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Original article

Non-destructive monitoring methods as indicators of damage cause on Cathedral of St. Lawrence in Trogir, Croatia

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ABSTRACT

Durability is one of the most important engineering properties of cultural heritage monuments. For the purpose of the preservation of structures for future generations, the causes of damage should be determined for the proper choice of type and location of strengthening. The condition of the foundation is difficult to determine without an extensive investigation which is critical because most often the cause of damage is found in such foundations. Geotechnical investigation techniques require the damage and destruction of a building's surroundings or the damage of a foundation with a boring device. Non-destructive methods, such as geophysical methods, are less reliable and the results of such investigations must be combined with the results of subsurface exploration. This paper is a presentation of results achieved through the monitoring of the activity of a number of joints on the Cathedral of St. Lawrence in Trogir, Croatia, which is a cultural heritage monument protected by UNESCO. Excavations for the purpose of flagging replacement in the zone around the east frontage were made in 1979. A probe beneath the main apse uncovered a water cistern where the connection between the mid and north apses is located, and instead of a staggered foundation, a wall with a depth of more than 2.2 m beneath the flagging was discovered. With respect to the given that churches were built on existing ones, it is possible to assume that this is a wall of the late-antiquity church described by Constantin Porfirogenet in the 10th century, built on and later adapted to the foundation for the new structure. The displacement in time of the construction elements of the cathedral were measured and recorded using non-destructive methods. Fissure displacement behaviour, air temperature and air humidity were monitored. The monitoring of the air humidity did not lead to any useful conclusion, so it was quickly dismissed. Observations of data were performed during two periods with an interruption between the two caused by insufficient monetary resources. Data from almost 8 years of continuous measuring are available. The aim of this paper is to present the data of the measured fissure displacements which were correlated with air temperature changes and mathematical models which were based on statistical analysis. Correlation coefficients show that the analysed fissures react to the air temperature changes with different intensities. The obtained data lead to the conclusion that the causes of the structural damage are not found within a displacement or failure of the foundations. Instead, the causes of the damage were found in other parts of the structure.

1. Research aims

The aim of this paper is to determine the causes of damage to the Cathedral of St. Lawrence in Trogir, Croatia, which is a cultural heritage monument protected by UNESCO. This paper focuses on the presentation of results obtained through the monitoring of the behaviour of a number of joints. Observations of fissure displacements and air temperature changes lasted almost 8 years, with a period of interruption. Data of the measured fissures displacements and air temperature changes have been interpreted by statistical analysis. On the basis of the performed calculations, models of fissures behaviour in time have been created. The models obtained were used for the determination of the causes of damage to the structure.

2. Introduction

Cultural heritage monuments are usually very old structures. During their existence, they have experienced many different natural disasters such as floods, earthquakes, fires, as well as the adverse effects of humans (adaptations, conversions, annexes, wars, etc.). These activities result in damage to these structures [1]. For the

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Fig. 1. Cathedral of St. Lawrence [8].

purpose of the preservation of this heritage for future generations, it should be protected in any manner, even through structural strengthening.

For the proper choice of the type and location of strengthening, the causes of damage should be determined [2–4]. The most common cause of damage is usually found in the foundations, probably because they are covered, so it is difficult to detect their actual condition without extensive investigations [5]. The condition of the foundation can be detected via visual inspection in open pits excavated next to the foundation, or with boreholes made through the foundation and which are used for inspection with a micro-camera. Both approaches require the damage and destruction of a building's surroundings or the damage of the foundation with a boring device. There is always the additional destruction of an already damaged structure. There are some non-destructive methods [6,7] which can be used for the inspection of foundations, such as geophysical methods, but they are less reliable. In any case, the results of such investigation should be combined with the results of a subsurface exploration. Even then, an understanding about the foundation is usually not complete.

This paper is a presentation of research results achieved through the monitoring of joint behaviour on one very precious cultural heritage monument, the Cathedral of St. Lawrence in Trogir, Croatia.

3. Historical data

The most famous monument in Trogir, is certainly the Cathedral of St. Lawrence (Katedrala sv. Lovre), called the Cathedral of St. John (sv. Ivan) by the people after the city patron, a contemporary of King Zvonimir and King Koloman. Cathedral of St. Lawrence (Fig. 1 [8]) in Trogir is a very complex cultural monument from the structural point of view [9].

It seems that it was erected on the foundations of an older basilica destroyed during the sack by the Saracens in 1123. Efforts of generations through four centuries and many great names were invested into its building. The Trogir Cathedral is a Romanesque-Gothic basilica with a nave and two aisles, three semicircular apses and a vaulted interior above which rises the Campanile. Romanesque massiveness and Gothic elegance have been harmoniously combined in its architecture. Heavy piers separate the wide central nave from the aisles. All have circular vaults. The aisles have Gothic ribs, and the nave was vaulted later (in the 15th century) also in a Gothic style. The cross vaults and the earlier flat terraces above the aisles were of Apulian influence. The outside wall is divided by pilasters and decorated with Romanesque blind arcades. A large vestibule was added in the 15th century, and the artistically executed Gothic rosette on the western facade is from the same period.

In the 15th century baptistery, chapels of St. John and St. Jerolimus also were added, with which a construction has become more complex. Today the cathedral is a cultural heritage monument protected by UNESCO.

Today in the cathedral are some of the most precious art masterpieces. One of them is the Radovan's Portal, finished in 1240. It is a monumental and perhaps unique work of this great Croatian artist, of whom the inscription on the base of the lunette says he is "the best of all in this artisanship". The second masterpiece, baptistry and Chapel of the St. Ivan of Trogir are characteristic of the two later phases in the development of the Dalmatian art. The baptistry is the most complete work of Andrija Alesi, born in Durres, assistant to Juraj Dalmatinac and co-worker of Nikola Firentinac. He finished it in a mixture of the Gothic and Renaissance styles in 1467. He decorated the portal with fruit and flowers and shallow fluted niches with Gothic shells at their tops.

3.1. Archeology

One very interesting piece of data about the archaeological foundations in the cathedral can be found in a report of I. Babić (1985) [10]. When he describes the data about his investigation along the eastern frontage of the cathedral he says:

> "In 1979, excavations for the purpose of flagging replacement in the zone along the east frontage were used as a probe beneath the main apse. On this occasion, where the mid and north apses connect, a water cistern was discovered. Unfortunately, because of the construction rate enforced by the contractor and investors, only a small number of explorations were conducted around the main apse. Nevertheless, it was discovered that instead of a staggered foundation, there is a wall with a depth of more than 2.2 m beneath the flagging, about 0.9 m beneath the sea level. With the ordinary excavation methods used, it was not possible to dig deeper because of seepage of sea water into the trench. But the discovered wall continues into the deep. What is the purpose of the wall, made of roughly cut stone? Is it the foundation of the cathedral, or what is more likely, is it a wall of the late-antiquity church described by Constantin Porfirogenet in the 10th century? An argument to counter the opinion that it is a wall of the late-antiquity church could be formed around the irregular structure of the wall and the broken line of wall in the ground plan, and, what is also occasionally found, a stepwise indent of the stone-line on top of the wall. But if these walls were a foundation, they should not be so deep. So it could be that a few upper stepwise indentations stand as a transition from the wall of the late-antiquity church to the foundation of the existing Romanic cathedral. One very significant detail is that this wall is not concentric in relation to the existing apse. This is very often the case in other churches which were built over the foundation of older ones. So it is more likely that this is a late-antiquity church wall, built on and adapted later to the foundation of a new structure."