the uses of the structure.

COMPARATIVE STUDY

To obtain a preliminary idea of the new design, its cost has been compared to that for a conventional steel arch bridge using the same parameters of the site as shown in Figure 6. For the conventional design, the main properties of the box section are; constant width of 1.5 m; depth at springing 1.4 m; depth at crown 0.8 m; thickness of plate 0.02 m for top/soffit plates and 0.016 m for the two side plates; longitudinal stiffeners 4 numbers, 0.14 m wide and 0.02 m thick; cross stiffeners, 0.14 m wide, 0.02 m thick placed at 1.0 m centres; foundation bolts, 0.075 m in diameter and 8 numbers at each abutment. For the purpose of comparison, as the deck slab and steel portals are common for both designs, the quantities for only the steel arch rib and bolts are considered. The required steel quantities are given in Table 3. The last column gives the relevant equivalent steel quantity of structural steel for both the schemes with the proposed scheme being used as reference. The equivalent quantity of structural steel is obtained by multiplying the quantity of prestressed steel by 1.75 and adding to the quantity of structural steel. As can be seen, the cost advantage for the new design is clearly recognizable.

Table 3 Quantity comparison for structural parts of superstructure

System	Structural Steel, MN	Bolts, MN	Equivalent Quantity of Structural Steel in MN, (%)
Proposed design	0.7716	0.0248	0.7964 (100)
Conventional design	1.0830	0.0248	1.1080 (139)

STRUCTURAL ADVANTAGES

The new design offers comprehensive advantages which may be summarized as:

(1) Prestressing of structural steel increases the strength of the structure leading to a more economical design.

(2) Slender arch rib elements lead to significant advantages in handling and transportation.

(3) Reduced depth of structure for comparable spans, thereby reducing approach — roadway costs for the large number of overpasses.

(4) Lighter structure reducing the inertia effects induced by seismic events.

(5) Greater economies can be achieved when design is used with high strength and weather resistant steels.

(6) The bridge has exceptional grace and beauty and neatly expresses its function.

CONCLUSION

The paper introduces a new concept in steel arch bridge design. It illustrates how innovative design and modern methods of construction can be used to provide a bridge type that will be a viable alternative for examination when conditions favor the use of an arch bridge design.

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