Structural Analysis of Historic Construction – D'Ayala & Fodde (eds)

Seismic resistance assessment of heritage masonry buildings in public use in Ljubljana

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ABSTRACT: Recently developed parametric approach for seismic vulnerability and seismic resistance assessment and its correlations with previous methodologies are described in this article. The methodology is based on the previously collected parameters of seismic resistance analysis of existing, mainly heritage masonry buildings all over Slovenia. Using this methodology, seismic resistance of several groups of masonry buildings has been assessed. Most of them are in public use in the Municipality of Ljubljana (MOL): fire stations, health centres, older buildings of elementary schools and kindergartens, some buildings of authorities and administration and older residential buildings. The results are presented in dependence of the year of construction, as well as the share of a certain vulnerable level in each group. The results again showed the reflection of the professional knowledge into design, construction practice and the level of seismic resistance.

1 INTRODUCTION

A huge part of building heritage in Slovenia was built in the period before 1895, when the most intense earthquake hit Ljubljana region. Till then building practice was based upon the experience, but from then on first seismic code was prepared to prescribe measures for adequate seismic safety. It was an ordinance for earthquake resistant construction of buildings, a very prescriptive-type code based mainly upon the observation, how a structure suffers damage during earthquake. From that first, most prescriptive type of seismic code the vital professional knowledge has been incorporated into the following codes. Not really earlier than the destroying earthquakes hit Friuli and Montenegro in 1976 and 1979 the design-engineers became more aware of destructive potential of earthquakes. Noticeably higher seismic resistance level of building stock was enabled by the application of last national code from 1981, which is now being replaced by Eurocode 8.

Adequate seismic resistance and general safety for expected earthquakes is more or less assured for new buildings with careful design and construction. But we must take care also for older buildings of our architectural heritage and protect them from the consequence of earthquakes. In spite of all technical knowledge and different tools for accurate seismic analysis are available, that kind of approach for seismic behaviour assessment would require too much time and expenses. Therefore more simple, but reliable enough methodologies have been developed to assess the seismic vulnerability and seismic resistance of existing buildings. These methodologies are usually applied to a certain group of buildings, that have either the common owner (manager) or they have the same specific use. The results are first of all the general information of a group and afterwards on that base certain priority plan for aseismic strengthening can be prepared.

2 METHODOLOGIES FOR SEISMIC VULNERABILITY AND SEISMIC RESISTANCE ASSESSMENT

2.1 *Previous methodologies*

When assessing the seismic risk of a certain area the expected intensity of earthquake has to be defined on one hand and the seismic resistance of built-up area on the other hand. Entire territory of Slovenia is earthquake-prone, but the earthquakes of the highest intensity are unfortunately expected just in the central region around Ljubljana where the population density is the highest as well (Fig. 1). The buildings that were constructed before the application of first seismic code are expected to suffer the majority of earthquake damage.

Since the strategy for seismic vulnerability reduction should begin with seismic resistance assessment of buildings in a certain area, some methodologies have been developed also at Slovenian National Building and Civil Engineering Institute in Ljubljana, Slovenia (ZAG). The experience of original

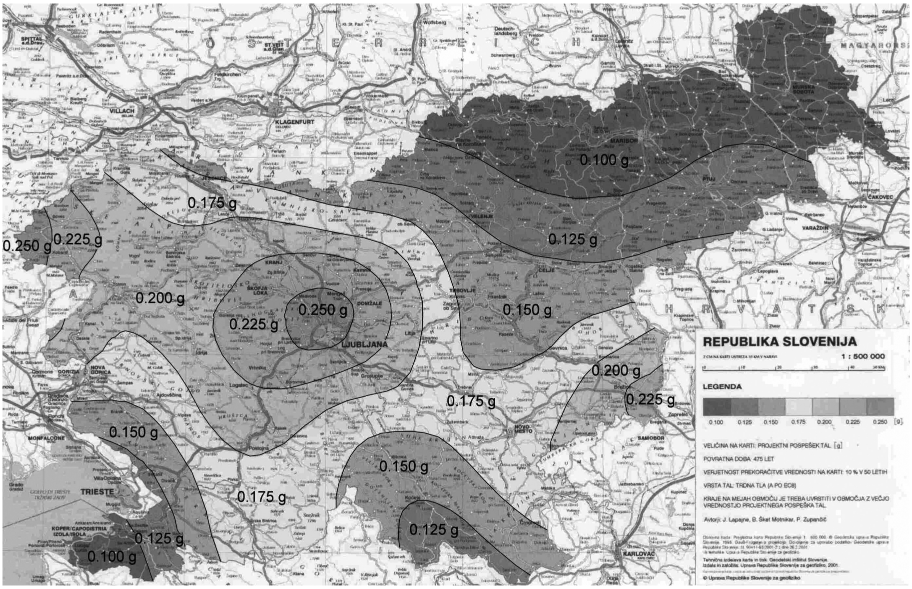

Figure 1. Design ground acceleration map of Slovenia for T = 475 years return period earthquakes (2001).

methodologies used in the world and specific type of residential and public buildings in Slovenia has been taken into account. A simple method for seismic vulnerability assessment of masonry buildings was prepared in 1986. It was a parametric method with five main parameters as: type and quality of walls, quantity of walls, layout of walls in plan, connectedness of walls and the height of building. The values of these parameters were numerically estimated within the range from 1 to 5. The sum of these values, each multiplied by a given weighting factor, was the final value of seismic vulnerability Vs.

2.2 *Seismic vulnerability assessment method RAN-Z*

The method RAN-Z, where the seismic vulnerability is assessed as well, was developed in 1995 (Peruš et al. 1995). This method uses similar parameters as the previous one: the structural type, the regularity, the amount of structural walls, the existing damage extent, the confinement, the height of the building and the seismic zone. Beside the difference in the range of their values, the method is based upon the use of neural network and this represented the main step further. The data base, that the neural network uses to identify the correlation between the values of input parameters and the values of seismic vulnerability assessment, has been prepared with the results of a questionnaire, fulfilled by six top experts of earthquake engineering in Slovenia. The vulnerability is numerically evaluated within the range from 1 to 9 and it is directly connected to the 9-grade expected damage scale, previously used in Slovenia.

The buildings with low vulnerability level are labelled with "green". In the case of design earthquake they are supposed to suffer no damage or minor damage as damage in plaster, cracks at chimneys, gable walls and sliding to falling of roof tiles:

- green I: no damage,
- green II: non-structural damage,
- green III: minor structural damage.

After an earthquake they can remain in use. The buildings with medium vulnerability level are labelled with "yellow". In the case of design earthquake structural damage may be expected – from thinner cracks to crushed elements:

- yellow I: slight structural damage,
- yellow II: medium structural damage,
- yellow III: heavy structural damage.

Certain repair of the building structure of this level is going to be needed to get the previous structural safety. For this reason, these buildings may temporary not be in use. The high vulnerable buildings, labelled with "red", are expected to be damaged to such extension where the repair is not reasonable and they should be demolished:

- red I: serious structural damage,
- red II: partial collapse,
- red III: total collapse.

2.3 *Seismic resistance assessment method PO-ZID*

In 2001 the newest method PO-ZID was developed (Lutman et al. 2002), where seismic resistance is primarily assessed instead of seismic vulnerability. This method also uses neural network, where the modelling successively consists of the choice of parameters, collection of available data, creating the database and the proof of the model effectiveness. In order to determine the correlation between the input parameters and the output parameters, a sufficiently large database of well-distributed and reliable data is needed. It consists of all masonry buildings, that have been systematically investigated and their seismic resistance has been analytically evaluated at ZAG during last 30 years. The base is being simultaneously enlarged with new results in order to increase the accuracy of the method.

The choice of input and output parameters was the most vital part of the modelling. The set of parameters have been namely selected on the basis of experience and in order to approach the analytical results as much as possible. After many trial and error procedures, it has been found that the best results can be obtained by taking into account the derived input parameters instead of the basic ones. The main parameter is derived with the original expression for the shear resistance of a wall:

$$VK_{in-s} = \frac{C_R \rho^*_{in}}{g_{tot}} \frac{f_{t-ref}}{1.5} \sqrt{\frac{\sigma_{o-avg}}{f_{t-ref}} + 1} \quad (1)$$

where σ_{o-avg} = average compression stress due to vertical load; ρ^*_{in} = equivalent wall/floor area (A^*_{in}/A_{floor}). Since the walls have different tensile strengths, A^*_{in} is total equivalent wall cross-sectional area (referred to the reference tensile strength f_{t-ref}); and g_{tot} = total weight to floor area (G_{tot}/A_{floor}).

In order to upgrade this basic estimation, additional non-dimensional input parameters have been included: the participation parameter of shear walls in the direction under consideration (Eq. 2), the participation parameter of the walls perpendicular to the direction under consideration (Eq. 3) and the non-dimensional eccentricity of the layout.

$$d^*_{Ain-s} = \frac{A^*_{in-s}}{A^*_{in}} \quad (2)$$

$$d^*_{Aout} = \frac{A^*_{out}}{A^*_{in}} \quad (3)$$

Considering the available database, acceptable correlation with the chosen output parameter has been observed only for the ultimate seismic resistance coefficient SRC_u, while the ultimate ductility factor q has been found too sensitive.

The ultimate seismic resistance coefficient SRC_u is assessed independently for both two directions in the layout. The final result is the SRC_u of minor value, multiplied with the confinement factor k_{np}:

$$SRC_{u\text{-}np} = k_{np} \min(SRC_{u-x}, SRC_{u-y}) \quad (4)$$

3 SEISMIC RESISTANCE ASSESSMENT OF HERITAGE MASONRY BUILDINGS IN PUBLIC USE IN LJUBLJANA

3.1 *Fire stations*

The authoritative services in the Municipality of Ljubljana (MOL) started to establish and develop the database of seismic vulnerability of existing building stock in order to prepare a plan for measures for the case of earthquake. Due to high importance of fire stations and health centres these buildings were assessed at the very beginning.

In 2001 the seismic resistance of 42 fire stations in Ljubljana has been estimated. The year of construction varies a lot: the oldest fire station is from the times of Maria Teresia and the newest is about 10 years old. Usually these buildings have two storeys, some built of stone masonry, the majority built of brick masonry (full or perforated blocks), the newest are even of reinforced-concrete. For all this buildings the available technical documentation about the design and the construction has been inspected. The buildings themselves have been afterwards inspected visually.

First, the seismic resistance of every fire station building was assessed by using PO-ZID method. In Figure 3 the seismic resistance is presented in dependence on the year of construction. The values of seismic resistance are relative: it is the ratio between the estimated seismic resistance coefficient of the building and the seismic resistance coefficient, which is required by the seismic code. The code, chosen for this comparison, is still valid national seismic code

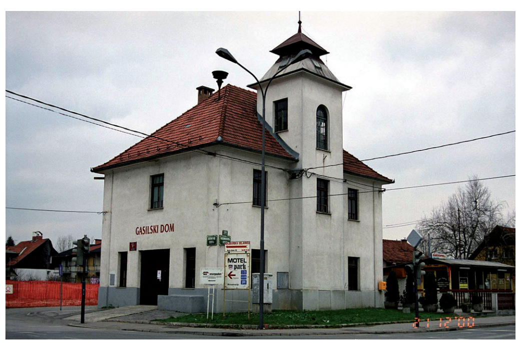

Figure 2. Typical older fire station in Ljubljana.

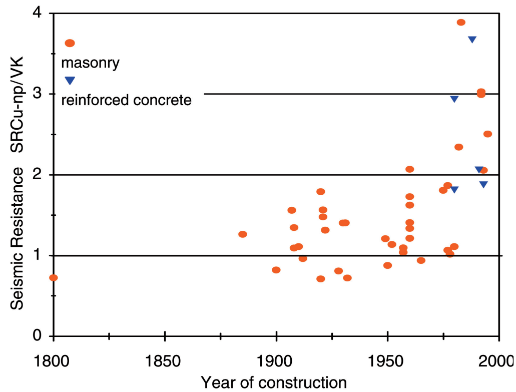

Figure 3. Fire stations in MOL: Seismic resistance (SRC_u/VK).

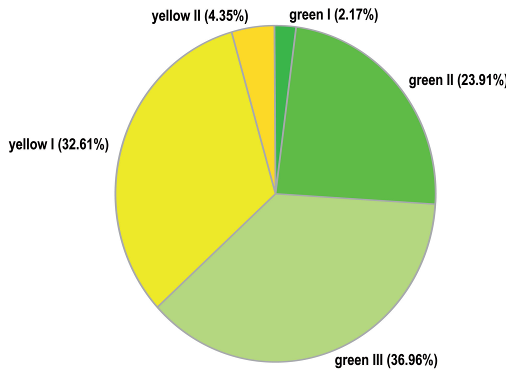

Figure 5. Fire stations in MOL: Seismic vulnerability (RAN-Z).

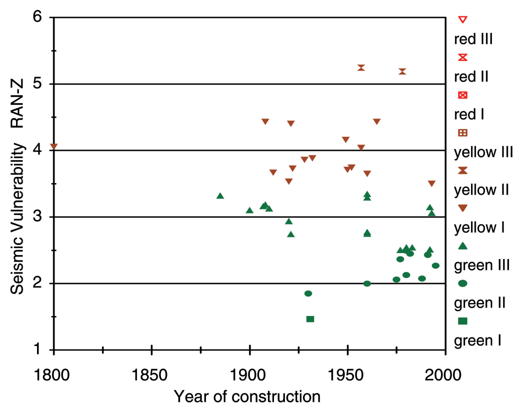

Figure 4. Fire stations in MOL: Seismic vulnerability (RAN-Z).

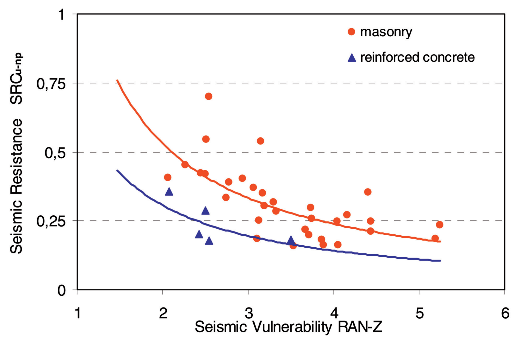

Figure 6. Seismic resistance/Seismic vulnerability relationship.

from 1981. If $SRC_{u-np}/VK > 1$, the required seismic resistance by national seismic code is exceeded.

Besides and independently, the seismic vulnerability was assessed with the method RAN-Z. The estimated values are shown in Figure 4, also in dependence on the year of construction.

Since the seismic vulnerability level varies from low to medium, serious damage is not expected at any fire station due to an earthquake of VIII degree on EMS intensity scale, expected in Ljubljana according to seismic hazard map of Slovenia. Fire stations are estimated as low vulnerable (63%) or medium vulnerable buildings (37%) (Fig. 5).

From both two diagrams (Fig. 3 and Fig. 4) it may be summarized that newer buildings are generally more resistant and less vulnerable than the older ones, as the consequence of growth of professional knowledge.

Since seismic resistance and seismic vulnerability have been assessed separately for this first group of buildings, the correlation between these two parameters has been found out: one for masonry and one for the reinforced-concrete buildings (Fig. 6). The obtained correlations are sensible: higher seismic resistance means lower seismic vulnerability and the opposite. These two correlations were then used to assess seismic resistance from seismic vulnerability, previously assessed with RAN-Z method.

Similar correlations have been also found between the results of the newest method PO-ZID and the results of the oldest method from 1986. Afterwards these correlations were applied to the results of all previous methodologies.

3.2 *Health centres*

The next group includes buildings of health centres and some hospitals as well. Some of them are about 100 years old, some were built between WW I and WW II, the majority in the fifties and sixties (Fig. 7)

Figure 7. Typical building of health centre in Ljubljana.

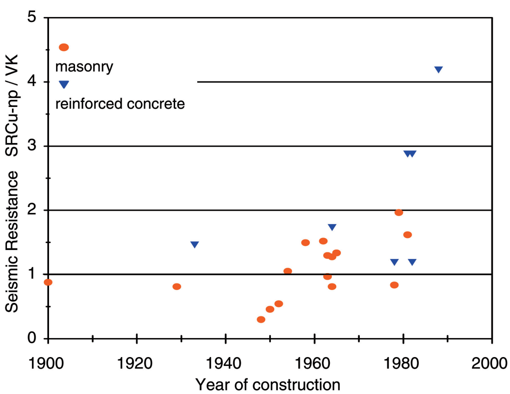

Figure 8. Health centres in MOL: Seismic resistance (SRC_u/VK).

and some in the nineties of last century. The older buildings are usually constructed of masonry and the newer buildings of reinforced-concrete.

The results of seismic resistance assessment are presented in dependence on the year of construction (Fig. 8). Higher seismic resistance has been again found for newer buildings comparing to older ones. Buildings with reinforced concrete structure are less vulnerable than buildings of masonry type. The total share of buildings, usable after an earthquake of VIII degree intensity, is only 44%, temporary unusable would be 48% of them and even 8% of health centres are expected to suffer damage above reparable (Fig. 9).

3.3 *Elementary schools and kindergartens*

Older buildings of elementary schools and kindergartens, altogether 96 buildings, were assessed in 2003 with the newest method for masonry and reinforced-concrete buildings. A lot of them were built in times

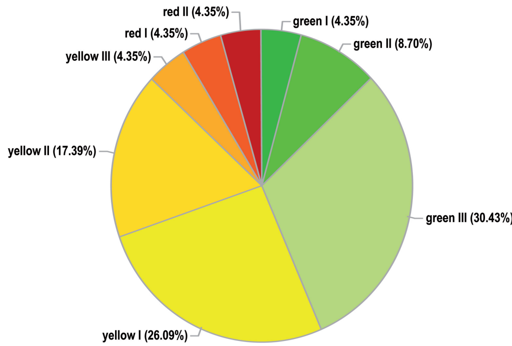

Figure 9. Health centres in MOL: Seismic vulnerability (RAN-Z).

Figure 10. Typical urban school building from before WW I.

of Austria-Hungary (Fig. 10), some between WW I and WW II. After WW II the first reinforced-concrete school buildings were built, in most cases designed without consideration of seismic load. A lot of them are older village schools. Some kindergartens are former dwelling houses from before WW II. In previous group all fire station buildings were included, the newest as well, while this group includes only buildings built before 1970, when the seismic code from 1963 and 1964 have consistently been incorporated in the design practice.

The results (Fig. 11) are not very optimistic: the buildings from before WW II have quite similar seismic resistance, usually beyond the requirements of the 1981 national seismic code. Besides we should be aware that the seismic load according to this code is not adequate for the masonry buildings. In the case of reinforced concrete school buildings from this period serious structural damage can be expected in the case of design earthquake. Only 11% of all buildings are estimated as low vulnerable, the majority of them are medium vulnerable and even 4% would suffer heavy damage from the earthquake of VIII degree EMS intensity scale (Fig. 12).

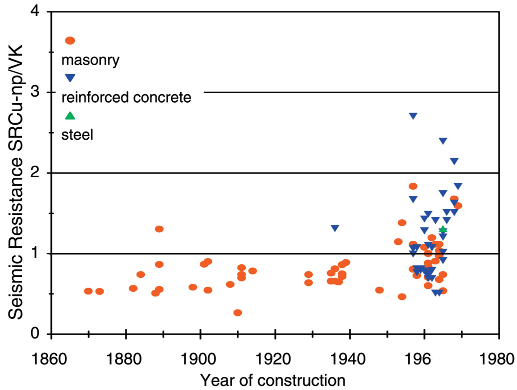

Figure 11. Older buildings of elementary schools and kindergartens: Seismic resistance (SRC_u/VK).

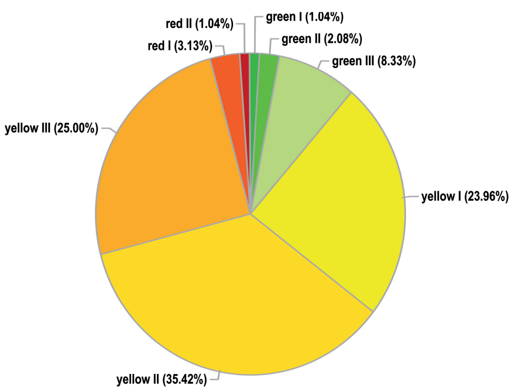

Figure 12. Older buildings of elementary schools and kindergartens: Seismic vulnerability (RAN-Z).

3.4 *Buildings of authorities and administration of the municipality of Ljubljana*

This is a small group. Quite a lot of these buildings are parts of the old Ljubljana downtown (Fig. 13), many of them built after WW II, less of them are new. Most of them were assessed directly with newest method PO-ZID in 2004, while the results of previous methods were transformed into the new output parameters with the application of derived correlations (Fig. 14). All known structural interventions were taken into account. Unfortunately not many renovation interventions included measures for seismic strengthening, although they could be carried out in phases. Many restorations of old buildings' facades were carried out even without placing simple steel ties to confine the building.

Many older administration buildings are very vulnerable (Fig. 15): even one third of them would be heavy damaged by an earthquake of VIII degrees, a good half would suffer moderate damage and only 8% of buildings would suffer only non-structural damage.

Figure 13. The city hall of Ljubljana.

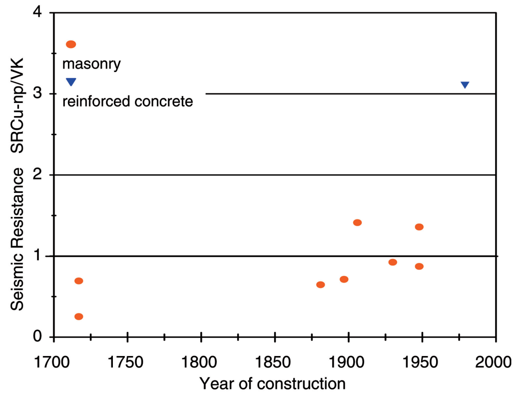

Figure 14. MOL authorities and administration buildings: Seismic resistance (SRC_u / VK).

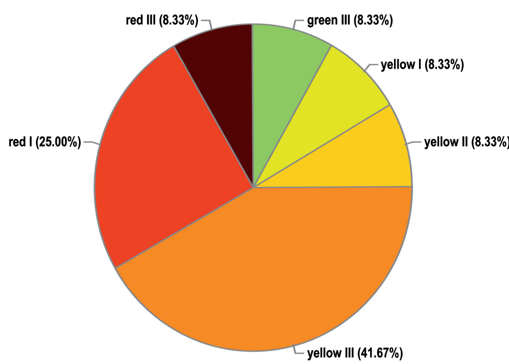

Figure 15. MOL authorities and administration buildings: Seismic vulnerability (RAN-Z).

Figure 16. Older residential building from before WW II.

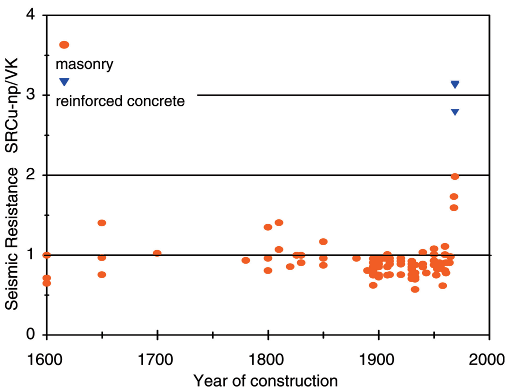

Figure 17. Older residential buildings in MOL: Seismic resistance (SRC_u/VK).

3.5 *Older residential buildings in Ljubljana*

It is a large group of 186 older residential buildings (Fig. 16), mainly in quarters of old Ljubljana town. For most of them seismic vulnerability was assessed with the older method about 20 years ago. Those results were transformed into the present form. Recently some new assessments were done for residential buildings with reinforced concrete structures. The results of this group are characteristic for these quarters and not for the whole region of Municipality of Ljubljana.

The results of this group (Fig. 17) are obviously not so widely spread as the results of previous groups. The main reason may be found in the fact that old results were transformed into the new form. The seismic vulnerability of the majority was assessed with "yellow III" level, where heavy damage could be expected (Fig. 18). The exceptions are the results of newest method PO-ZID and the results of the analytical push-over method, which are also included. Among low vulnerable buildings in this group we find the first confined masonry buildings – labelled with "yellow I" and of course the buildings with reinforced concrete shear walls, assessed with level "green III".

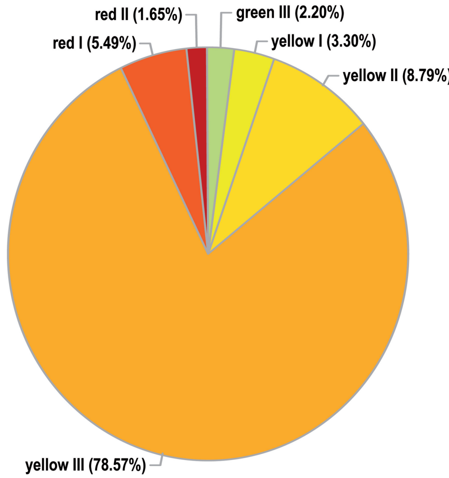

Figure 18. Older residential buildings in MOL: Seismic vulnerability (RAN-Z).

Table 1. Shares of seismic vulnerability levels for groups of buildings under consideration.

Group	n	YC_{avg}	Vulnerability level Green	Yellow	Red
Fire stations	46	1949	63%	37%	–
Health centres	23	1962	43%	48%	9%
Older buildings of elementary schools and kindergartens	96	1946	12%	84%	4%
Buildings of MOL authorities and administration	13	1895	8%	58%	33%

YC_{avg} . . . average year of construction.
n . . . number of buildings.

3.6 *Seismic vulnerability – comparison of the results*

The comparison of the share of a certain vulnerable level in all assessed groups has been drawn out (Table 1). Beside each group, there are the average year of construction and the number of buildings in each group.

In the case of fire stations far and away the least damage is expected (63% of "green"). The elementary schools, where the average age is similar as in the case of fire stations, the results are quite different – only

11% of low vulnerable buildings. The results of health centres are somewhere between, although they were built later. For these three groups all seismic codes require higher seismic resistance than for common residential and business buildings. Far more vulnerable are the buildings of Ljubljana administration, which are also the oldest.

4 CONCLUSIONS

The majority of buildings representing cultural heritage in the Municipality of Ljubljana are built of masonry. Many of them still have timber floors of low weight, which are not causing high inertial forces. Improper confinement and inadequate in-plane rigidity are consequently the main drawbacks resulting from this reason. Insufficient rigidity is also a deficiency of early reinforced-concrete floor structures – hollow tile floor structures, which transfer vertical load mainly in one direction. Inadequate seismic resistance is typical for buildings with lower amount of structural walls, irregular in plane, for buildings with more than three floors and mainly for buildings built before WW II.

Early reinforced-concrete structures are typical irregular in plane, being much more resistant in one than in the other direction. The reinforced-concrete columns are often very slender, with minor size of the cross-section of only 12 cm, besides they are very poor with stirrups. The lack of structural redundancy, potential plastification and seismic energy dissipation zones are their main structural deficiencies. It can be concluded once more, that the professional knowledge reflected in design, construction practice and consequently in the level of seismic resistance.

The results of these assessments are basically used as general information of seismic resistance of a group of certain type or in certain area. Upon this information a priority lists are made, first, in order to make plans for seismic risk reductions, and, second, to prepare activities for seismic strengthening of a certain building.

By presented methods only few percents of entire building stock of Municipality of Ljubljana have been assessed. It has been done this way in the case of buildings of higher importance for public safety and civil protection in the immediate post-earthquake period, as well in the case of buildings with higher social and economic importance.

In the process of seismic resistance and seismic vulnerability assessment of all other buildings the use of existing data base and even more rapid and more simple methods are planned. Reliable seismic vulnerability maps are going to be filled with these results and updated after every structural strengthening of a particular building.

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