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PRELIMINARY EARTHQUAKE SURVEY OF BUILDINGS – CASE STUDY OF SENJ

Josipa Mihaljević [(1)], Davor Grandić [(2)], Paulo Šćulac [(3)]

[(1)] *Research assistant, Faculty of Civil Engineering, University of Rijeka, josipa.mihaljevic@uniri.hr*
[(2)] *Professor, Faculty of Civil Engineering, University of Rijeka, dgrandic@gradri.uniri.hr*
[(3)] *Assistant Professor, Faculty of Civil Engineering, University of Rijeka, paulo.sculac@uniri.hr*

Abstract

Senj is a medieval town located on the eastern coast of Kvarner. In addition to the destruction caused by World War II, Senj has been hit by strong earthquakes throughout history. The appearance of significant earthquakes in this area is not surprising because, according to the seismic area classification of the Republic of Croatia, Senj is located in an area where the horizontal peak ground acceleration equals 0,24g. Within the historic city center of Senj, some stone masonry buildings date back to the 12th century. Those two facts present a good reason for selecting Senj as a representative research area. In order to evaluate the overall behavior and seismic resistance of existing buildings, it is first necessary to visually establish the characteristics of stone masonry buildings (typology of buildings). The connection of timber floors with stone masonry walls needs to be addressed as well. It needs to be investigated if the timber floor forms a diaphragm or whether it is flexible in its plane because it significantly affects the behavior of masonry buildings during an earthquake. Visual inspection of buildings indicated that most of the buildings were built with mixed materials (which is a result of fast renovation after great destruction in World War II), which implies the use of stone elements, brick parts, and mortar. In almost all stone masonry buildings, a tie system is present as a kind of reinforcement that ensures the integrity of the buildings.

Keywords: preliminary assessment, heritage buildings, stone masonry. seismic resistance, Senj

1. Introduction

Senj (Roman Senia) is a medieval town characterized by spontaneous development throughout history. The rapid development of the city took place in the 15th century in different directions, with trade being especially emphasized because Senj was an important port center at that time [1]. Numerous historical representations of the city have been preserved in the form of vedutes and cartographic representations. However, most of them did not faithfully depict the state of the city at that time. The oldest urban plan of the city from 1749 is shown in Figure 1. a), while Figure 1. b) shows the historic city center of Senj before the Second World War. The Second World War left the city of Senj with great damage caused by numerous aerial bombardments. In terms of urbanism, it is one of the most significant historical events for Senj. Various authors [1, 2, 3] state that 80% of the historic city center was destroyed, and this is confirmed by some of the remaining archive documents.

Another important influence should not be ignored: a stream flowed through the historic city center, which usually turned into a torrent during the melting of snow and heavy rainfall, and on one occasion demolished 50 houses [1]. The aforementioned torrent is thought to have brought the drift of gravel and sand that formed part of the coast. Over time, the stream was regulated outside the city walls. With the sudden development of Rijeka in the 16th century, Senj lost its importance. Senj's trade revived in the 18th century, resulting in the construction of new buildings and the refurbishment of old ones to accommodate the need for storage space. According to the administrative division, Senj is one of four towns located in Lika-Senj County. It is surrounded by the slopes of Velebit and Kapela and occupies most of the eastern coast of Kvarner.

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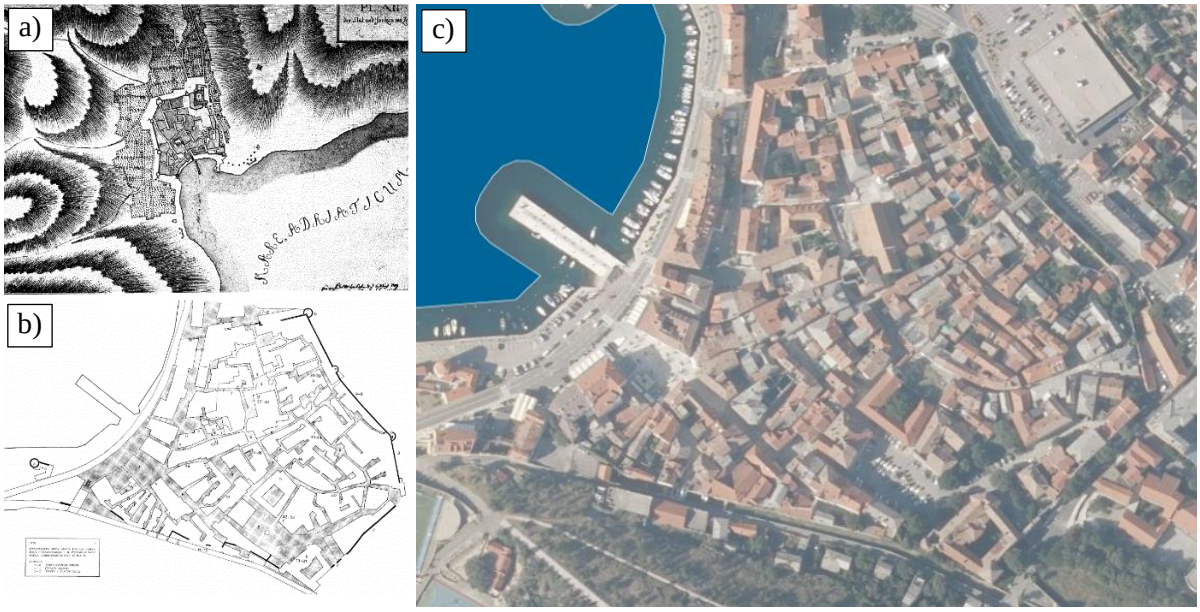

Figure 1. Old town center of Senj: a) the oldest urban plan of the city from 1749 [1]; b) the historic city center of Senj before the Second World War [1]; c) ortophoto view of the historic city center of Senj 2019/20[6]

In addition to war destruction, floods and fires, Senj has been hit by earthquakes of great magnitude throughout history. Božičević talks about Senj as a seismically active area in his work Earthquakes in Senj [4]. The paper describes the first classification of the territory into six earthquake zones with regard to the expected strength of the earthquake, which are also graphically shown on the map. Significant earthquakes that hit Senj and its surroundings have been documented, and are presented here in Table 1. The seismic area classification of the Republic of Croatia for the return period of 475 years is shown in Figure 2 [5], which shows that the area of the city of Senj is in the red area, i.e., that the horizontal peak ground acceleration is 0,24g.

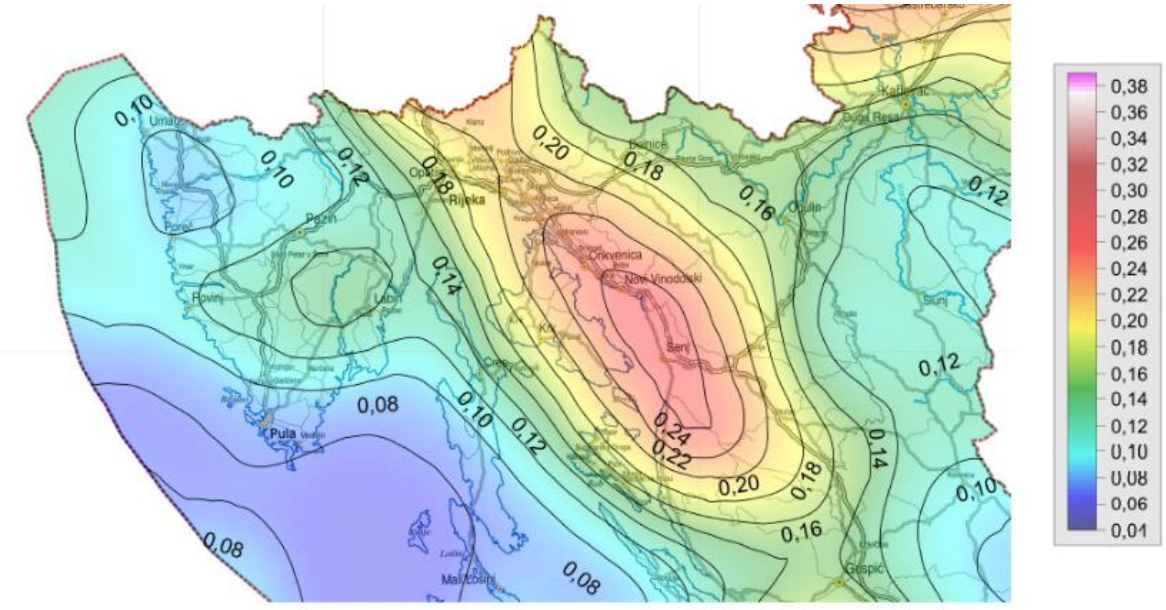

Figure 2. The seismic area classification of the Republic of Croatia for the return period of 475 years [5]

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Table 1. Chronicle of strong earthquakes in the vicinity of Senj (according to data from [4])

Chronicle of strong earthquakes in the vicinity of Senj (Earthquakes of the sixth degree and higher according to MCS)	
1639 Senj	18. I. 1902 Novi Vinodolski
1648 Senj	1. II. 1905 Novi Vinodolski
24. IV. 1776 Bakar	4. III. 1906 Brinje, Senj
26. XII. 1857 Kraljevica	4. IX. 1908 Novi Vinodolski
5. XII. 1868 Senj	12. III. 1916 Grižane, Bribir
30. III. 1869 Senj	14. VII. 1916 Brinje, Senj
3. I. 1870 Senj	14. X, 1916 Crikvenica
19. IV. 1873 Senj	30. VII. 1920 Baška, otok Krk
30. III. 1877 Senj	5. IX. 1925 Grižane, Bribir
23. IX. 1878 Senj	11. IX. 1925 Grižane, Bribir
3. V. 1885 Senj	1. I. 1926 Crikvenica
18. VII. 1890 Novi Vinodolski	21. X. 1926 Senj
30. VII. 1890 Novi Vinodolski	5. II. 1939 Omišalj, otok Krk
13. IX. 1890 Novi Vinodolski	6. II. 1939 Omišalj, otok Krk
3. V. 1891 Novi Vinodolski	18. II. 1939 Omišalj, otok Krk
12. VI. 1893 Grižane, Bribir	30. VI. 1949 Baška, otok Krk
9. VIII. 1895 Brinje, Senj	20. I. 1949 Baška, otok Krk

2. Visual inspection of buildings

A visual inspection of buildings gives an insight into the existing condition of the buildings in the observed area. It is the first step in determining the parameters for assessment, i.e., the behavior and seismic resistance of existing buildings. The first step of the visual inspection would be to determine the typology of the buildings, while the second step is related to the masonry typology.

2.1 Building typology

The building typology includes the layout and number of storeys. Due to the lack of design documentation, the floor layout of the buildings can be determined through the orthophoto map of the historic city center of Senj (Figure 1.c)). The historic city center of Senj occupies an area of about 0,07 km^2 and is surrounded by city walls for which there is no exact information on when they were actually built. Certain documents mention how the walls changed their position over time, which would mean that the historic city center expanded. From a series of historical documents related to the 13th and 14th centuries, it can be noticed that the space inside the city walls was not as densely built as is the case today [1]. The densely built/populated area within the city walls forms a network of narrow and winding streets, so it can be assumed that Senj has retained the medieval character of the city. The construction of individual buildings developed horizontally, while the majority of buildings are characterized by one-storey construction [1].

According to the orthophoto map (Figure 1. c)), it can be seen that the buildings mostly have a regular floor plan (rectangular or square). However, some objects fall out of the scope of "regular." The majority of them are objects that had special significance in Senj's past. First of all, there is Frankopan's castle. In addition to these building, which stands out for its size, there is also a building that previously served as a Franciscan monastery and a cathedral. Due to the extremely dense typology, the buildings lean against each other (perhaps some of them are connected in a certain way?). Within the city center of Senj, buildings with two to three stories prevail. The buildings located close to the coast are up to 4 stories high, but it should be mentioned that they are more recent buildings built on the place of demolished, badly damaged salt warehouses after World War II.

It is interesting to note that there were 14 sacred buildings within the historic city center, in a relatively small area, 12 of which were churches and two of which were monasteries. Most of the churches have lost their sacred significance and have been converted into residential and commercial

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buildings. Also, numerous buildings of profane architecture have been repurposed over time and, for this purpose, often extended and rebuilt either for residential or business purposes [1]. Vaulted streets (passages) are one of the architectural features characteristic for the historical city center of Senj. Observing individual buildings, cracks formed around the window openings at the level of the first and second floors which can be seen in the Figure 3 (middle photo).

Figure 3. The facades of buildings within the historic city center of Senj

2.2 Masonry typology

The next step would be to determine the masonry typology, which implies the type and structure of the stone masonry walls. It also covers the recognition of the used materials. Material is meant for the use of stone blocks, part of bricks, and mortar. Stone masonry walls can be made of roughly shaped and processed stone elements. Stone masonry buildings built of roughly shaped are divided into several types: a wall built of rubble stone, a wall built of boulder stones, a cyclopean stone masonry , and a wall built of slab stone. Processed stone elements are divided depending on the method of processing, so the brickwork can be made of roughly processed stone, finely processed stone, or by stonemasons [6].

Figure 4. Masonry typology

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For example, in the case of mortar, one can see what kind of sand was used (fine or coarse), which affects the strength of the mortar itself. It is difficult to discuss about the type of masonry when "open" access to the wall does not exist. Since there are several ruins within the historic city center, it was possible to see that the buildings were built as single leaf masonry, up to 50 cm thick (Figure 4). It is assumed that the other buildings were built according to the same or a similar principle. There are few buildings built with finely processed stone elements, while in most buildings mixed materials are used (Figure 4). Mixed material means the use of stone elements, brick parts, and mortar. Here, the regularity of the alternation of tone and brick layers cannot be precisely identified. Brick fragments were added to a thick layer of mortar. Apart from brick fragments, pebbles can be seen in the mortar. Some written sources [3] emphasize the use of stone elements made of white-gray limestone, tufa (quarried in the Gacka bed), and gray hard limestone. Figure 4 (below, left) shows part of the wall of one observed building where empty joints are clearly visible, which is the result of a weak bond between the mortar and the stone elements. Precisely in such places, it was observed that mortar with fine aggregate (sand) was used and that it crumbles under the fingers, which indicates low mortar strength.

Figure 5. Timber floor construction

According to photo documentation [8] and by observing the badly damaged buildings in some parts of the historic city center, it can be concluded that the floor structures were formed by single timber beams placed at equal spans and supported on load-bearing facade walls (Figure 5). The floor consists of planks laid on joists, on which additional floor layers are placed. The underlay of the floor structure is formed by the formwork (slats) on which the reeds are placed and the final layer of plaster. However, to be able to say with certainty which is the predominant type of timber floor construction, it

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is necessary to further research this area. The connection between the timber floor structure and the stone masonry wall is of great importance considering the behavior of the structure during earthquakes. One of the structural details that are characteristic of almost every old stone masonry building are the tie rods, which are shown in Figure 6. The ties were made of wrought iron.

Figure 6. Tie rods visible on the facade of the building (left) and inside the section of the Wall (right)

3. Conclusion

Certain buildings within the city center date back to the 15th century, while several of them date from the 12th century. Senj was chosen as a representative research area due to the large number of historic stone masonry buildings in the historic city center and the area with high horizontal peak ground acceleration. First of all, it should be pointed out that such old buildings were not designed according to standards that take into account seismic effects. The visual inspection aims to collect as much data as possible about the condition of existing buildings, which will be used for further analysis of the buildings in order to evaluate their seismic resistance. A visual inspection revealed that the buildings mostly have a regular floor layout and were built mostly with mixed materials. The stone elements are mostly broken or roughly shaped, but in some places, buildings built with regular shaped stone elements have been observed. It is assumed that brick fragments and pebbles were used to fill wide joints between stone elements, i.e., to reduce the thickness of the mortar layer. Observing the walls, it is not possible to clearly determine the regularity in the sequence of alternating layers of stone elements and bricks in buildings built with mixed materials. On some buildings, we observed "empty" joints between the stone elements, which is an indication of the mortar's deterioration. Due to the great damage caused during the Second World War, there was a need for quick action - reconstruction and repair of buildings, which is partly considered the cause of the mixed structure of the masonry. When it comes to floor structures, according to what has been observed, we can assume that the other buildings have the same type of timber floor construction. A characteristic of masonry buildings in general, and also of those in Senj, is the use of tie rods, which are mostly visible on the facades of the buildings. The lack of design documentation and limited access to the interior of the structure requires an additional inspection of the timber floor structures in order to accurately identify the typology characteristic of this area. This preliminary assessment will serve as the basis for future research on the seismic resistance of masonry stone buildings in a representative area.

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