Seismic behavior of masonry buildings - Lessons from the Bovec earthquake of April 12, 1998

Tomaževič, Miha[1], Klemenc, Iztok[2], Lutman, Marjana[3]

ABSTRACT

On April 12, 1998, the region of Upper Posočje in western Slovenia suffered from a M = 5.5 earthquake, with estimated epicentral EMS intensity VII - VIII. No building collapsed. However, out of about 1000, mostly stone-masonry buildings, where damage has been reported, more than 300 have been found unusable. On the basis of the results of the in-situ lateral resistance tests of masonry walls, typical for the region, the seismic resistance of a series of buildings has been assessed. Since no ground motion data existed from the earthquake, the values of effective ground accelerations have been estimated by correlating the observed degree of damage and seismic resistance of buildings. The observed behavior of buildings has also been used to analyze the effectiveness of strengthening methods, applied to the buildings in 1976, when the same area, near to Italian border, suffered from Friuli earthquakes.

INTRODUCTION

Slovenia is an earthquake-prone country (Fig.1). In the last two decades, the western-most region of Slovenia, the Soča River Valley (Posočje), a mountainous, in most part rural area near to the border with Italy, suffered from two earthquakes. In 1976, more than 6000 buildings have been damaged by the earthquakes with epicenters in Friuli. Although the epicentral distance was more than 30 km, the intensity of the earthquake in the most affected parts of Posočje was estimated to VIII by MSK intensity scale. On April 12, 1998, a local earthquake of estimated epicentral intensity VII-VIII by EMS (European Macroseismic Scale) struck the region of Upper Posočje. The epicenter of M = 5.5 earthquake was located about 6 km Northeast from the town of Bovec, and the focal depth was somewhere between 15 and 18 km. Unfortunately, no strong-motion data of the main shock have been recorded in the epicentral area.

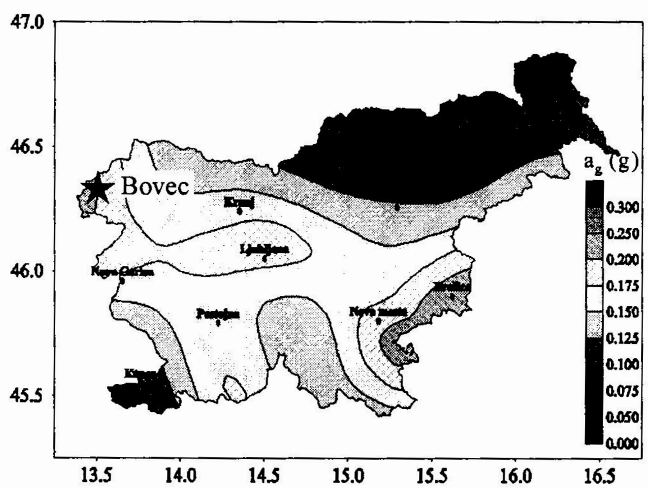

Fig. 1. Design ground acceleration map of Slovenia for T = 475 years return period earthquakes.
Geophysical Survey of Slovenia, preliminary map

Although not strong by the magnitude, the earthquake of April 12, 1998, caused considerable damage to buildings in a distance of about 10 km from the epicenter. Out of 952 inspected buildings in the region, not including barns, stables and other secondary buildings, where damage has been reported by the residents, 337 have been found as temporarily unusable.

[1] Professor, [2] Researcher, [3] Senior Researcher, Slovenian National Building and Civil Engineering Institute, Dimičeva 12, 1000 Ljubljana, SLOVENIA

Among them, 123 have been damaged seriously, in some cases even beyond repair, whereas 214 buildings suffered repairable damage. More than 710 people have been temporarily moved to mobile homes, placed near to their damaged houses.

Since the same region suffered from two earthquakes in two decades, the earthquake of 1998 provided a good opportunity for the verification of the efficiency of methods, used for the retrofit of buildings, damaged in 1976. However, it has to be mentioned that the impact of earthquakes of 1976 was not so severe in the remote villages, which suffered in 1998, so that not many buildings in the recently damaged area have been completely retrofitted in 1976. Nevertheless, there is sufficient evidence to point out the main advantages and deficiencies of the strengthening methods. To study the consequences of earthquake of 1998, a research project has been initiated, where the seismic behavior of buildings has been analyzed by taking into account the results of in-situ tests of masonry walls in both existing and strengthened conditions. Although preliminary, the main conclusions of the project will be discussed in this paper.

BUILDING TYPOLOGY AND OBSERVED DAMAGE

Traditional stone-masonry buildings

Traditional construction material in the region is locally available lime-stone. With exception of traditional buildings, categorized as important architectural heritage of the region, stone-masonry buildings in most towns and villages have been built after the WW I. Typically, stone-masonry houses are 2-3 storeys high, with the walls built of two outer layers of bigger stones, with an inner infill of smaller pieces of stone, in poor mud mortar with a little lime. Connecting stones are rare. Sometimes, stones are cut, or partly cut at the corners. Floors are wooden, and so are originally lintels. In the cases where the owners renewed their houses, wooden lintels have been replaced with r.c. or prefabricated ceramic ones. Except of a limited number of buildings in towns, there is no evidence of either wooden or iron ties. The roofs are covered with ceramic tiles, sometimes laid in mortar. Consequently, the seismic behaviour of such buildings is poor. When subjected to seismic loading, the walls separate at vertical joints and intersections, and delaminate and/or disintegrate as well (Fig.1). Although brick and masonry block replaced stone in the last 30 years, stone-masonry houses still represent the majority of the existing building stock.

Fig 1. Typical partial collapse of a gable and disintegration of walls of a traditional stone-masonry house

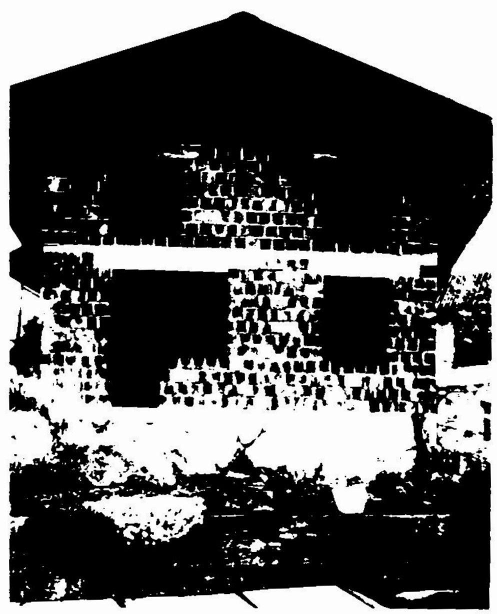

Fig. 2. Severe damage and dislocation of the upper story of a hollow block masonry building without bond beams and columns

Brick- and block-masonry buildings

Different types of masonry units, including normal format brick and hollow ceramic and concrete blocks, laid in lime or lime-cement mortar are the basic construction material, used for the construction of buildings in the region in the last several decades. Floors are either monolithic reinforced-concrete slabs or slabs made of prefabricated ceramic elements. In all cases, r.c. bond-beams, which connect the walls, are constructed at floor levels. However, vertical r.c. tie-columns, a standard characteristic of masonry construction in seismic regions enforced by the first Yugoslav seismic code of 1964, are many times omitted.

In the case of the brick- and block-masonry construction, the buildings generally behaved well. Most of the observed damage was due to the mistakes made by the owners of buildings, who have built their houses by themselves. There were cases where the new houses have been built with masonry units with horizontal holes, as well with units and/or mortar of poor quality. Sometimes, the spacing of structural walls was too large, and the slabs were slender. Often, the houses have been built without vertical tie-columns at the corners and wall intersections, and without bond-beams along the walls in the attics and gables (Fig.2).

Methods for strengthening and repair

In order to achieve adequate performance of existing stone-masonry buildings during earthquakes, two basic criteria should be fulfilled:

1. structural walls should be sufficient in number and strength to resist the expected seismic loading, and
2. structural walls should be adequately tied and connected to ensure structural integrity during an earthquake. Floor structures should be capable to distribute seismic loads onto the walls and rigid enough to prevent excessive out-of-plane vibration of the walls.

In the case of stone-masonry, the systematic filling the voids with injected cementitious grout represents an obvious and efficient method of strengthening. The grout, consisting of cement and water, with finely grained inert aggregates and additives added to achieve special effects, is injected into the wall through injection tubes and nozzles, which are built into the joints between the stones uniformly over the entire surface of the wall at 0.5 m - 1.0 m intervals, depending on the structure of the walls. Holes are drilled between the stones to a depth of at least half of the thickness of the wall, and metallic or plastic injection nozzles are put into the holes several centimeters deep. Low pressure not exceeding 1 bar is needed to inject the grout.

In order to ensure the integrity of existing masonry structures during earthquakes, wooden floors are either replaced by r.c. slabs, anchored to supporting walls, or the walls are tied with steel ties and wooden floors anchored to the walls and/or braced with diagonal ties. Usually, the ties are placed symmetrically on both sides of the walls, threaded at the ends so that they can be bolted on the steel anchor plates at the ends of the walls. After placing and slightly prestressing the ties with a key, the nuts are welded on the anchor plate. All the steel parts of the tie are protected against corrosion by paint and covered by plaster.

During the reconstruction of the region of Posočje, damaged by the earthquake of Friuli of 1976, the tying of the walls with steel ties, the replacement of wooden floors with r.c. slabs, and the grouting of stone-masonry walls with cement grout were the methods, recommended for the seismic retrofit of stone-masonry buildings. Basically the same, but technologically improved methods, are still used nowadays.

MECHANICAL CHARACTERISTIC OF STONE-MASONRY WALLS

Because of specific properties of masonry materials and the way of construction, it is not easy to fully reproduce the existing stone-masonry in the laboratory, although thorough mechanical and chemical analyses of the properties of constituent materials would have been previously carried out. Therefore, the values of mechanical characteristics, needed for seismic resistance verification, have been determined by testing the existing stone-masonry walls in-situ. In order to obtain data on the efficiency of cement grouting, two pairs of walls, existing and cement-grouted, have been tested in the same building.

Taking into consideration the quality of masonry and technical possibilities of carrying out the tests, three buildings have been selected: a typical residential house (building A) and two public buildings (buildings B and C). The walls have been separated from the surrounding masonry and tested either as vertical cantilevers (building A) or fixed-ended (buildings B and C). In the first case, vertical load has been applied by means of hydraulic jack, whereas in the other, the walls have been tested under the existing working load conditions. Horizontal load has been applied at the upper boundary or at the mid-height of the specimens, respectively. The load has been step-wise increased until serious damage has occurred to the walls, with unloading at each step of the test. Horizontal displacements and diagonal strains have been measured by means of LVDT-s. Typical disposition of the test and typical crack patterns at ultimate state are shown in Figs.3 and 4, respectively.

Fig 3. Disposition of the in-situ lateral resistance test: wall tested as vertical cantilever

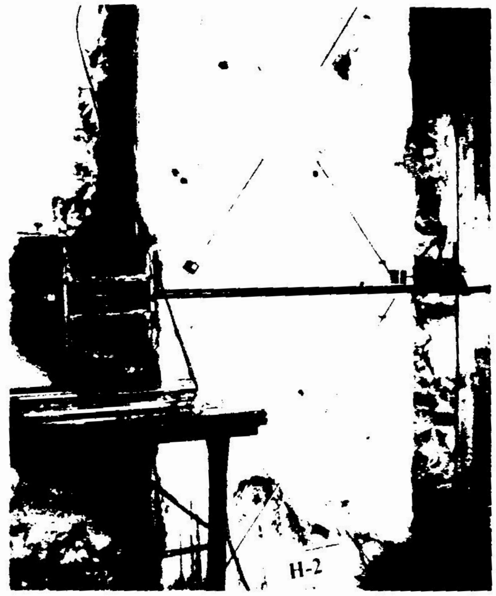

Fig. 4. Cracks patterns in a tested cement-grouted wall at ultimate state: wall tested as fixed-ended

As expected, all tested walls failed in shear. Taking into consideration the shear resistance theory, the tensile strength of the masonry f_t is defined as the principal tensile stress, developed in the wall at maximum resistance, assuming that the walls behave as elastic, homogeneous and isotropic structural elements (Turnšek and Čačovič, 1971):

$$f_t = \sqrt{\left(\frac{\sigma_o}{2}\right)^2 + (b\tau_{H_{max}})^2} - \frac{\sigma_o}{2}, \qquad (1)$$

where σ_o = the working stress in the wall's section, τ_{Hmax} = the average shear stress at the attained maximum resistance H_{max}, and b = the shear stresses distribution factor, which depends on the dimensions of the walls and vertical/lateral load ratio.

The dimensions of tested walls and test results are summarized in Table 1, where the degree of improvement in tensile strength of stone-masonry in terms of ratio between the tensile strength of cement-grouted and existing walls is also indicated.

Table 1. Dimensions of tested walls and test results

Building	State	Dimensions l x d x h (m)	Working stress σ_o (MPa)	Tensile strength f_t (MPa)	Shear modulus G (MPa)	Strength ratio grouted/existing
A*	Existing	0.98 x 0.52 x 1.63	0.54	0.06	84	1.83
A*	Grouted	1.00 x 0.52 x 1.60	0.65	0.11	174	
B	Existing	1.00 x 0.65 x 2.54	0.20	0.06	181	2.83
B	Grouted	1.00 x 0.65 x 2.52	0.19	0.17	337	
C	Existing	0.98 x 0.64 x 2.51	0.18	0.10	151	2.20
C	Grouted	1.03 x 0.66 x 2.50	0.23	0.22	470	

* Note: walls tested as vertical cantilevers

Typical lateral load - deformation relationships, obtained during the in-situ tests of existing and cement-grouted walls, are shown in Fig.5. As can be seen, the tensile strength of stone-masonry, which determines the seismic resistance of stone-masonry buildings of the particular type considered, is significantly improved by cement-grouting of stone-masonry walls.

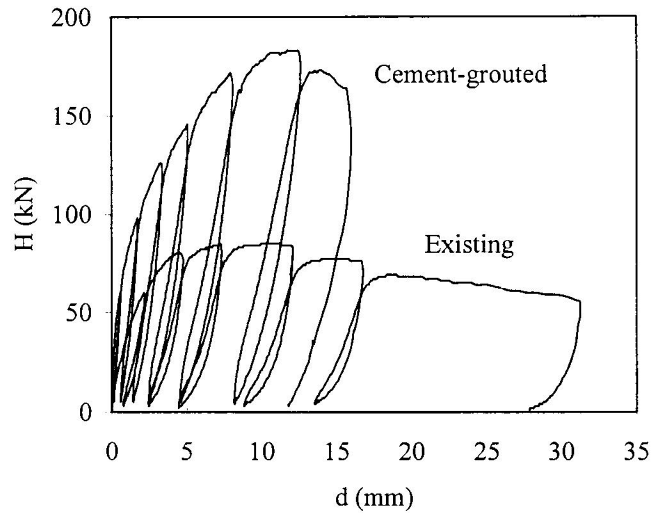

Fig. 5. Typical lateral load - deformation relationships, obtained by in-situ lateral resistance test of existing and cement-grouted stone masonry wall (building C)

ASSESSMENT OF SEISMIC RESISTANCE OF STONE-MASONRY BUILDINGS

In order to obtain information about the seismic resistance of stone-masonry construction in the region, a number of typical buildings has been analyzed. A limit states method of the type of the push-over analysis (Tomaževič et al., 1978) and the experimentally obtained values of tensile strength of existing and cement-grouted stone-masonry, given in Table 1, have been used. The results of calculations are presented in Table 2 for both, existing and strengthened buildings.

Table 2. Seismic resistance of existing and strengthened stone-masonry buildings in terms of coefficient of seismic resistance (CSR = H_u/W)

Building	No. of stories	Wall area (%)		Existing			Strengthened		
		x-dir.	y-dir.	f_t (MPa)	CSR_x	CSR_y	f_t (MPa)	CSR_x	CSR_y
1	2	15.9	12.0	0.08	0.16	0.17	0.14	0.21	0.21
2	2	12.5	7.4	0.08	0.18	0.16	0.14	0.23	0.20
3	2	11.0	11.0	0.06	0.20	0.23	0.11	0.26	0.31
4	2	12.4	10.8	0.06	0.25	0.25	0.11	0.30	0.28
5	2	9.6	9.2	0.06	0.22	0.19	0.11	0.30	0.33
6	2	11.4	13.0	0.06	0.23	0.26	0.11	0.30	0.33

Taking into account the relationship between the effective ground acceleration a_g and ultimate base shear coefficient BSC_u, given in Eurocode 8 (Eurocode 8, 1994):

$$BSC_u = \frac{S_e(T)}{q}, \tag{2}$$

where $S_e(T) = a_g\ S\ \beta_o$ is the spectral value. Assuming soil parameter S = 1.0, maximum normalized spectral value β_o constant between T = 0.1 s and T = 0.4 s (β_o = 2.5), and structural behavior factor q = 1.5 (plain masonry), the values of ultimate base shear coefficient BSC_u, given in Table 1, can be used to estimate the values of effective ground acceleration a_g causing ultimate limit state of the building under consideration. The results of this analysis are given in Table 3.

Table 3. Estimated values of effective ground acceleration a_g, which the buildings can resist (in g)

Building No.	No. of stories	Existing		Strengthened	
		x-direction	y-direction	x-direction	y-direction
1	2	0.10	0.10	0.13	0.13
2	2	0.11	0.10	0.14	0.12
3		0.12	0.14	0.16	0.19
4		0.15	0.15	0.18	0.17
5	2	0.13	0.11	0.18	0.20
6	2	0.14	0.16	0.18	0.20

Under these assumptions, the values of effective ground accelerations during the earthquake of April 12, 1998, did not exceed 0.15 g, which is slightly less than EC 8 design value proposed for the case of EMS intensity VIII earthquakes (a_g = 0.2g). Unfortunately, there are no instrumental data which would confirm the calculated values of a_g, or verify the EC 8 assumed values of spectral amplification β_0 and structural behavior factor q for this particular type of buildings. Although the calculated values of a_g are relatively low, it can be seen that poor behavior of existing buildings could have been expected, whereas adequately retrofitted buildings in most cases should not suffer significant damage.

CONCLUSIONS

Whereas the buildings, thoroughly strengthened after the earthquake of 1976 by using recommended technical measures, survived the earthquake of 1998 without, or with only minor damage, substantial damage has occurred in the cases where the relevant guidelines have been only partly respected. This was especially the case where the existing wooden floors have been replaced with r.c. slabs, not properly anchored and connected to the walls, and the walls have not been strengthened by cement-grouting. In such a case, the rigid slab pushed the outer wythe of the wall outwards, thereby causing the development of horizontal cracks just below the slab, delamination of walls and and pushing out of corners.

To achieve good seismic behavior in the zones where the design (effective) ground accelerations up to 0.2 g are expected (EMS intensity VIII), the integrity of masonry structural system should be provided by means of tying the walls with steel ties and anchoring the floors into the walls. Stone-masonry walls should also be strengthened by cement grouting to resist the expected loads. In the case where wooden floors are replaced with the r.c. slabs, the slabs should be adequately supported on the inner load-bearing wythe of a stone-masonry wall, and adequate anchors should be provided to connect the slab with the outer wythe. Also, steel ties should be provided on the outer side of the wall to ensure the integrity of the structure. If this is not the case, the rigid slabs will push the outer wythe of the wall outwards, thereby causing the development of horizontal cracks just below the slab, as well as delamination and falling out of the outer wythe of the wall at these zones.

As has been indicated, the replacement of wooden floors with rigid slabs is not always necessary. In the case where the walls need not to be strengthened, the tying of the walls with steel ties will provide the integrity of the structure and, hence, utilize the available resistance. However, if the walls need to be strengthened, a properly supported and anchored r.c. slab, with steel ties provided on the outside of the walls, represents the best technical solution.

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REFERENCES

Eurocode 8. 1994. *Design Provisions for Earthquake Resistance of Structures. Part 1-1: General Rules - Seismic Actions and General Requirements for Structures.* ENV 1998-1-1: 1994, Brussels, Belgium, CEN.

Tomaževič, M., Turnšek, V., Terčelj, S. 1978. "Computation of the shear resistance of masonry buildings." *Report ZRMK-IK*, Ljubljana.

Turnšek, V., Čačovič, F. 1971. "Some Experimental Results on the Strength of Brick-masonry Walls," *Proc., 2nd International Brick-masonry Conference*, Stoke-on-Trent, pp. 149-156.