Journal of Cultural Heritage xxx (2017) xxx–xxx

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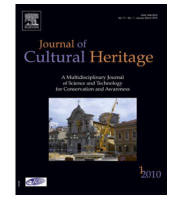

Case study

Megalithic stone beam bridges of ancient China reach the limits of strength and challenge size effect in granite

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A R T I C L E   I N F O

Article history:
Received 9 June 2016
Accepted 8 November 2016
Available online xxx

Keywords:
Stone beam
Granite strength
Stone architrave
Size effect

A B S T R A C T

In all ancient monuments, stone beams and architraves have unsupported spans that seldom reach 7 m, while ordinary spans are usually much less. These structural elements were and still are believed to be prone to failure, so that several relieving systems (arches, chambers, gaps) were adopted through history to prevent collapse. The perception that stone beams could not exceed a certain span is coherent with the so-called size-effect theory of rock and concrete, which predicts that large elements are proportionally weaker than small ones. While the rest of the world started using architectural design to avoid these problems, in the Fujian region of China (near Xiamen) from the XI to the XII century megalithic stone beam bridges with spans of up to 21 m were being built. These bridges have resisted over the centuries. A spectacular example of these bridges, tending to disprove the size-effect theory and challenging all previous ancient constructions, is the Jiangdong bridge, of which only a part survives, but which should be restored, preserved, and declared human heritage monument.

1. Introduction

1.1. A limit of 7 m span for unsupported stone beams

Stone beams for architraves, bridges and coverages were widely used by ancient civilizations but would only seldom reach spans of 7 m (Fig. 1). This length should be considered as a maximum limit for stone in all ancient (but also modern!) architecture, including Asian, Egyptian, Greek, Roman, and also pre-Colombian civilisations.

Two examples of long stone beams can be found in ancient Egyptian constructions, namely, the relieving-complex above the King's chamber in the great Pyramid (with several granite beams spanning more than 5 m), and the great lintel-blocks of the Nectanebo II gateway at Karnak (with sandstone architraves spanning more than 7 m, Fig. 1). In both cases, a relieving system has been used so that the beams are only loaded by their own weight (Clarke and Engelbach [1]). Relieving void spaces and relieving masonry arches are seen all around the world and, in more recent times, stone beams have been often reinforced with metal bars, as for instance in the 8.5 m long architrave of the Propylaia at the Acropolis of Athens (Cotterell [2]).

The limit of 7 m as the maximum span for stone beams was not connected with the quarrying, cutting, handling, and transporting of large stones. The Egyptian obelisks and the huge "le Grand Menhir Brisé" near Locmariaquer are clear demonstrations that managing large stone blocks was not a problem for ancient civilizations. So that the natural conclusion is that the maximum span was dictated by a *strength* criterion.

Strength in stone materials is also connected to the concept of size effect, which can be simply illustrated as follows. Failure in rocks and brittle materials is related to the presence of defects and the maximum size of these sets the rupture threshold.

Therefore, since a large specimen of material is likely to contain defects of larger size than a small specimen, the former will resist proportionally less than the latter. This idea, going back to Galilei [3] (in his *Discorsi* he states at p. 129 that a large bone is proportionally weaker than a small one), has been elaborated in different ways and is nowadays accepted to hold for unreinforced concrete and rock (Bazant and Planas [4]).

It can therefore be concluded that the limit of 7 m for the maximum unsupported length of a stone beam that was respected by all ancient civilizations, and has never been challenged in the modern architecture, is in line both with the Galilei's theory and the modern concept of size effect. However, stone beams of

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http://dx.doi.org/10.1016/j.culher.2016.11.009
1296-2074/© 2016 Published by Elsevier Masson SAS.

Fig. 1. Examples of stone beams from left to right: the clapper bridge at Postbridge (XIII century, span 3.75 m); the Nectanebos II gate at Karnak (the unsupported length of the beams is 7.2 m; note the relieving gaps between the beams); the relieving chambers inside the great pyramid of Cheops, where granite beams span 5.2 m.

unsupported length much higher of 7 m were realized in the ancient China.

1.2. Chinese ancient stone bridges with beams spanning over 20 m

In the fourth volume [5] of his famous "Science and civilisation in China" series, Needham [5] reports about megalithic stone bridges in the Fujian region of China with stone beams up to 21 m in length. In particular, he writes:

> "[. . .] Stone beam bridges are familiar to English people because of the small 'clapper' bridges of the West Country [see Fig. 1]. But in China the principle was used on a much greater scale. [. . .]
> [. . .] during the Sung period, there was an astonishing development, the construction of a series of giant beam bridges, especially in the Fukien region. Nothing like them is found in other parts of China, or anywhere outside China. These structures were (and are) very long, some of them more than 4000 ft., and the spans extraordinarily large, up to 70 ft., a duty which necessitated the handling of masses of stone weighing up to 200 tons".

In his book, Needham [5] refers to Fugl-Meyer [6] who reports:

> "[. . .] the giant bridges are found only in this limited territory; and [. . .] they could be built only during a very short period, all tend to prove that they are the works of a single genius, a great master of primitive bridge building. Perhaps, they represent the handiwork of a few of his disciples – men not dignified nor learned enough to be mentioned in the records".

In his Table 66, Needham reports on 12 "megalithic beam bridges of Fukien". Here, the Po Lam (now called Jiangdong) bridge is quoted to have the greatest span length exceeding 70 ft (21.3 m), while the Thung-An bridge is quoted to reach a span of 66 ft (20 m) and the Lo-Yang (called now Luoyang) bridge of 65 ft (19.8 m).

These unsupported spans are far greater than any, anywhere in the world and challenge the concept of size effect. It is therefore important to trace these bridges in China and to check whether or not the information provided by Needham and Fugl-Meyer is correct. This is the subject of the present article (see also an extended version of the present article and a movie available at http://www.ing.unitn.it/~bigoni/ponti), which reports about the stone bridges of the Fujian region and their current conditions.

2. Stone beam bridges of the Fujian region

The stone beam bridges listed by Needham in his Table 66 ([5], p. 156) were initially researched on Google Earth and on the internet and later an expedition was organized in collaboration with the Xiamen university to check the status of the bridges. Reference is made in the following to the numeration of the bridges introduced by Needham in his table.

With the exception of number 3, all the bridges are made up of longitudinal stone beams spanning from pier to pier, to make the deck of the bridge on which there is no pavement.

While some of the original beams of bridge number 12 are still visible (near the water and below the modern deck), it was impossible to assess the age of the beams of the other bridges, which could have been replaced even in modern time. All the beams are made up of granite and all piers are built in dry masonry.

Below is an update of the list of the bridges given by Needham:

- number 1: was not found;
- number 2: Hongshan bridge (end XV century) on the Minjiang river.
  Ruined piers (with the typical ship-bow shape) of the bridge with traces of a modern deck were traced using Google Earth to be near the Minjian North Port (Fuzhou) and close to a modern bridge;
- number 3: Longjiang bridge (built during the Song dynasty) on the Longjiang river.
  This bridge was traced using Google Earth and connects Chenguangcun to Qiaotou. The bridge looks from photos found in the Internet to be in good condition. A peculiarity of this bridge, not observed in the others, is that there is a deck made up of stone beams placed orthogonally to long lateral supporting stone beams. In this way, the lateral beams are subjected to a great load, for this reason this bridge deserves more consideration than that given in the present study;
- number 4: Luoyang Bridge (mid XII century) on the Luoyang river (Fig. 2, upper part).
  This bridge is in excellent condition and restrict to light traffic. Needham reports a maximum span of 19 m, but no beams of span larger than approximately 11 m were found. The thickness of the beams ranges between 40 and 80 cm. Typical dimensions are 9 m span, 70 cm thick and 50 cm wide. The bridge has been shortened during the centuries;
- number 5: this bridge seems to be a repetition of number 8;
- number 6: Shunji bridge (early XIII century) on the Jinjiang river.
  Ruins of the bridge (ship-bow piers) were traced using Google Earth near a new bridge crossing the river at the Jinjiang park. Photos found on the Internet show that the ancient piers were used to support a new deck, which eventually collapsed;
- number 7: Fou Bridge (mid of XII century) on the Jinjiang river.
  The remains of a bridge, which do not look ancient, was traced on Google Earth close to a modern one near the Mazu Palace;

Please cite this article in press as: F. Bigoni, et al., Megalithic stone beam bridges of ancient China reach the limits of strength and challenge size effect in granite, Journal of Cultural Heritage (2017), http://dx.doi.org/10.1016/j.culher.2016.11.009