Technical Report

Historical Architecture Improved by Titanium

Norihiro EJIRI*

Abstract

Most of the historical architecture in Japan is made of wood, with some structures having survived for many centuries, and in some cases, for even more than 1 000 years. Unexpectedly, iron materials were widely used for joints within these constructions. Since iron is susceptible to corrosion, some joint parts made by this material have already lost their integrity and function. In order to retain our historical architecture for the coming generations, the development of new materials that can be used as an iron substitute is effective. Use of titanium began in the 20th century. This material is light and strong; furthermore, it has low thermal conductivity and high corrosion resistance. The usage of titanium in wooden structures seems to be more suitable than iron. I have been using the innovative material for seismic retrofit and reinforcement of historical buildings. In this article, the possibility of using titanium as a construction material is described using four examples.

Historical buildings (traditional architecture) in Japan are generally considered to be those with a history of several hundred years. In recent years, reinforced concrete and steel-framed buildings that are about 50 years old have begun to have historical value. However, most of the so-called historical buildings were basically made of wood, and the oldest one is the five-story pagoda of Horyuji Temple, which was built 1 300 years ago. It is said that iron is not used in these historical buildings, but those that I have already surveyed have used more iron than anyone could have expected. Some of these iron materials are no longer functional due to corrosion.

Although wood is recognized as a non-durable material due to decay, in fact, the oldest buildings in Japan are made of wood. In order for these wooden buildings to survive for hundreds of years or more, it is desirable to have a material whose performance can be sustained. It is a well-known fact that titanium is a metal with excellent corrosion resistance, but there are other reasons why it is suitable for use in historical buildings.

Although the thermal conductivity of titanium alloys differs among the literature, it is about 8.0 W/(m·K), which is 1/8 of steel. Since the thermal conductivity of wood is 0.15 W/(m·K), the possibility of condensation is much lower than that of metal. In addition, the linear expansion coefficient is smaller than that of steel. Although the number of data and research examples on the linear expansion coefficient of wooden material is small, there are gaps in the joints and fittings of historical buildings, so it is considered that the structure itself does not change much due to temperature changes. In the case of reinforcing with dissimilar materials, such materials deform the structure more than the expansion and contraction of the wooden materials themselves, so materials with low thermal deformations are more suitable for such purpose. When reinforcing with steel-based materials, the increase in weight is very significant because wood is light. In extreme cases, the weight of the reinforcing material increases the seismic force, and the size of the reinforcing material has to be increased contradictorily. On the other hand, the specific strength of titanium alloy is about three times that of steel, so it can be reinforced with one-third the weight. From the aspects of 1) durability, 2) thermal conductivity, 3) linear expansion coefficient, and 4) specific strength, titanium alloy is the most suitable among steel-based materials for reinforcing historical buildings (see **Table 1**).

As a supplementary note, it is said that the more rusted a nail is, the better it bites into the wood and the harder it becomes to pull out. While performing structural analyses, nails are not expected to gain strength by rusting as in the case of high-strength bolt friction joints, and the basic mechanism is thought to be penetration into the wood. Although the effect of rusting may be proven in the future, at present, it is considered better for the joint material to be rust-free.

Considering the above advantages, I will describe examples of using titanium alloy in historical buildings.

The first example is a case study of the horizontal reinforcement

* President, Ejiri Structural Engineers,
Professor, Department of Housing and Architecture, Faculty of Human Science and Design, Japan Women's University
2-8-1 Mejirodai, Bunkyo-ku, Tokyo 112-8681

Table 1 Physical properties of titanium alloy

	α-β Titanium	β Titanium	Steel
Thermal conductivity (W/m·K) (20°C)	7.5	8.08	63 (SPCC)
Linear expansion coefficient (1×10^{-6}/K) (20°C)	8.8	8.5	12.0 (SPCC)
Specific strength	202≤	157–199	51–65 (SS400) t=5

Source: Website of The Japan Titanium Society, http://www.titan-japan.com/technology/physical_properties.html

t: thickness

Photo 1 Panoramic view of roof system of Sutra Repository, Zenkoji Temple

Photo 2 Titanium alloy sheet wrapped member shown in Photo 1

Photo 3 External view of reinforced deck supporting structure (Kiyomizu Stage, Kiyomizu-dera Temple)

Photo 4 Reinforced member joint of structure shown in Photo 3 (using titanium alloy bolt)

used in the roof frame of Sutra Repository at Zenkoji Temple in Shinshu (**Photo 1**, **Photo 2**). In this case, titanium sheets were used to fix the metal connection to the wooden members. Since the area covered by the metal material was considered to be quite large, the titanium sheet was used to prevent condensation as much as possible. Usually, carbon fiber sheets or aramid fiber sheets are used for such wrapping, but the need for adhesive to affix it inside the roof makes its construction extremely difficult. In some cases, box-shaped steel plates are used for pinching wooden members, but it is very difficult to make the metal connections fit the existing members with different dimensions. The titanium sheet has high followability for members with different dimensions, and its strength can be controlled by the number of rolls.

In the second case (**Photo 3**, **Photo 4**), titanium was used for the exterior rather than the roof system. In order to make the reinforcement as durable as possible, carbon fiber-stranded wire was combined. A titanium round bar is threaded with a female thread, a titanium alloy bolt is attached to one side, and a carbon fiber-stranded wire is fixed to the other side with adhesive. Since the titanium bolts were forged and the female threads were processed to improve the adhesion performance of the carbon fiber strand, the strength of the joint was confirmed by a tensile test. In this case, a further advantage is added to the features of the titanium alloy. It is concerned that carbon fiber, which is easily conductive to electricity, has potentiometric corrosion with steel materials. However, titanium alloy does not cause potentiometric corrosion due to its high electrical resistance. This is a very important property for historical buildings that require ultra-long term durability, and confirms that titanium is the most suitable material for combining different materials.

The third example is the use of a titanium alloy sheet to fix the beam joint (**Photo 5**, **Photo 6**), expecting for its followingness. In historical buildings, not only sawn lumber, but also naturally-shaped logs are often used. When an earthquake occurs, these members may shift at the joint, so two irregularly shaped elements are connected by using followability of the titanium alloy sheet.

The fourth case is that of the Tomioka Warehouse (**Photo 7**, **Photo 8**). In this case, titanium tubes were used for the joints between bolts and carbon fiber stranded wires, and titanium plates and bolts were used to prevent the brick walls from leaning outward. Since the good appearance and design of this reinforcement are required, it is necessary to make the joint shape as small as possible, so that high specific strength of titanium is effective.

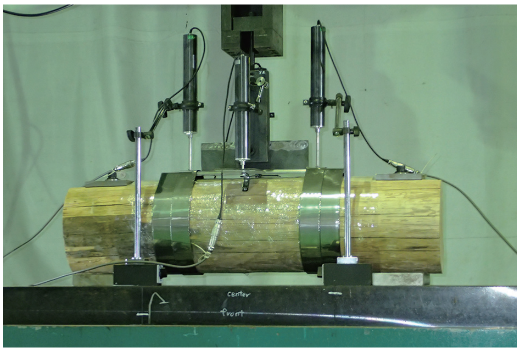


Photo 5 Strength test of titanium alloy sheets

Photo 7 Reinforcement of Tomioka Warehouse No. 3

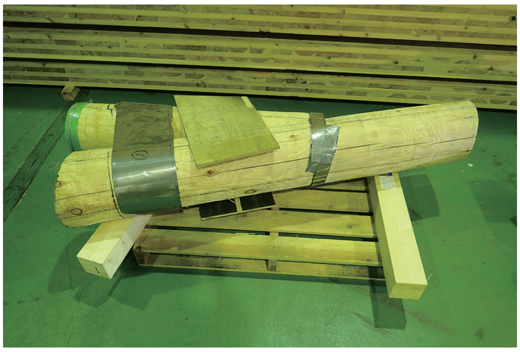
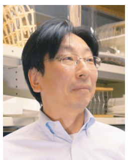


Photo 6 Specimen of reinforced beam joint

Photo 8 Reinforcement of Tomioka Warehouse No. 1

Finally, the examples introduced here are titanium alloy sheets, titanium alloy bolts, and titanium alloy steel pipes (for carbon fiber bonding), but they are actually only partially applied. The current situation is that the adoption of these materials is determined by factors other than purely structural performance, such as economic efficiency, delivery time, and the level of understanding of the people involved in each project, etc. I hope that as many examples as possible will be accumulated and that these materials will become popular (widely distributed) materials.

I would like to mention one more advantage of using titanium alloy for historical buildings. Titanium did not exist before the 20th century, and it has just started to be used in buildings in the 21st century. In the case of reinforcing historical buildings, reversibility is expected. Titanium can be identified by future generations as a product of the current era; thus, it excels in reversibility more than steel in terms of recording (remembering) the reinforcement history.



Norihiro EJIRI
President
Ejiri Structural Engineers,
Professor
Department of Housing and Architecture
Faculty of Human Science and Design
Japan Women's University
2-8-1 Mejirodai, Bunkyo-ku, Tokyo 112-8681