ISSN (Online) 2456-1290

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Vol 3, Issue 1, January 2018

Introduction to Flexiarch Bridge

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Abstract: **--This paper describes the advantages and disadvantages of arch bridges. To overcome the drawbacks of conventional arch bridges, a new innovative segmental flexible concrete arch bridge are developed by Queens University Belfast with the help of Macrete Ireland Ltd. The Study is aimed at introducing this new type of arch bridge. Various advantages of flexi arch over other arch bridges are explained. Different construction methodologies of the flexible arch are studied. Installation of Flexi arch plays an important role in the construction of the bridge. These installation procedures are briefly explained with the help of figures. For a segmental arch bridge, shape and size of voussoirs are very crucial as the numbers of voussoirs is connected to each other to form an arch. Paper describes the calculation of geometrical properties of an arch from span and rise of the bridge. The study explains the necessity and reliability of this new bridge over conventional bridges and an attempt are made to justify the use of Flexi arch bridge in today's scenario.**

***Keywords*: Arch bridge, Flexiarch, Voussoir.**

I. INTRODUCTION

Arch bridges have been used throughout the world since the start of the civilization. Number of thousand year old arch bridges present all over the world still in working condition are the proof of their durability and sustainability. Along with structural efficiency, arches provide aesthetic appearance to the structure. Material used in construction of arch bridges have changed over the centuries from stone masonry to brick and the reinforced concrete. Evolution of precast concrete methodologies have made the longer span and lesser rise of arch possible. Although these new arches are efficient, they have major disadvantages such as reduced life period due to corrosion in reinforcement which leads to increased maintenance cost. Along with the complex design and construction methodologies of arch bridges, time and cost requirement for formwork and centering of arch is very high. Thus conventional girder bridges, truss bridges or suspension bridges are preferred over arch bridges.

Fig. 1. Flexiarch Bridge [7]

In order to overcome the drawbacks of arch bridges, School of Civil Engineering at Queens University Belfast with the help of Macrete Ltd, have come up with the flexible arch system known as Flexiarch, which is the modern way of constructing arch bridges without any disadvantage of conventional arch bridge and additional benefit of unrestricted flow of water through the arch. Flexiarch is an innovative arch structure made of number of trapezoidal voussoir blocks connected to one another with the help of polymer strip on the top which acts as a reinforcement. Thus there is no possibility of corrosion. This flat form is then transferred to the construction site and lifted with the help of cranes. Arch is formed under its self-weight when it is picked up at designated locations and then it is placed on the precast footings. Number of these arches are installed laterally throughout the carriage way. The structure then acts as conventional arch. Thus further installation procedure is similar to that of other masonry arch bridges. Fig. 1 shows the completed Flexiarch bridge.

II. PREVIOUS LITERATURE

Flexiarch was first introduced in Queens University, Belfast under knowledge transfer partnership with Marcete Ireland Ltd. Reference [1] shows construction of third scale flexiarch model to the correct taper for given span and rise and connected by polymer reinforcement. Number of variables were considered for laboratory testing. Uniformly graded backfill fails much prior to arch whereas well graded material when used as a backfill gives very less deformation. Arch fails by formation of mechanism and three hinges form at third span point. Hollow core voussoirs when used with well graded backfill gives more deflection and less peak load as compared to solid voussoirs. Well graded backfill can be formed by mixing 20 mm, 10 mm and 6 mm aggregates with sand and grit. Optimum moisture content of this fill was found to be 6 %. Peak friction angle of 39° and 44° was found experimentally. It was observed that increase in friction angle makes the backfill stronger [1]. When concrete backfill is used deflections are less than that in granular backfill. Arch recovers by a significant amount after removal of all loads. Maximum deflection occurs at 3rd span which recovers up to 70% after removal of load [2]. As the level of backfill above the crown decreases, load distribution decreases and thus more loads are transferred to arch ring. Under the dynamic loading it is found that bridge fails due to exceeding the bearing capacity of backfill and road and not because of hinge formation of masonry arch. Hence it is important to provide properly compacted backfill with high friction angle [3]. Polymer used in Flexiarch carries the tension during lifting of the arch. Reference [4] gives the formulation for calculation of tensile strength of polymer. Factor of safety of 9 was observed for 6 kN tensile strength polymer. It is possible for a bridge to span at different angle than right angle. For such cases, square arch needs more width as compared to equivalent skew arch. In skew arches voussoirs are inclined by certain angle with their vertical axis. Unlike square arc, skew arches experience torsional forces and assume S shape in flat form as shown in Fig. 2[4].

Fig. 2. Flat Skew Flexiarch [4]

As angle of skew increases from 15 to 30 and 30 to 45, peak load carried by the arch decreases. In case of skew arches, load is transferred along the shortest load path. Either along square span direction or along shortest direction [5]. Some research also focuses on comparison between arches made by hollow core and solid voussoirs. Hollow core voussoirs reduce the weight of the arch by nearly 20%. Although both arches fail by hinge formation failure load for hollow core arch was found to be 25% less for 20% lighter arch [6]. Apart from construction of a bridge Flexiarch can be extensively used for other works like bridge widening, retention of service and strengthening pre-existing bridges [7]. Flexiarch can also be looked upon as a possible replacement of a viaduct. It consist of less embedded CO2 and energy as compared to other conventional bridges [8].

III. ADVANTAGES OF ARCH BRIDGES

Arch bridges can be constructed using variety of materials. Man-made materials like concrete or reinforced steel can be used or natural materials like stone or bricks masonry can be used. All forces on an arch bridge are pushed down and are spread evenly to the footing. Shape of the arch ensures that there will be no moment in arch due to dead load once the arch is in position which makes arch extremely strong. Generally, structure gets weaker with time but in arch bridges, with time and load, material gets compacted and arch gets stronger with time.

Long span bridges are also possible to be constructed as arch bridges by building more arches.

Along with structural capabilities arches provide aesthetic appearance to the structure.

IV. DISADVANTAGES OF ARCH BRIDGES

Construction and installation of Arch bridges is relatively difficult as compared to other types of bridges because of the unconventional design.

Due to complex design and installing methodologies, labor and time required for construction of arch bridge is more.

Reinforced concrete arch bridges are mostly used these days. These bridges are susceptible to corrosion which reduces the life of structure significantly.

Due to corrosive reinforcements in RC bridges and variability in stone properties in masonry bridges, regular maintenance of these bridges is must.

Arch bridges require lot of material in construction of arch ring and backfill which can be avoided in other types of bridges.

Installation of arch bridge requires complex centering and formwork assemblies which becomes more difficult to provide when water is flowing under the bridge.

Cost of arch bridge increases significantly because of above mentioned problems.

As all the forces are transferred to the base by the arch ring, arch bridges require very strong supports.

V. MATERIAL

Following is the brief discussion on material required for Flexiarch bridge.

A. Concrete

After the installation of flexiarch, all the forces are taken by concrete as polymer reinforcement is assumed to carry no stresses after placement. Thus high quality concrete should be used to increase the durability during service period and to reduce the variability in case of stone masonry.

B. Polymer

The polymer strip is spread over the entire upper surface of arch and is supposed to carry the self-weight of an arch. As polymer strip does not take any compression it should be able to sustain the tensile stresses occurred during lifting of the arch. Strength of polymer can be decided by multiplying the moment on lifting point by certain Factor of safety and designing the polymer for that moment.

C. Backfill

Any well compacted material with designated strength can be used as a backfill. Number of experiments have been performed in the recent past to compare different types of backfill. Well graded material because of more void content fails at significantly lower load than uniformly graded material. Backfill material in flexiarch can vary according to site conditions and availability. Well compacted soil or plum concrete have been effectively used in the recent constructions of flexiarch.

VI. CONSTRUCTION DETAILS

As discussed earlier, Flexiarch is constructed at construction base where all construction facilities are available and then transported to the bridge site. Material required for construction of arch is concrete of required compressive strength and a strip of polymer reinforcement. Size of the voussoir block is calculated using arch geometry as discussed in section VIII. Trapezoidal shaped voussoir blocks are constructed using moulds of required dimensions such that the wedge is formed between two voussoirs. Moulds can be constructed using appropriate material. Material like Lexan plastic have been effectively used for casting. Lifting hooks are fixed in the blocks using steel rebars during casting for lifting purpose. Voussoir blocks used can be either solid blocks or hollow core. In order to produce hollow core voussoirs, circular tubes are fitted in centre of each mould and then concrete is casted. Once the concrete is set tubes are removed to form hollow core in the voussoir block.

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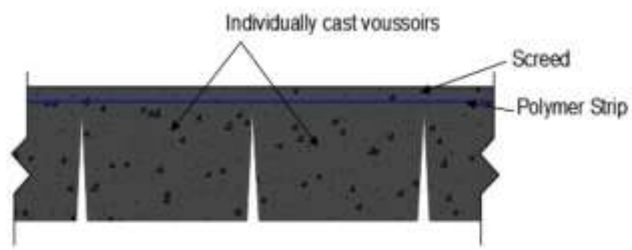

Fig. 3. Decrete casting

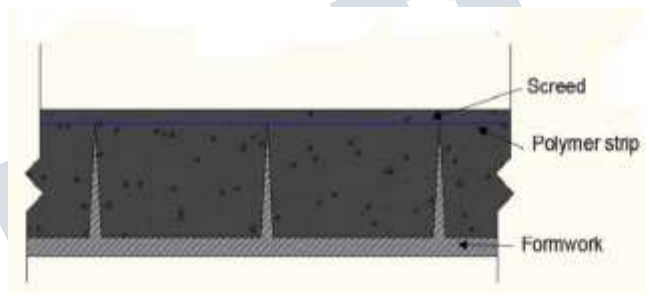

Fig. 4. Monolithic casting

Voussoir blocks can be constructed in two ways. Either the blocks can be constructed individually and then joined together or they can be casted monolithically using single mould as shown in Fig. 3 and Fig. 4.

After the concrete is set, blocks are cured and then the top surface of voussoirs is roughened to get the proper bond between blocks and screed. Once the surface is roughened, polymeric reinforcement is spread over the top surface and bonded. Plain concrete screed of 40 mm thickness is then applied over an entire arch which fixes the polymer between blocks and screed. In order to ensure proper bond between blocks and screed, adhesive is applied on top surface of voussoir blocks. Minimum 7 days of curing of screed is done. Thus blocks get connected to each other with the help of screed and geotextile and we get the transport ready flat form of flexible arch. Required number of these flat arches are constructed and then transported to the site. When the arch is lifted to gain the required shape under its self-weight, cracks formation in the screed at joints is allowed as all the stresses during installation are to be taken by polymer strip.

VII. INSTALLATION OF FLEXIARCH

Once construction of arch decks is done, they are installed on bridge site. Installation of Flexiarch involves, placement of flat arch on transportation media from casting site,

ISSN (Online) 2456-1290

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Vol 3, Issue 1, January 2018

transporting the arch, lifting the deck to form an arch and placement of this arch on precast footings. Once the arch is formed and wedges between the voussoirs are filled, it is not possible for an arch to regain the flat form, thus lifting of the arch from proper locations on the arch is important. While lifting the flat arch to be kept on transportation media, it is lifted at three pre designated locations on arch to assume m shape as shown in Fig. 5. Arch is lifted from 1/4th and 3/4th

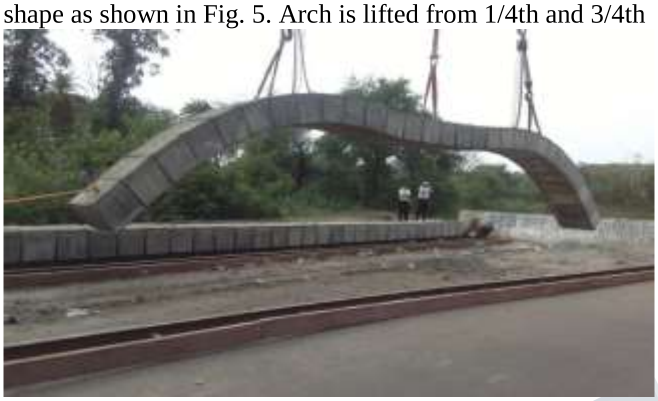

Fig. 5. Half lift of Flexiarch [9]

point on span and is loosely supported at center thus it gains the flat form when placed on transport vehicle. Similarly all the arches are placed and transported to the site. Once on site, arches can be lifted at center and loosely supported at few more points to form the full arch as shown in Fig. 6. Theses arches are then kept on precast footing at site. For proper placement of an arch, top surface of footing and bottom surface of arch need to be coplanar, which needs the footing to be inclined by certain angle. Calculation of inclination angle of footing plane is described in section VIII. Ends of the arch are then fixed on footing using wooden blocks. Number of these arches are then kept laterally throughout the carriage way width. After installation of arches, spandrel walls are installed on both the ends of carriage way as shown in Fig. 7. Spandrel wall should spread throughout the arch and should further extend along the span

Fig. 6. Full lift of Flexiarch [9]

for some distance. Function of the spandrel wall is to restrict the backfill laterally and to support the parapet above. Between the two spandrel walls uniformly graded soil or PCC or other appropriate fully compacted material is installed as a backfill. Required height of the spandrel wall and backfill is maintained at the crown for proper stress distribution. Precast parapet walls are installed once the backfilling is done. In the carriageway backfill is topped by pavement of road and then bitumen or concrete road is constructed.

Fig. 7. Installation of Spandrel wall [9]

VIII. GEOMETRICAL PROPERTIES

Arch shape can be made parabolic or circular. As multicenter arches do not have any significant advantages, circular arches are preferred. Rise of an arch depends upon the height required under the bridge and it varies from site to site. Rise of an arch should be kept as large as possible in order to reduce the horizontal thrust on abutments. In order to determine the geometrical properties of an arch, internal rise and span of the arch is decided from the site conditions. Data required for calculation of voussoir properties is depth of an arch ring 'd' and number of voussoirs 'N' in one arch ring. Generally odd numbers of voussoirs are taken so as to make the lifting easier. Width of voussoirs at intrados and extrados can be calculated by dividing their respective lengths by number of voussoirs in an arch ring. Fig. 8 shows the abbreviations used in arch geometry.

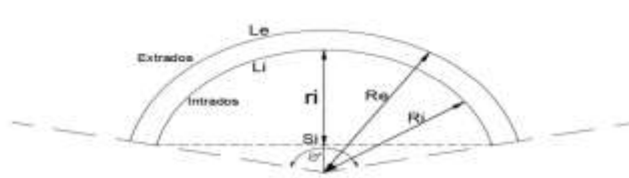

Fig. 8. Arch Geometry

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ISSN (Online) 2456-1290

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Vol 3, Issue 1, January 2018

For rise 'r' and span 's' of an arch, following are the calculations required to calculate voussoir dimensions.

$$R_i = \frac{r_i}{2} + \frac{{s_i}^2}{8 * r_i}$$

$$\theta = 2 * \sin^{-1}\left(\frac{s_i}{2 * R_i}\right)$$

Where,
R_i = Radius of intrados,
r_i = Rise of intrados,
s_i = Internal Span of an arch and
θ = Angle subtended by the intrados
Thus length of an intrados L_i can be calculated using,

$$L_i = R_i * \theta$$

Width of voussoirs at intrados = $\frac{L_i}{N}$
In order to calculate the length of extrados angle subtended by the arch is kept constant and radius of intrados is increased by depth of voussoir.

$$L_i = R_e * \theta \text{ Or,}$$

$$L_i = (R_i + d) * \theta$$

Thus width of voussoirs at extrados = $\frac{L_e}{N}$.
Span of the extrados s_e can be calculated using,

$$s_e = 2 * R_e * \sin\frac{\theta}{2}$$

Area covered by an arc can be calculated using,

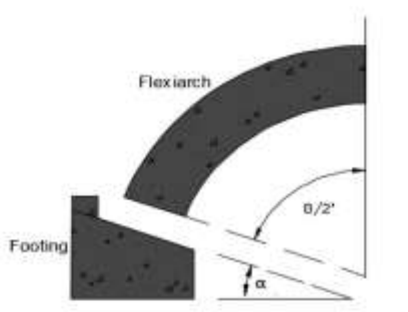
$$A = 0.5 * R^2 * (\theta - \sin\theta)$$

Thus cross section area of an arch ring,

$$A_c = A_e - A_i \text{ Or,}$$

$$A_c = 0.5 * (\theta - \sin\theta) * ({R_e}^2 - {R_i}^2).$$

As discussed in section VII, plane of footing should be parallel to arch base. Thus footing plane should be inclined to horizontal plane by certain angle α. This angle α can be determined with the help of Fig. 9.



It can be observed that,

$$\alpha + \left(\frac{\theta°}{2}\right) = 90°$$

Thus inclination α of footing plane is given by,

$$\alpha° = 90° - \left(\frac{\theta°}{2}\right)$$

IX. DISCUSSION

Flexiarch is constructed off site, where all construction requirements are fulfilled and then transported to the construction site. Thus design and construction complexities occurring in other arch bridges are avoided.
As installation is mechanically operated minimum labor and installation time is required.
As polymer reinforcement is used, there is no possibility of corrosion in the arch ring which increases the life of structure significantly.
As there are no bearings or steel reinforcement, minimal maintenance is required thus reducing the maintenance cost.
Low maintenance and faster construction procedure reduces the overall cost of bridge significantly.
Arches are placed mechanically, with the help of cranes on precast footings. Hence centering is not required and arches can be installed without disturbing the flow underneath.
These advantages along with the additional benefits of conventional arch bridge make the Flexiarch bridge most feasible choice for medium span bridges.

REFERENCES

1. J. Bourke, S. Taylor, D. Robinson, and A. Long, "Analysis of Flexible Concrete Arch," 6th International Conference on Arch Bridges, Fuzhou, China, pp. 134-139, 2010.

2. S. E. Taylor, A. Gupta, J. Kirkpatrick, A. Long, and I. Hogg, "Production of a Novel Flexible Concrete Arch," Third Symposium on Bridge and Infrastructure Research in Ireland, Dublin, Ireland, pp. 1-8, 2006.

3. M. Lydon, S. E. Taylor, V. Sivakumar, D. Robinson and D. Hughes, "Monitoring of a Novel Flexiarch Bridge System to Investigate Soil Structure Interaction," 5th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-5), Cancun, Mexico, pp. 1-9, 2011.

4. P. McNulty, S. Taylor, D. Robinson and A. Long, "Behaviour of a Novel Skew Flexiarch Bridge System," Conference on Bridge and Concrete Research in Ireland, Dublin, Ireland, pp. 1-8,

2012.P. McNulty, “Behaviour and Analysis of Novel Skew Flexible Concrete Arch Bridge System,” Ph. D. Thesis, Queens University Belfast, UK, 2014.

5. J. Bourke, S. Taylor, D. Robinson and A. Long, “Modelling of Solid and Hollow Voussoir Flexiarch Systems,” Journal of Bridge Engineering, vol. BE1, ICE, pp. 61-73, 2013.

6. Long, D. McPolin, J. Kirkpatrick, A. Gupta and D. Courtenay, “Flexiarch: From Concept to Practical Applications,” Structural Engineer, vol. 92(7), pp. 10-15, 2014.

7. Long, S. Nanukuttan, D. Mcpolin, A. Gupta and D. Robb, “Flexiarch System : Renaissance of Arch Culture,” 8th International conference on Arch Bridges, (ARCH 2016), Wroclaw, Poland, pp. 561-570, 2016.

8. Slideshare, “Arch Bridge Project at Nagpur,” Arch Infrastructure, <https :// www. slideshare. Net /archbridge /arch- bridge- project- at- nagpur-india >, 2017.

