Mechanical behaviors of the arch-type stone bridge

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ABSTRACT

This paper presents the structure of the arch-type stone bridge and its mechanical behavior verified by strain measurements taken during the construction. The arch-type stone bridge was constructed by combining an arch-stone structure and a socket structure without the introduction of a reaction structure. The arch-type stone bridge, fitted with a socket structure on the upper part of its arch-stone structure, is created by suppressing the deformation of the arch stones. As a result of the strain measurements of the arch stones during the construction, the compressive strain levels of the arch direction were 198-244μ and the temperature-strain coefficients were 5.1-10.8 μ°C. These types of mechanical behavior verify that the arch-type stone bridge is in a stable mechanical state.

Key words: arch-type stone bridge, granite, strain measurement, temperature-strain coefficient

1 INTRODUCTION

Arch-type stone bridges have been used extensively from ancient Roman times up to the present. As the beginning of arch-type stone bridges in Japan, the Megane-Bashi in Nagasaki Prefecture was constructed in 1634. Since then, a number of arch-type stone bridges have been constructed in Japan, mainly on the island of Kyushu, and they are still being used today.

The merits of arch-type stone bridges are as follows: they are basically maintenance-free and they can be used over a long term. In recent years, countermeasures against the deterioration of concrete and steel bridges have become an urgent social issue. Accordingly, the practical use of arch-type stone bridges as short span bridges is expected in the future.

From these points of view, this paper presents the structure and the mechanical behaviors of the Mizuma-Dera Yakuyoke-Bashi arch-type stone bridge (herein-after called the arch-type stone bridge) during its construction in Osaka Prefecture, Japan. The construction period lasted from October 2009 to March 2010.

2 STRUCTURE OF THE ARCH-TYPE STONE BRIDGE

Figure 1 shows the completed state of the arch-type stone bridge. Figure 2 presents a structural illustration of the bridge. The arch-type stone bridge is 16.64 m in length, 5.2 m in width, and 3 MN in total weight. The ratio of the radius (8 m) to the height of the circular-arc part (4.05 m) is almost 2.0, as shown in Fig. 2.

The biggest problem during the planning and construction stages was how to deal with the site conditions on the north road side. The following tough circumstances were encountered: the construction work could not be performed by occupying the road because of the traffic conditions around the site; the stone wall on the north city road side was quite fragile; and the water channel was buried under the road near the arch-type stone bridge.

As countermeasures to the above problems, the idea of constructing a reaction structure on the north road side, which would have prevented horizontal movement,
was abandoned. And it was decided that a socket structure, which does not need a reaction structure, would be built, as shown in Fig. 2. The socket structure consisted of a structure fitted with a cast-in-place reinforced concrete frame on the upper part of the arch stone structure. The arch-stone structure and the socket structure were constructed separately; it was not a monolithic construction. It was taken into account that only the socket structure would be easily replaced in the future, and that the arch stones would remain in their current positions.

In particular, the mechanical importance of fitting the socket structure onto the upper part of the arch-stone structure is the anticipation of the mechanical effect which inhibits the deformation of the arch stones. As a result, the construction work could be accomplished without reconstructing the existing structure on the road side. The cost of the construction was drastically reduced, and the construction period was greatly shortened.

The bedrock anchorage of the arch stones through the foundation stone was performed with rhyolite as the bedrock, whose compressive strength is 7.5 MN/m². Figure 3 shows the state of the bedrock anchorage. Considering the fact that the force from the arch stones would be transmitted mechanically to the bedrock in a more rational manner, the surface of the foundation stone was set to a 30° diagonal angle so that the foundation structure would inhibit the deformation of the arch stones.

Figure 4 exhibits the appearance of the arch stones during the construction. One row of arch stones consisted of either three stones (the combination of stones is 1.7 m in length) or four stones (the combination of stones is 0.85 m and 1.7 m in length). The three- and four-stone rows were placed alternately. Figure 5 shows the sectional configuration of an arch stone and the positions of the strain gauges. It is 65 cm in height, 46.5 cm in width at the top, and 43 cm in width at the bottom. The rows of arch stones total 39, including the finally fixed key arch-stone row of arch stones, and 19 each in bilateral symmetry. The granite used for both the arch stones and the foundation stones has a compressive strength of 150.6 MN/m², a cleavage tensile strength of 5.9 MN/m², a pure tensile strength of 5.0 MN/m², and an elastic modulus of 51.7 MN/m².

3 MECHANICAL BEHAVIORS

3.1 Strain Measurements

Engineering methods to perceive the mechanical state of stone bridges include configuration measurements and strain measurements (Tamano et al., 2009). As for the safety management of arch-type stone bridges by deformation measurements, there is a limit to perceiving the distinct mechanical tendencies, because the deformation is extremely small. At this point, the strain gauge measurement method can
perceive the microscopic mechanical changes of arch-type stone bridges.

The strain measurements were performed as follows. On February 6, 2010 strain gauges and a temperature sensor were installed on the faces of the stones in a mechanically free condition. The temperature of the stones was 4.7°C when the strain gauges were installed.

Figure 6 presents the positions of the strain gauges and temperature sensor. Figure 7 illustrates the setting condition of the rosette gauge and an arch stone's strain. The strain gauges were installed at 5 points: the key arch stone (the central measuring point) and the right- and left-side arch stones (south measuring point 6, south measuring point 12, north measuring point 6, and north measuring point 12). The temperature sensor was installed at south measuring point 6.

This paper defines the compression strain as plus (+) and the tensile strain as minus (-). Furthermore, in cases where the linear expansion coefficients (11.0 μĈ) of the installed strain gauge are different from those of the granite arch stone, the strain measurement includes the difference as the apparent strain. Accordingly, it was confirmed that the apparent strain was zero and that the linear expansion coefficient was 11.0 μĈ with the test piece (10 cm long × 8 cm wide × 2 cm thick) of the same granite as that used for the arch stone in the mechanically free condition with a stone temperature of 0 to 30°C.

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\begin{align*}
\varepsilon_{\text{max}} &= \frac{1}{2} \varepsilon_1 + \varepsilon_2 + \sqrt{\varepsilon_1^2 + \varepsilon_2^2 + 2 \varepsilon_1 \varepsilon_2} \\
\varepsilon_{\text{min}} &= \frac{1}{2} \varepsilon_1 + \varepsilon_2 - \sqrt{\varepsilon_1^2 + \varepsilon_2^2 + 2 \varepsilon_1 \varepsilon_2} \\
\varepsilon_{\text{1}} &= \frac{1}{2} (\varepsilon_1 + \varepsilon_2 + \sqrt{\varepsilon_1^2 + \varepsilon_2^2 + 2 \varepsilon_1 \varepsilon_2}) \\
\theta &= \arctan \left( \frac{\varepsilon_1 + \varepsilon_2}{\varepsilon_1 - \varepsilon_2} \right) \\
\gamma_{\text{1}} &= \sqrt{\varepsilon_1 - \varepsilon_2}^2 + \varepsilon_2^2 \\
\end{align*}
\]

Fig. 6. Positions of installed strain gauges and temperature sensor installed.

Fig. 7. Setting condition of the rosette gauge and illustration of the rosette gauge.

Fig. 8. Measured and calibrated strain \( \varepsilon_1 \) (central measuring point: out-\( \varepsilon_1 \), see Figs. 5 and 6).

### 3.2 Measurement Results and Examinations

Figure 8 illustrates the changes in the measured and calibrated strain values at the central measuring point: out-\( \varepsilon_1 \) after finishing the steel centering demolition on March 21, 2010. The arch-type stone bridge was separated from the steel centering by removing the wooden wedges, which fixed the steel centering and the
Table 1. Measured strain values and their analyses.

| Measuring point position | Measured strain | Temperature-strain coefficient $\varepsilon_1/\Delta T$ ($\mu$/°C) | Maximum principal strain $\varepsilon_{\text{max}}$ ($\mu$) | Minimum principal strain $\varepsilon_{\text{min}}$ ($\mu$) | Angle $\theta$ (°) | Maximum shear strain $\gamma_{\text{max}}$ ($\mu$) |
|--------------------------|-----------------|-------------------------------------------------|-----------------|-----------------|-----------------|-----------------|
| South measuring point 6  | in              | 235, 218, 197                                  | 5.4             | 257, 196         | -1              | 61              |
|                          | out             | 198, 221, 211                                  | 6.9             | 221, 198         | 0               | 23              |
| South measuring point 12 | in              | 232, 143, 200                                  | 9               | 234, 141         | 0               | 92              |
| Central measuring point  | in              | 241, 230, 200                                  | 5.1             | 228, 184         | 0               | 43              |
| North measuring point 6  | out             | 240, 204, 175                                  | 10.8            | 272, 172         | -1              | 101             |
|                          |                 | 244, 89, 196                                   | 7.3             | 249, 84          | 0               | 166             |
|                          |                 | 198, 141, 173                                  | 6.9             | 198, 141         | 0               | 57              |

**Table 1** Measured strain values and their analyses.

Results for the maximum principal strain, $\varepsilon_{\text{max}}$, the minimum principal strain, $\varepsilon_{\text{min}}$, the angle from the $\varepsilon_1$ direction to the $\varepsilon_{\text{max}}$ working direction, $\theta$, and the maximum shear strain, $\gamma_{\text{max}}$, were calculated using the measured strain values and are described in Table 1. The data at north measuring point 12 was deleted because of a defect in the measurement. The most important strain measurement value for considering the mechanical stability of the arch-type stone bridge is the arch-stone’s arch direction strain, $\varepsilon_1$, showing a compressive strain of 198-244$\mu$. The working direction of $\varepsilon_1$ and $\varepsilon_{\text{max}}$ is almost equal to the calculated values for angle $\theta$ (0–−1°). It is obvious that the arch direction force works the most effectively on the arch stones. In other words, the arch stones are in a mechanically stable condition. The maximum shear strain of $\gamma_{\text{max}}$ is considerably smaller than the maximum shear strain of $\gamma_{\text{max}}$ that breaks the granite.

Figure 9 illustrates the relation between the stone temperature and the strain (the temperature-strain coefficient), which exhibits the mechanical restrained degree at the central measuring point: out-$\varepsilon_1$ after finishing the steel centering demolition and under a constant external loading condition (Tamano et al., 2014). In Fig. 8, the strain values after finishing the steel centering demolition were calibrated by the temperature-strain coefficient to the stone temperature of 4.7°C, under which the strain gauge was installed.

The temperature-strain coefficients at 8 measuring points are described in Table 1. The temperature-strain coefficients vary for every measuring point, but they are all within 5.1-10.8$\mu$/°C. The values are 46-98% of the fully restrained condition, that is, the linear expansion coefficient of granite of 11.0$\mu$/°C. These strain characteristics show that the arch-type stone bridge, whose restrained degree is mechanically large, is in a mechanically stable condition.

### 4 CONCLUSIONS

The following is a summary of this study.

1. The arch-type stone bridge was constructed by combining a socket structure and an arch-stone structure without the introduction of a reaction structure. The arch-type stone bridge, fitted with a reinforced concrete frame on the upper part of its arch-stone structure, was created by suppressing the deformation of the arch stones.

2. The measured temperature-strain coefficients vary for every measuring point, but they are all within 5.1-10.8$\mu$/°C. The values are 46-98% of the fully restrained condition, that is, the linear expansion coefficient of granite of 11.0$\mu$/°C. These strain characteristics show that the arch-type stone bridge, whose restrained degree is mechanically large, is in a mechanically stable condition.

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