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

Ferdinando Bigoni[1], **Davide Bigoni**[1,*], **Diego Misseroni**[1] **and Dongdong Wang**[2]

[1] ***DICAM, University of Trento, via Mesiano 77, I-38123 Trento, Italy.***
[2] ***Civil Engineering Department, Xiamen University, Xiamen, China***
[*] ***Phone: +39 0461 282507; E-mail: bigoni@unitn.it***

ABSTRACT

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.

Keywords: Stone beam; granite strength, stone architrave, size effect.

Introduction

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.

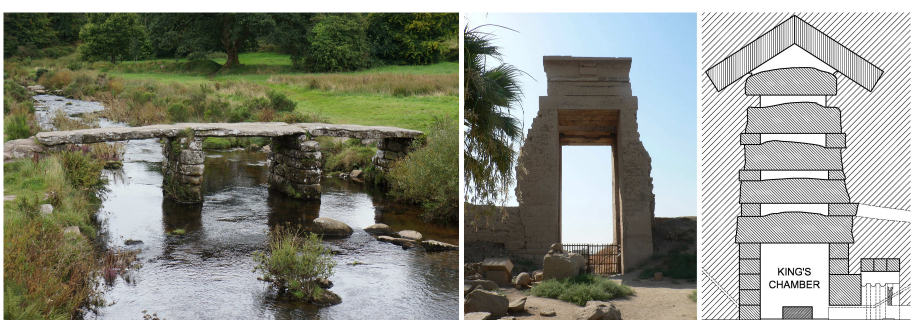

Fig. 1. Examples of stone beams from left to right: The clapper bridge at Postbridge (XIII Century, span 3.75 m); The Nectanebos II gate at Karnak (the unsupported length of the beams is 7.2 m; note the relieving gaps between the beams); The relieving chambers inside the great pyramid of Cheops, where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

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[2]). 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[3]).

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[6] (in his *Discorsi* he states at pag 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[1]).

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

Chinese ancient stone bridges with beams spanning over 20 m

In the fourth Volume[7] of his famous 'Science and civilisation in China' series, Needham[7] 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 4,000 ft., and the spans extraordinarily large, up to 70 ft., a duty which necessitated the handling of masses of stone weghing up to 200 tons. '

In his book Needham[7] refers to Fugl-Meyer[5] 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 the movie at `http://www.ing.unitn.it/~bigoni/ponti/`), which reports about the stone bridges of the Fujian region and their current conditions.

Stone beam bridges of the Fujian region

The stone beam bridges listed by Needham in his Table 66 ([7] pp. 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 deack 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 thickness 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.

- Number 8: Anping Bridge (mid of XII century) on the Shijiang river (Fig. 2 central part).

  The bridge is in excellent condition and restricted to pedestrian traffic. It is a National monument. The spans of the granite beams were found to be approximately 9 m (while Needham reports a maximum span of 4.5 m) and the thickness of the beams 75 cm.

- Number 9: Tong'an Bridge (end XI century) on the Dongxi Brook river.

  This bridge was traced using Google Earth and is close to the modern bridge near the Xiamen No. 12 Middle School. The photos from the internet show a small bridge in mediocre condition with approximately 10 spans (much less than the 18 reported by Needham). It was impossible to check the maxiumum span of 60 ft reported by Needham, which is so great that the bridge deserves more attention than that given in the present study.

- Number 10: Jiangdong bridge (also called Po-Lam bridge, early XIII Century) on the Jiulong river (Fig. 3).

  This bridge was reported by Needham to have the greatest span (greater than 21 m). In 2001 the bridge was declared one of the National cultural relics in China. Only 5 ancient piers (plus one more recent which was added at the midspan of the longest beam) remain of the old bridge, while 9 new piers have been built. A new and ugly upper deck in reinforced concrete has been recently constructed. Three granite beams of 14.60 m (1.2 m thick) are still in place. Two pieces of beams on each pier testify that beams spanning 18.60 m were present. A beam of 19.20 m (1.2 m thick and 1.26 m wide) has an extra pier added at midspan which is necessary, since two cracks near the supports are visible in the beam. This is still the longest surviving beam in the world. The remaining parts of this ancient bridge should be restored and declared to be a human heritage monument.

- Number 11: Zhongshan Bridge (late of XII century) on the Jiulong river.

  The ancient bridge has been completely lost and a new bridge has been built.

- Number 12: Guangji bridge (end of XII century) on the Hanjiang river (Fig. 2, lower part and Fig. 4).

  This bridge is a National monument. The deck of the bridge has been recently reconstructed and lifted (because the level of the water has increased). Some of the ancient beams are still in place under the new deck and near the water. Other ancient beams have been placed in a park near the river (Fig. 4). The beams have been measured at 14 m long (Needham does not report the greatest span) and to be 1.2 m thick.

Note that there is often some discrepancy between our measures of the spans and those reported by Needham (except for the greatest span of more than 21 m). A source of discrepancy with the Needham's measures can be related to the fact that he was referring to the total length of the beam, while we have measured the maximum unsupported length. Generally speaking, the information provided by Fugl-Meyer and Needham[5,7] has been confirmed, so that the huge spans mentioned by them were realized and some are still is in place.

Fig. 2. Megalithic stone beam bridges: Luoyang (mid XII Century, number 4); Anping (mid XII Century, number 8); Guangji (end of XII Century, number 12).

Challenging the size effect theory

The tensile strength of granite can strongly vary from one rock deposit to another and is, generally speaking, not easy to assess. The only data relative to the granite employed for the construction of Chinese bridges were provided by Fugl-Meyer, who reports values of strength obtained from experiments performed on granite quarried in the Fujian region. According to these data,[5] the uniaxial tensile strength of granite (weighting 2560 Kg/m^3) may range between 3 and 7 MPa. These values broadly falls within the range found by Wijk et al.,[9] reporting a strength between 3 and 11.8 MPa and a ratio between uniaxial tensile and compressive strength, ranging between 1/20 and 1/40. Deere and Miller[4] and Stowe[8] report higher values of tensile stress, about 12 MPa, and ratios between tensile/compressive strength respectively 1/19 and 1/12. These values should however be taken with caution, since there is always a substantial scatter of data in the tensile strength of a brittle material. Assuming for the granite a unit weight of 2560 Kg/m^3, a crowd load load of 3900 N/m^2 on the bridge deck, and that the beams of the stone bridges behave as simply supported rods (note that Fugl-Mayer assumes that the ratio between the length of the beam an its depth is equal to 15, while a value 17.5 was measured for the Jiangdong bridge), the Navier equation for bending (which does not take into account any size effect) predicts the maximum stress σ_{max} to be given by

$$\sigma_{max} = \frac{3(q_w + q_a)l^2}{4bh^2},$$

where $q_w + q_a$ are the two loads (per unit length, in particular, 'w' denotes the weight of the beam and 'a' the crowd load) applied on the beam, which has an unsupported length l (equal to 21 m for the Jiangdong bridge) and width and the height b and h (both equal to 1.2 m for the Jiandong bridge). According to the formula, the maximum tensile stress in the granite beams of the Jiandong bridge can be calculated to be approximately equal to 8 MPa, which is '*possible*', but at the very limit of the material strength. Note that the European regulation UNI EN 1991-2 2005 'Traffic loads on bridges' (Section 4.3.5, load model 4) prescribes a crowd load of 5000 N/m^2, higher than that considered by Fugl-Mayer. Using this value, instead than 3600 N/m^2, a maximum tensile stress of 8.2 MPa is obtained, which does not change our conclusion. This conclusion is similar to that pointed out by Fugl-Meyer,[5] who was unaware of the size effect theory, so that his calculations were performed with the

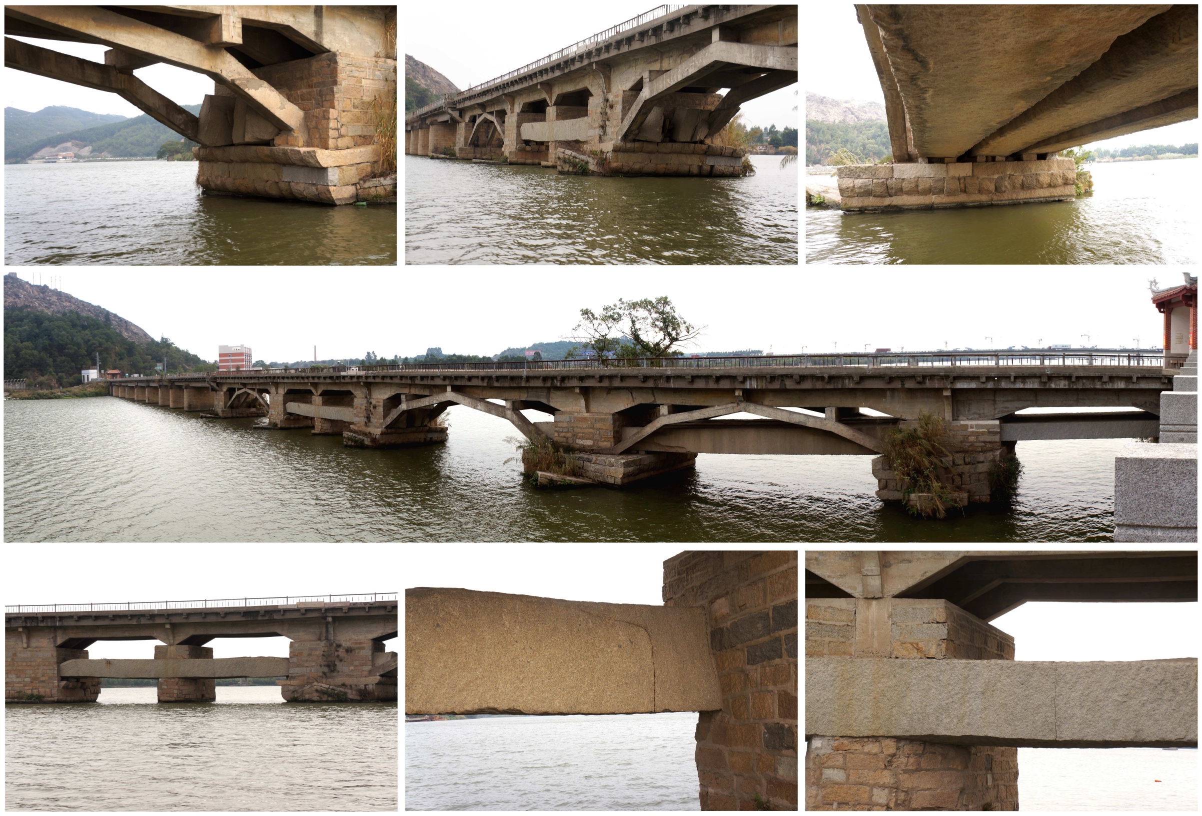

Fig. 3. The Jiangdong bridge (number 10, also called Po-Lam bridge, early XIII Century), with the greatest span in the world covered by a stone beam. Upper part, from left to right: Two pieces of ruined beams (once spanning 18.60 m) still in place; Three stone beams spanning 14.60 m are still in place; One end of the longest beam (a crack is visible near the supporting masonry. Central part: a general view of the bridge. Lower part, from left to right: a view of the longest span stone beam, with the added central support; A view of a detail of the bridge; The central support added at midspan of the longest stone beam ever realized in the world.

Fig. 4. Ancient granite stone beams of the Guangji bridge (number 12), preserved in a park near the bridge. The spans range between 10 and 14 m.

above-reported formula and allowed him to state:

‘[the calculated length of the span] *is exactly the upper limit of single spans in stone truss bridges in China. [...] it can be seen that the Chinese builder has reached the utmost limit of economy. In fact two-thirds of the bridges put up will break if subjected to any unexpected load.*’

The presented calculations, those performed by Fugl-Meyer,[5] and the field observations of the stone beams suggest that the Chinese megalithic bridges are a great engineering achievement, which show that by taking extreme care in quarrying and handling large stone blocks, the size effect can be reduced to a negligible factor.

Conclusions

Stone beams and stone architraves are common in ancient architecture all over the world and then as now the unsupported length of these features never exceeds 7 m. The one great exception being the megalithic stone bridges in the Fujian region of China. These bridges built between the XI and the XIII centuries, have stone beams of unsupported spans commonly exceeding 14 m and in one example 21 m. These bridges were probably designed by the same engineer and his pupils and represent structures where the limits of strength have been challenged and the fact that they are still standing after so many centuries tends to disprove the size effect theory.

The Jiangdong bridge is a unique example of megalithic stone bridge, where the greater unsupported span of 21 m has been reached (see also the movie at `http://www.ing.unitn.it/~bigoni/ponti/`). This bridge is unique in the world, so that it should be restored, preserved, and declared human heritage monument.

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References

1. Bazant, Z.P. and Planas, J. 'Fracture and size effect in concrete and other quasibrittle materials', CRC Press (1998)
2. Clarke, S. and Engelbach, R. 'Ancient Egyptian construction and architecture', Dover, new York (1990) .
3. Cotterell, B. 'Fracture and life', Imperial College Press, World Scientific (2010).
4. Deere, D.U. and Miller, R.P. 'Engineering classification and index properties for intact rock', Technical Report N. AETL-TR-65-116 University of Illinois Urbana, Illinois (1966) .
5. Fugl-Meyer, H. 'Chinese bridges', Kelly and Walsh, Shanghai, Hong Kong, Singapore (1937).
6. Galilei, G. 'Discorsi e Dimostrazioni Matematiche, intorno a due nuove scienze attenenti alla Mecanica & i Movimenti Locali con una Appendice del centro di gravità da alcuni Solidi', Elsevirii, Leida (1638).
7. Needham, J. (1971) 'Science and civilisation in China', Vol. 4 *Physics and physical technology, Part III: Civil engineering and nautics*, Cambridge University Press.
8. Stowe, R.L. 'Strength and deformation properties of granite, basalt and tuff at various loading rates', *Report: U.S. Army Engineer Waterways Experiment Station Corps of Engineers*, Vicksburg, Mississippi (1969).
9. Wijk, G., Rehbinder, G. and Lögdström, G. 'The relation between the uniaxial tensile strength and the sample size for bohus granite', *Rock Mechanics* 10, 201-219 (1978).