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Role of blasting tehnology in removal of the part of Northern tower of Zagreb Cathedral

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Abstract

Zagreb Cathedral was seriously damaged in the earthquake that hit Zagreb in March, 2020. The top of the southern tower broke and crashed down, while the northern tower was badly damaged. Because of high risk of collapsing and causing even greater damage to the Cathedral and surrounding buildings, it was necessary to remove the damaged part. Important and demanding phase of the removal has been conducted with blasting technology application. By small, directed explosive charges, connection anchors of the tower and lower loading stone coronet had been detached. Instantaneously, steel rope of counterweight mass lead sphere has also been cut. Blasting demolition technology is common practice during the earthquake recovery period and is applicable for demolition of whole or parts of damaged buildings. Blasting works that have been performed on the cathedral are unique because of safety limitations, its importance as a monument, altitude and rendering condition. The part of the bell tower that could collapse weighted about 36 tons, with a total height of 13.47 meters including its cross. This paper describes how design and technical solution were developed, how research and testing were carried out and how the blasting part of removal, immediately before tower lifting, was performed.

Key words: blasting, Zagreb earthquake, cathedral, northern tower

1 Blasting in civil engineering

The use of explosives (energy material) is common in the military and some civil, i.e., economic fields. The civil application of explosives or explosive substances is very diverse and wide as they are used for blasting in mining and civil engineering, oil and gas exploration, geological exploration, mechanical engineering and shipbuilding, space technology, automotive industry, agriculture, medicine, demining, film, and fireworks. In Croatia, explosives are mainly used in blasting for the needs of mining and construction, i.e., for obtaining solid mineral raw materials and excavations. Excavation by blasting is the dominant applied technology of excavation in solid rocks during the construction of foundation pits, construction of tunnels, routes of motorways, roads and railways. A significant, and in some cases irreplaceable, technology is the demolition of buildings by blasting. Demolition by blasting in relation to mechanical demolition and decomposition processes in a has significant advantages and, in some cases, there is no alternative. The advantages are shown in low consumption of energy, materials, low working hours per unit volume or mass of the demolished building, in the short-term impact on the environment, and in the possibility of demolition of tall and very protracted buildings. Blasting, as a method of demolition, except in regular activities of removing buildings, is extremely important in mending the consequences of war or natural disasters such as earthquakes. Blasting for the mending of earthquake consequences was used significantly after the Skopje and Banja Luka earthquakes where the total number of demolished buildings was 150 and 52, respectively. In the case of both regular and remedial demolition, the application of blasting can be carried out in a safe manner in densely built-up and populated areas, with the application of appropriate safety measures. Examples are the demolition of the naval command building in Šibenik and the demolishing of the Diokom factory buildings in Split.
In addition to the aforementioned "regular" use of explosives in demolition and other construction works, certain interventions can only be performed adequately by using explosives, which allow simultaneity and distance, and thus the safety of the intervention. Such was the case of removing the damaged northern tower of the Zagreb Cathedral after the 2020 earthquake.

2 Zagreb Cathedral

Zagreb Cathedral is the most famous and tallest Croatian religious object and one of most valuable objects of Croatian cultural heritage. It is dedicated to the Assumption of Mary and to kings Saint Stephen and Saint Ladislaus. The construction of the Cathedral in transitional Romanesque-Gothic style began around 1094, but it was not completed and dedicated until 1217. The Cathedral has been reconstructed many times during the past. The first reconstruction, in Gothic style, was done by bishop Timothy (1263-1287) because the Cathedral was severely damaged in the Tatar invasion. Th reconstruction continued into the 14th then the 15th century. In the 16th century the cathedral was fortified by walls and towers and in the 17th century its massive renaissance tower was built [1].

Figure 1. Cathedral before earthquake 1880 and Cathedral before earthquake 2020

The fires and enemy attacks have damaged the Cathedral several times, but it suffered its hardest damage in the 1880 earthquake. After the earthquake it underwent a major reconstruction in Gothic Revival style (1880 -1906) under the supervision of Herman Bollé and by the design of F.Schmidt. It was then when the Zagreb cathedral got its present form with two slim towers, a high roof, new pillars in the sanctuary and altars which replaced the 18th century baroque one [1]. Renovation of the Cathedral's two towers began in 1990 and it was at this time that scaffolding was first erected around the towers. The restoration they required was a painstakingly slow process, hampered by the brittle, porous stone which Herman Bollé had chosen to build them from and by the restoration funds relying solely on contemporary donations. The towers have not been completely free of this scaffolding for three decades which meant that some citizens of Zagreb and Croatia had never seen the Cathedral without it.

3 Zagreb earthquake

At approximately 6:24 AM CET on the morning of 22nd March 2020, an earthquake hit Zagreb, Croatia, with an epicentre 7 kilometres north of the city centre. The earthquake had a magnitude of 5.3 Mw and a depth of 10 kilometres according to Advanced National Seismic System and 5.5 ML according to the Seismological Service of Croatia. The maximum perceived intensity was VII (very strong) on the Modified Mercalli intensity scale (MMI). It was the strongest earthquake in Zagreb since the earthquake of 1880 [2]. To make the situation even worse the earthquake happened amid the coronavirus lockdown. Citizens of Zagreb were instructed to leave the buildings and go to open areas all while keeping social distancing in mind. More than 30 aftershocks were recorded within seven hours after the main earthquake. A 15-year-old girl, Anamarija, was the only victim and 27 other persons were injured. The material damage was quite high; 26,197 buildings are reported to have sustained damage, 1,900 of which are unusable. Some neighbourhoods were left without electricity and heat, and in some areas without internet. Most of the damaged buildings were built in the 18th and 19th century and are located in the historic centre of Zagreb. Most of the museums in the city's centre were damaged by the earthquake, including the Museum of Arts and Crafts, the Croatian History Museum, and the Schools Museum. Two buildings of the Komedija theatre reported significant damage. Minor damage was also registered on the Faculty of Law, the Croatian Music Institute [2]. One of the buildings with major damage was the Zagreb Cathedral.

4 Damage on Zagreb Cathedral and decision on north tower removal

Immediately after the earthquake, it could be seen that the Cathedral doesn't have the upper part of its southern tower anymore (as shown on figure 2).

Figure 2. Zagreb cathedral without its southern tower and damages on Zagreb Cathedral [3]

Few days after the earthquake, Cathedral renovation designer and supervising engineer, Mr. Damir Foretić, made a detailed report where all damages on the cathedral were noted. The southern tower broke at height of 92 m, where a 10,3 m long piece fell and caused significant damage during the fall. One part of the tower fell on the roof of the Cathedral, damaging and piercing it in several places with most of the stone elements falling into the courtyard between the Cathedral and the Archbishop's Palace [3]. There were a lot of other damages and all of them had been marked and described in the report. During the inspection, a drone had been used in order to take pictures of the northern tower. After reviewing the videos from the drone, significant damage was confirmed, and after another drone recording the conclusion of members of the expert commission and colleagues from the working group was unanimous - part of the north bell tower should be removed as there is a serious possibility of collapse [3]. The part of the bell tower that could collapse weighted about 36 tons, with a total height of 13.47 meters together with its cross. Damages parts are shown on figure 3.

Figure 3. North-east and north part of northern tower (photo by Josip Ninković)

Immediately, the first plan for northern tower removal was made by Mr. Foretić and other members of the working group. The plan was to lower the tower using a 500-ton crane, then tower was to be secured as shown in the figure 4.

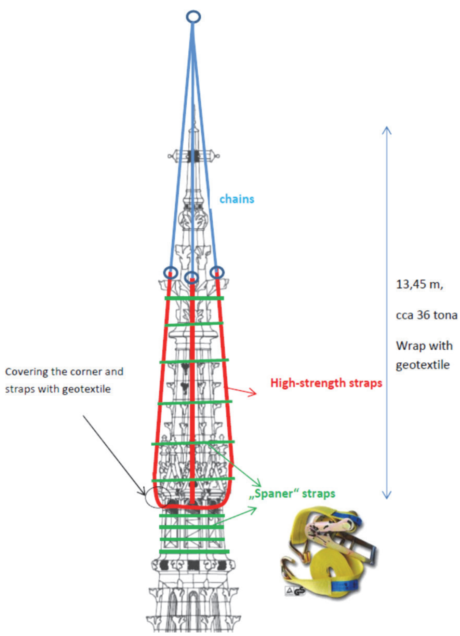

Figure 4. Preparation of northern tower for lowering by 500-tons crane [4]

Prior to the descent, it was necessary to separate the top of the tower from the rest of the building, as it was badly damaged and statically disturbed it represented a threat to the people who will work on removing. The solution for a safe way of separation was controlled blasting.

5 Preparation for blasting

On behalf of Cathedral Restoration Committee Mons. Ivan Hren, the curator of the Zagreb Cathedral and chairman, contacted University of Zagreb, Faculty of Mining Geology and Petroleum Engineering and asked for help in calculation of blasting parameters and executing of blasting. Professor Mario Dobrilović and Assistant Professor Vječislav Bohanek from Department of Mining Engineering and Geotechnics are named on behalf of the Faculty of Mining Geology and Petroleum Engineering to perform these difficult tasks. Conclusion after the first meeting of working group was that the Croatian Army should conduct the blasting designed by the Faculty. Members of Engineer Regiment from Karlovac; Colonel Miroslav Car, Sergeant Krešimir Marjanović and Sergeant Damir Vulaković became part of the blasting team.

Figure 5. Blasting team with Cardinal Bozanić

In order to remove the upper part of north tower, the blasting team had two main tasks to carry out. First task was explosive cutting of a steel rope,15 mm in diameter, that connects the top of the tower to a counterweight of about 4 tons. The role of wire rope was to stabilize upper part of the tower. The second, even more complicated part, was to perform a blast that would release the metal wedges that connect the two rock segments of the Cathedral. There were four rock segments and each of them had three metal wedges. As can be seen in figure 7, some of them were already released as a result of earthquake. Both tasks had to be performed simultaneously. Steel wire rope and metal wedge and the positions of metal wedges in the cross section of the tower are shown on figure 6.
The second task was that much more difficult than the first one because there was no available data in literature to be used as a guideline. Also, there was no data at all on previous blasting in this type of rock. The Cathedral was built from lithothamnian limestone called Bizek, which is the autochthonous stone in the Zagreb area. The basic characteristics of the lithothamnian limestone are porosity, low density and perforated texture [5].

Figure 6. Steel wire rope, metal wedge and positions of metal wedges

In order to perform the blasting successfully, it was necessary that the calculation about quantity of explosive and positioning of the explosive charge is empirically proven. All tests were done on samples taken from parts of the Cathedral's southern tower. Stone samples varying in shape, size and mass were used along with steel wire rope in different lengths. The first tests were done on the steel wire rope and quantity of explosives and the shape of explosive charge had to be determined for successful cutting. These tests were performed in a laboratory for testing of explosives at the Faculty of mining, geology, and petroleum engineering. PETN explosives were used for testing and charges were made different by its shape and mass, the positions of the charges varied, and one or two charge setups were used. After each shoot an inspection was carried out on the steel rope and the efficiency of cutting by explosive was measured.
Obtained samples of stone were smaller than those on which blasting was supposed to be performed. The quantity of explosive and the position of explosive charge were calculated in order to cause fragmentation where the metal wedges are, but not to damage the rest of the stone block. Also, different materials had been tested in order to prevent fly rock or debris damage during the blasting.

Figure 7. Stone block testing [6]

Report of laboratory testing was analysed and afterwards the polygon tests were performed in the courtyard of the Cathedral. Tests were done with the members of the Croatian army responsible for carrying out the blasting. During this testing bigger samples of stone were used in order to make the testing more realistic. The aim of these tests was to confirm results of laboratory testing and to:
- determine the optimal amount of explosive charge for fragmentation of stone blocks,
- determine the optimal amount of explosive for cutting of steel rope,
- determine the initial means and manner of initiation and
- determine the method of protection against scattering of fragmented material during blasting.

All blasting was recorded by a high-mounted Chronos high-speed camera. These recordings were very useful for the evaluation of blasting results. The testing setups for the stone block and the steel wire are shown on figure 7, results on blasting on figure 8, and protection on figure 9.

Figure 8. Stone block and steel wire test setups

Figure 9. Results of trial blasts

Last trial blasting was done on 16th of April and the final conclusion was made. Quantity of explosive for cutting of steel wire rope is 15 g, and two different charges would be used for demolition of the metal wedges, 5 g for middle wedges, and 3 g for side wedges of each element. Chosen explosive was PEP 500 plastic explosive and electric detonators were used for their initiation. After the last trial blasting, the team was again lifted by crane to the upper part of the cathedral to check once again for the number of holes and the position for drilling.

6 Blasting

Preparation for the demolition was planned to start at about 8 o'clock on April 17th but it was postponed to 11 o'clock. The reason for this delay were gusts of very strong wind in the morning and due to safety reasons, it was not possible to lift the blasting team on the top of the Cathedral. The blasting team was divided into two groups - the first group was in charge of drilling the holes and setting the explosives in the stone block of cathedral and the second one for placing the explosive charge on the steel wire rope inside the Cathedral. Together with the blasting team in the crane basket was Mr. Tomo Capan who was informing the crane operator about their position.

Figure 10. Preparation for blasting

Figure 11. Blasting and lowering of northern tower (Photo: MORH/F. Klen)

After the placing of the explosive charge, a big role was played by alpinists who set up the cables and attached them to the crane. Also, police had to distance all people and journalist to secure the area and to secure the perimeter. Finally, after the long preparation, everything was ready for blasting and at about 6 pm Colonel Car gave the order for blasting.

The whole process was supervised by seven members of the Military Intelligence unit and three aircrafts led by the Commander of the Military Intelligence Major Mario Maslov. Videos from drones were visible in real time on a display at the command centre. It was extremely important to have all information in real time, especially the information about the effect of blasting. Immediately after the blasting a clean cut on steel wire rope was visible. The removal began several minutes later after drones made sure the blasting had released the metal wedges and that that part of the tower could be lowered in one piece by a 500-ton crane. Few minutes after the blasting the northern tower was placed in front of the Zagreb Cathedral. Many felt a big relief especial those who directly participated in this project.

7 Conclusion

The project was carried out in unusual times, after the earthquake and during the coronavirus lockdown on a building that has a special significance for most residents of Zagreb and Croatia. It is not surprising that media interest in this project was extremely high and Croatian citizens were able to watch the removal of the tower online in real time. Although all members of blasting team participated in many different blasting projects this one was something special and we are all very proud for having participated. For the end, it is an interesting fact that the northern tower was removed on the same date (17th of April) when the main architect of this Gothic cathedral towers, Mr. Herman Bollé, had died.

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