Characteristics of historical arch bridges in Korea

N.K. Hong and H.M. Koh
Korea Bridge Design & Engineering Research Center, Seoul National University, Seoul, Korea

S.G. Hong
Department of Architecture, Seoul National University, Seoul, Korea

B.S. Bae
National Research Institute of Cultural Heritage, Daejeon, Korea

W.K. Yoon
Korea Institute of Construction Safety Technology, Seoul, Korea

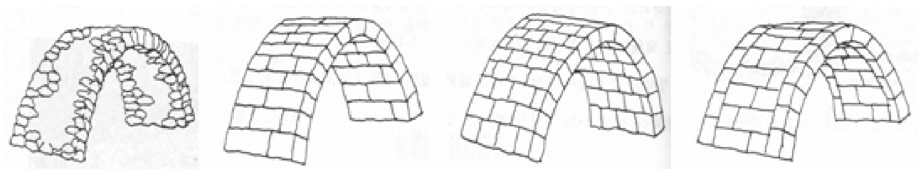
ABSTRACT: The history of construction of bridge structures in Korea dates far back to AD 413 based on the archives of Korean heritage. The stone arch bridge has been considered as one of the earliest advances in bridge engineering. Thanks to its better load-carrying capacity, Backwoon stone arch bridge, a single span voussoir bridge constructed in 760 AD has become the oldest extant stone bridge in Korea. However, many old heritage structures have been inadequately managed exclusive of engineering concerns. This paper first overviews traditional stone arch bridge systems in a general sense, and then discusses some safety issues of stone arch bridges whose structural type was used in many cases in Korea using the limit analysis of masonry arches.

1 INTRODUCTION

The history of construction of bridge structures in Korea dates far back to AD 413 based on the archives of Korean heritage (Sohn, 1992) and the oldest still existing bridge is Backwoon stone arch bridge (AD760). As such, the stone arch bridge represents one of the earliest recorded advances in bridge construction in Korea. Common types of Korean old bridges include stone slab bridges and stone arch bridges. The stone slab bridges were constructed owing to the simplicity of their shapes while the stone arch bridges to the high compressive strength of their material properties. For the case of the slab bridges, the substructures varied depending on the bridge width. As the width increased, substructure types became similar to a frame by laying a stone beam across piers. In the case of the stone arch bridges, semi-circular arch shapes were widely used with stones of about 30 cm by 50 cm, which seemed easy to handle. Variations on stone arch bridges have included small bridges as well as larger and longer multiple-span aqueducts. The majority of surviving stone arch bridges of the 14^{th} -18^{th} century period in Korea have shown the great strength inherent in the arch form and are thus remained as historical heritage. However, historic stone bridges have suffered not only structural degradation but also historic or cultural degradation due to several reasons: (1) urban development without a comprehensive consideration for cultural heritage; (2) restoration of cultural heritage without systematic maintenance management plan; and (3) rehabilitation considering only a few aspects such as structural safety impending at hand. In order to address such problems, concerns both about the conservation and maintenance are growing among preservationists in recognizing and protecting the cultural values. In this context, fundamental understating of stone arch bridges is needed prior to the development of management plans toward conservation of old stone bridges. This paper investigates traditional stone arch bridge systems in Korea why and how they are standing in a general sense. Construction technique of super structure (arch ring or voussoirs) and substructure (piers and abutments from which the arch is said to "spring") will be first reviewed. For some more detailed discussion of structural behavior of different arch systems, the results of plastic analysis conducted to the two arch systems that are similar in structural constituent but different in size. The limit analyses were done as a part of heritage conservation and preservation tasks. It is expected that this study will serve as a starting point for scientific approach in managing stone arch bridges in Korea.

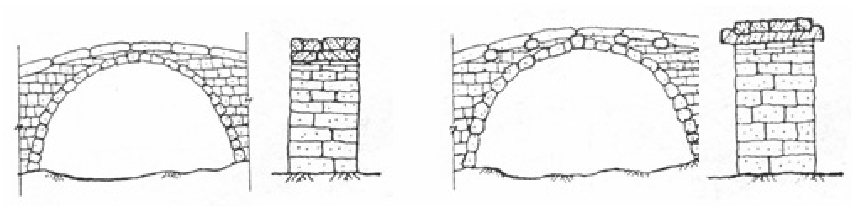
2 CONSTRUCTION OF TRADITIONAL STONE ARCH BRIDGES IN KOREA

Stone arch construction in Korea had utilized semi-circular arches with the aid of falsework during construction. Usages of stone arch bridges were varied from passageways toward temples or pedestrian bridges over small streams to larger and multi-span aqueducts. Figure 1 shows shapes of stones used in the construction of arch rings that consist of from untooled rough stones (Fig. 1a) to finished rectangular (Fig. 1b) and squared stones (Fig. 1c). Also, some arch rings were constructed with ribs (Fig. 1d). The finished rectangular stone arch frame was widespread among them. Regarding the decking systems, there were two common types with or without joist, as shown in Figure 2. The use of joists may be adopted from a tradition of timber structure design.



a. b. c. d.

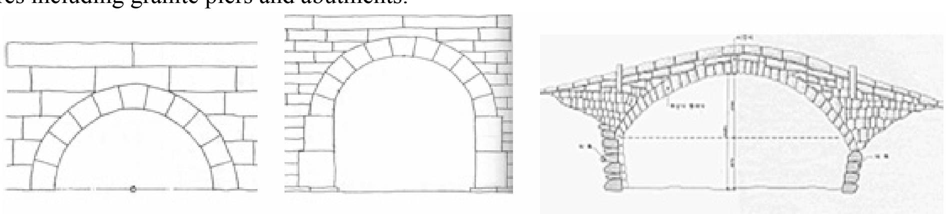
Figure 1 : Types of stones used in arch rings.



a. b. c. d.

Figure 2 : Types of deck systems.

Most small single arch bridges were founded in a natural streambed by diverting the water and excavating gravels to a good footing. From this the abutments were raised to the base of the arches, a point of springing. However, there were some variations in constructing substructures due to water level. These variations played key roles in generating different arch systems from semi-circular to segmental with or without piers and abutments, as shown in Figure. On the other hand large multi-span bridges or aqueducts were supported by well-constructed substructures including granite piers and abutments.



a. Semi-circular arch b. Semi-circular arch with pier c. Segmental arch with pier

Figure 3: Various stone arch bridge systems.

Table 1 describes important attributes of stone arch structures built during 15th through 18th centuries. From this table, the following things were observed:
- The semi-circular arches were widely used in most cases.
- The segmental arch was used to increase the main span length.
- The arch thickness does not seem to relate to the ratio of span/rise.

Table 1 : Stone Arch Bridges in Korea

Bridge Name(built year)	No. of spans	Span(m)	Rise(m)	Span/Rise	Thickness (mm)
Goheung-gyo (1445)	1	4.3	2.15	2.0	480
Ojackyo (1461)	4	4.0	2.8	1.4	530
Heunguksa-gyo (1631)	1	11.3	5.65	2.0	520
Seungsungyo (1698)	1	9.1	4.55	2.0	650
Songgwangsa-gyo (1730)	1	8.0	4.0	2.0	450
Chuckjingyo (1747)	1	9.3	2.8	3.7	400
Hwahonggyo (1794)	7	2.7	1.35	2.0	670
Mananngyo (1795)	7	3.9	1.95	2.0	480

3 CASE STUDY

As bridges are deteriorating with time due to various adverse environments, it is becoming more important to maintain structural performance regard to both their original functions and cultural significances. The damage and deterioration of stone structures are due to mechanical actions (e.g., forces and deformations) and chemical actions (e.g., efflorescence), which cause undesirable defects of material and structure (e.g., cracks, distortions, decay) and subsequently reduced the strength and stiffness. However, regular maintenance was not always adequately provided, and problems developed ranging from deterioration of parapet walls to bulging of spandrel walls due to accumulating moisture in the earth fill. Recently, the importance of cultural heritage has been greatly raised and concerns both about the conservation and maintenance are growing among preservationists in recognizing and protecting the cultural values worldwide. In this section two case studies of single span semi-circular arches which were investigated for the purpose of heritage conservation. The two arch structures are similar in structural constituent but different in size. In order to understand structural behavior focusing on their structural stability issues, the limit analyses were performed using the software of RING 1.5 (Matthew Gilbert, 2005).

3.1 Description of Case Studies

Case 1: Goheung-gyo

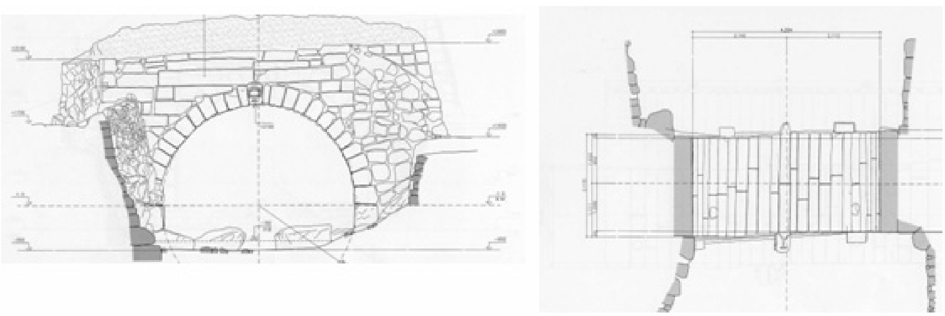


Figure 4 : Case 1 (Goheung-gyo).

Goheung-gyo was built between 1444 and 1445 as part of a town floodgate system. There were two floodgates of similar size one is at upstream and the other at downstream. However, while this town has been changed environmentally many times, old cultural heritage structures including these two arch bridges have been treated inappropriately. Only some historic structures were remained without cultural contexts at that time. Fortunately the two arch bridges still stand structurally safe. The arch span is about 4.3m and the arch ring made of 41 granite stones was on a footing system of natural rock bed as a footing system. The deck system whose width is about 2.16m was made with joists. Figure shows a detail of bridge elevation that was obtained by actual measuring.

Case 2: Moongyung-gyo

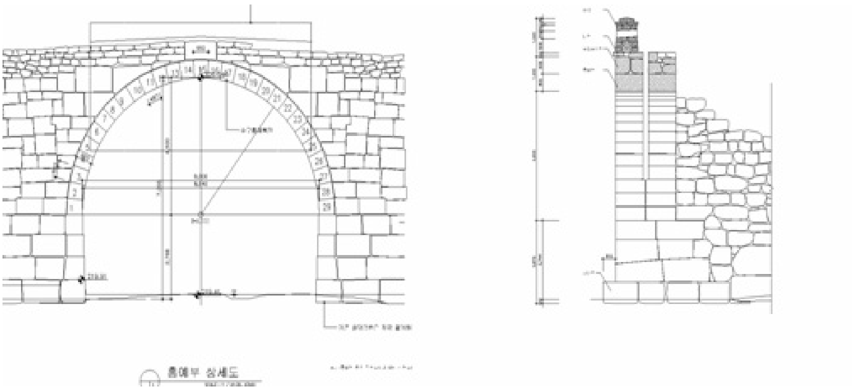


Figure 5 : Case 2 (Moongyung-gyo).

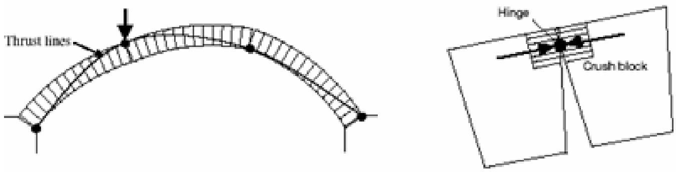
Moongyung-gyo was built between 1444 and 1445 as part of a town floodgate system. In fact this bridge was demolished previously and its picture taken in 1934 and some old documentation about this bridge is available. Recently the local government who takes control of this bridge site wanted to restore this bridge. Prior to the restoration, its structural safety issue was first checked if it has inherent structural problem or not when restored based on the original structural shape. In this bridge two important aspects are found: (1) an iron fence was installed in the middle of the bridge to defend against enemy attack; and (2) the semi-circular arch span is 9m large whose pier is about 2.7m high. Because of this fence which was inserted in the middle of arch bridge, it is considered that this bridge consists of two parallel but separated arch rings. Each arch span is about 9.0m and its arch ring made of 29 granite stones was constructed on a footing system of natural rock bed as a footing system. The deck system whose width is about 1.11m was made without joists. Figure 5 shows a detail of bridge elevation that was obtained from the old documentation.

Table 2 : Description of Stone Structures used for Case Studies

		Moongyung-gyo	Goheung-gyo
Arch Ring	Span (mm)	9000	4300
	Rise (mm)	4500	2150
	Thickness (mm)	600	440
	No. of units	29	25
Arch width (mm)		1110	2161
Abutment	Height (mm)	2766	560
	Width (mm)	800	540
	No. of units	4	1
Fill (mm)		5700	3480
Material Properties	Friction coefficient	0.6	0.6
	Stone weight density (kN/m3)	26	
	Fill weight density (kN/m3)		

3.2 The Limit Analysis Results of Case Studies

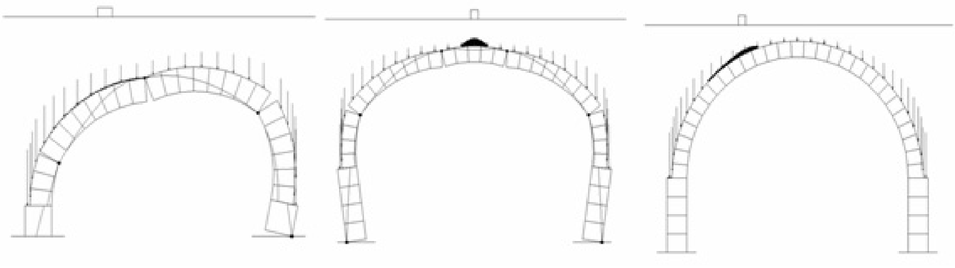
According to Heyman's extension of limit design to masonry structures, the safety of stone arches is a purely geometrical matter, considering that it is almost always possible to assess that mean compressive stresses are low even in structures showing several cracks. In order to check safety of stone arches it is generally used to draw the load's thrust line using the concept of plastic analysis techniques involving mechanisms, as shown in Figure 6. This study used RING 1.5 which has been developed for the analysis of short and medium span single and multi-span masonry arch bridges by adopting the concepts of plastic theory to masonry. Note that friction between voussoirs is assumed to be high enough to suppose that they cannot slide on one another, so that sliding failure cannot occur.



a. Thrust line b. Formation of plastic hinge

Figure 6 : Important concepts of limit analysis.

The limit analyses were performed to check if each of the stone arch bridge under consideration as case studies is stable or not. All the analyzed arch bridges subjected to unsymmetric single load of 1kN at a quarter point of the span. The results of the case studies are drawn with thrust lines if the structure is stable. Figure 4 shows that Goheung-gyo is stable with a failure load factor of 177.3 (Figure 7a) while Moongyung-gyo is stable under symmetric loading with a failure load factor of 46.35 (Figure 7b) and unstable under asymmetric loading (Figure 7c).



a. b. c.

Figure 7 : The results of the limit analysis.

3.3 Parametric Study

It is not easy to assess the safety of stone arches because it is uncertain that what parameter contributes how much to its safety. In order to address one of such issue, this study has investigated the safety of the stone arch system described in Figure 8 through a parametric study. More specifically, the values of minimum thickness of the arch ring for were obtained by varying the height of piers using nondimensional parameters. The investigation results are plotted in terms of the minimum thickness required for structural stability against pier height. To attenuate the effect of pier height on the structural stability issue, the following things are concerned: (1) the material properties remained unchanged through all the numerical analyses; and (2) the thickness of arch ring and piers are the same. Figure 9 shows the analysis results of the influence of pier height on the structural stability. Based on these results, the Moongyung-gyo structure is not stable under the current situation. This means this bridge must be enhanced from the view point of structural stability by proposing and reviewing possible alternatives prior to its restoration.

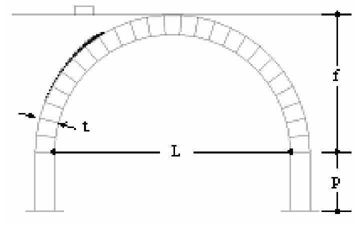


Figure 8: Parametric study model.

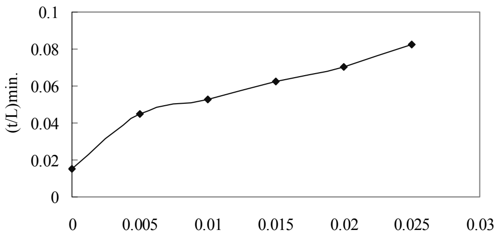


Figure 9: Minimum thickness (t/L) versus pier height (p/L).

4 CONCLUDING REMARKS

Not only an age of a bridge but also an inadequate management has appeared as major reasons for decay of old heritage bridges. More systematic care with an appropriate maintenance programming is both fundamental and effective for better conservation. In this relation, this paper overviewed traditional stone arch bridge systems in a general sense and then discussed some safety issues of stone arch bridges whose structural type was used in many cases in Korea using the limit analysis of masonry arches. Most old heritage stone arches in Korea seemed in semi-circular shape at first appearance. However, many of them are deviated somewhat from the original semi-circular shape which might be resulted from variations due to local site conditions. One of the variations was made by adding piers below the semi-circular arch ring. Accordingly their structural behavior is different from that of semi-circular arch structures. In this study the numerical analysis was done only for case studies focusing on the required minimum arch thickness for various pier heights. It was known that the required minimum thickness of an arch ring increases as the pier height increases through the limit analysis.

There are many influencing factors affecting the safety of old stone arch bridges including the followings: geometry, loads, material properties, degree of material deterioration. This study provides nothing but a starting point. More intensive visual inspection and numerical investigation must be done together for future study because most important material and mechanical behavior of ancient masonry structures are extremely uncertain.

ACKNOWLEDGEMENTS

This work is part of a research project supported by the Korea Ministry of Construction & Transportation through KBRC at Seoul National University.

REFERENCES

[1] Heyman J. 1982. The masonry arch. Ellis Horwood.
[2] National Research Institute of Cultural Heritage. 2003. A study on the conservation and management of stone cultural heritage, Vol. 1. NRICH: 851.
Seoul Metropolitan Government. 2003. Field Investigation and Structural Health Evaluation Report. Seoul.
[3] Matthew Gilbert. 2005. Ring - Theory and modeling guide. Computational Limit Analysis and Design Unit. The University of Sheffield.
[4] Sohn, Y. 1992. A Study on the Type of Old Stone Bridge in Korea. Ph.D. thesis, Hanyang University, Korea.