Seismic resilience of existing masonry building

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SUMMARY:
Croatia is located on seismically active grounds. Its built heritage is with a large percentage of the existing built environment consisting of masonry structures built prior the first earthquake regulations, which therefore pose a serious threat for the inhabitants and society itself. Knowing this, it is of essence to know the vulnerability of the buildings, which most of the old city cores are built of. But knowing the structural vulnerability is just a small percentage of the work needed to increase the resilience of the buildings and the society. The engineer role is to formulate the platform emphasizing the mitigation of disaster effects while participating in the decision system managing the disaster leading to the conclusion that a minor investment to prevention is better than the one addressed to a cure.
The current state of the structure is evaluated with a method which combines experimental data and engineering knowledge for evaluation of the seismic safety factors and expected structural performance under strong events. This method is also used for the choice of strengthening methods. The strengthening methods are evaluated balancing the costs and the benefits on the building resilience.
When the building owner is aware of the potential risk, and is willing to prepare the structure to cope the serious earthquake hazard the whole risk mitigation process is to begin, which is presented in this article. It is presented on a masonry structure dating from the beginning of the 20th century and it is of major social value, and therefore high resilience is of essence. The presented risk mitigation process consists of structural vulnerability estimation, comparison of the cost of retrofit to those of loss and recovery of functionality in a disaster. The methods of mitigation and decisions based on resilience of this example building are presented.

Keywords: earthquake risk mitigation, retrofit costs, recovery costs, resilience

1. INTRODUCTION

When comparing the destructive forces to duration ratio, earthquakes have to be the most influential and the most destructive natural impact influencing our built environment. Just 20 – 30 s of shaking by a larger scale earthquake leaves nations wrestling with the destruction left behind for years, even decades.(Elnashai 2002) The built environment in Croatia, but large areas of Europe prone to earthquakes as well, are characterized by unreinforced masonry buildings built by some old regulatory norms, and experiential building codes.

Around 1920-s to 1930-s for the first time, the influence of the earthquakes were considered to be taken as a partial horizontal load for all buildings, and for the first time the same were introduced into the building codes. In Croatia the earthquake was recognized as a threat around 1960-s after an earthquake of 6.9 magnitude of the Richter scale in Skopje, Macedonia.(Sigmund and Zlatović 2000) All the buildings built before were not designed to cope with earthquakes.

The old cores of our cities, Croatian and those of the Europe as well, are by now making around 20% of building inventory that wasn't designed to cope with earthquakes at all and another 40% of the built inventory is designed to resist the earthquake partially. Previously mentioned 20% of the built inventory is by now mostly built heritage, buildings with historic value. These buildings are regional cultural assets worth preserving. At times, they also represent a potential source of revenue and stimulus for the economical revitalization of their neighbourhoods.

The built heritage buildings in Croatia are mostly still constructively existing and are still in use hosting important national organizations as hospitals, governmental emergency response organization, schools, universities, etc., which are vital for a quick and simpler recovery in case of an earthquake(Academies 2011). The maintenance of these buildings is performed mainly cosmetically, ignoring the structural substance and sometimes even endangering its stability. Loss of functionality of these buildings during and after an earthquake may pose a threat not only for the inhabitants, but also for those who are depending on the help of these organizations. This may cost the society and the country lives, and may set back the capability to recover months, even years (Alesch and Petak 2002).

Increasing the earthquake resilience of the society is a complex technical, social, economical and political process that request multidisciplinary approach (Petak 2004). Retrofitting of buildings is the technical side of resilience. When approaching a retrofitting project it is helpful to know how to estimate its state and to eventually increase their earthquake resistance. On the presented case study building evaluation is outlined and process of its retrofit.

2. THE EXAMPLE BUILDING

1.1. The historical meaning of the building

It would be wrong to present the building on itself without knowing and presenting the city in which the Municipality court was built. The Osijek city has old roots dating even from 6^{th} and 5^{th} century B.C. The first mention of Osijek in the historical literature is during the 12^{th} century. As Osijek is situated right beside the Drava river, during the past times, Osijek was known as a place where the river was crossed, and on that behalf Osijek was developing as a small middle-ages trading town. The real development of a town Osijek is experiencing during the Osman ruler ship, where the Sultan Suleiman the Glorious is developing a real military fortress within the margins of the today's old city.

During the year 1687, after 161 years of Osman rulers-ship, when the Osman soldiers heard that the Christian military is coming under guidance of general Hans Dünnenwald und Ivan count Drašković during the night of June 26^{th} 1687 Osman military with all the Osman people fled from Osijek, when a new era for the city begun. Within the boundaries of the previous fortress the today's downtown developed, but for military reasons outside the fortress during the Austro-Hungarian Empire the upper town, the todays most impressive part of the city developed in the time from 1866-1910. The upper town is now receiving all the features of a city centre, and the whole city life is now moving to the upper town.

The Municipality court building of Osijek was built in year 1896. during the ruler ship of Austro-Hungarian Empire. The is situated in the upper town of Osijek right beside the park of King Tomislav, whit witch the Municipality court in Osijek is composing an architectural and urban unity. Hereby the building of the court is an infallible part of the city spirit, and a skeleton of the social life in the city of Osijek.

1.2 The building design

The layout of the building is majorly shaped rectangular-wise, but with 2 shorter wings on its end under an angle to the main building structure. The ground floor layout is dominated in the middle point of the building with the entrance foyer with three-way stairs which are connecting the building vertically from the basement to the 1^{st} floor. The layout of the building is also marked with a long hallway stretched out through the whole length of the building situated in the middle of the building transversally. On the second floor is the main court room, which is an impressive 2 stories high room with relief decorations on the wall in the Baroque style (see **Fig. 1** and **Fig. 2**).

Figure 1. Photo of a historical layout of the Municipality court

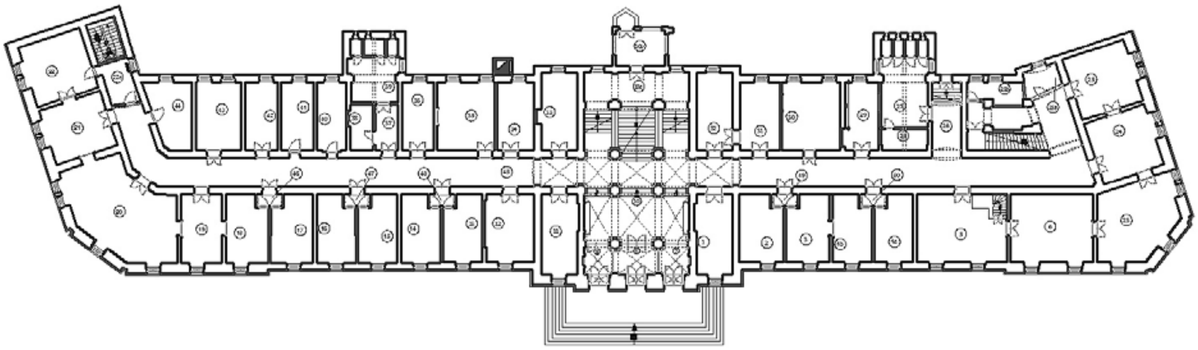

Figure 2. Layout of the Municipality court building

1.3 The construction

The original construction was built according to the design codes of national (public) buildings built by Austro-Hungarian Empire. The building was built with the old format brick 29x14x6.5cm. The bearing construction consists of main bearing walls, vault ceilings in the basement, and similar construction in the foyer and a middle part of the hallway through the whole height of the building. The rest of the floors were wooden.

The thickness of the walls is different on each storey starting with 60 – 75 cm in the basement. The walls are 60 cm in the ground floor and on the 1st floor, and on the 2nd floor the walls are 45 cm thick. The ground floor level floors where constructed on masonry vault ceilings of the basement, and the floors in a small part of the hallways and in the foyer on each storey the ceilings are constructed as massive brick arches.

The floors in the rest of the building are wooden, constructed on fir beams placed 90 cm apart each, but varying in thickness according to the span of the floor. (See **Fig. 3.** and **Table 1**.)

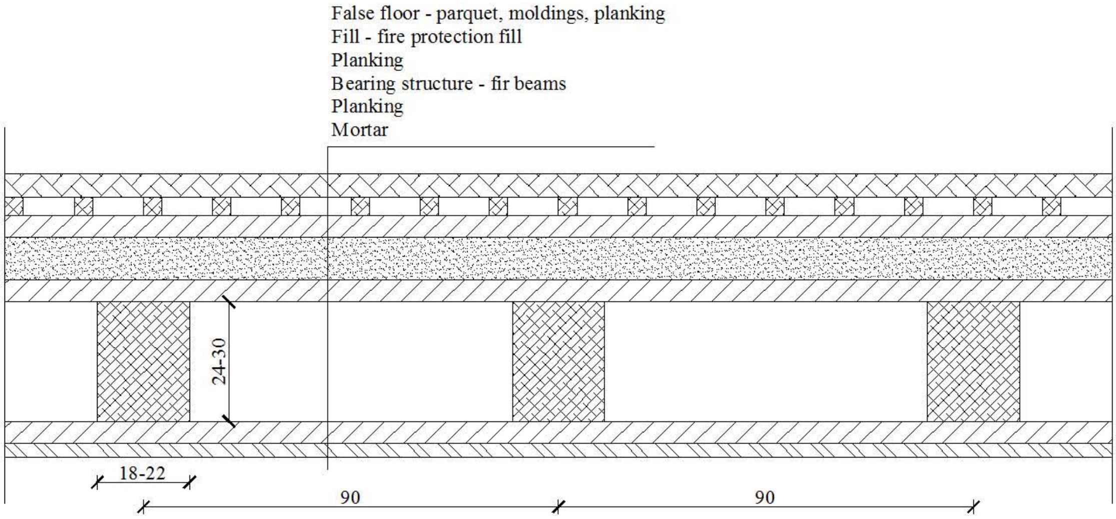

Figure 3. Wooden floor detail

Table 1. Beam dimensions

Span (m)	Beam width	Beam height
5	18cm	24cm
6	20cm	26cm
7	22cm	28-30cm

3. RETROFITTING PRELIMINARIES

Croatia is seismically active region covering with expected earthquake peak accelerations ranging from 0,05 to 0,35g. It has been a long time since the last time such an earthquake struck Croatian grounds, and the social awareness of this threat is lower each day, but this is the reason the vulnerability for such an unprepared society is larger by each day.

The Municipality court in Osijek was built in 1896, and has been in continual use ever since. The building was maintained only cosmetically, and the real state of the bearing structure was completely unknown. The modern use of the building sets some new requests on the building use, but also on the buildings structure. The building needed some adjustments as disabled persons access to each part of the court which besides the entering ramp requested mounting of 2 elevators to the building. The court needed additional usable working space, and some complaints on unpleasant vibrations within some rooms of the building were filed.

3.1 The building screening

Preliminary structural investigation includes building inspection with records of the structural geometry, structural system, and observed damages. The standard non-destructive material and structural element tests are used for determination of the basic building material characteristics.

Ambient vibrations or micro-tremor measurements are performed for obtaining the fundamental dynamic characteristics of the structure: natural frequencies, mode shapes and damping values. Its advantages are that they do not require heavy and expensive equipment to introduce the excitation forces can be conducted without traffic interruption and enable identification of vibration modes with frequencies bellow 1 Hz. The disadvantages are related to the lack of control and quantification of the excitation forces.

Although sometimes the ambient vibrations measurements on such buildings (masonry buildings with soft floor structures) are not really representative for structural testing since the behaviour of the unbounded masonry walls in an earthquake cannot be foreseen, but the general dynamic behaviour of the building can be approximated and used for further analysis.

With this building one has to keep in mind that the building is protected as built heritage, and the general inner and outer appearance may not be changed, but the structure has to be strengthened due to the increase of static loads, the earthquake loads for which the building was never designed, and for the complaints on unpleasant vibrations of the floors.

At first the vibrations of the floors were screened in order to get an insight of the floor constructions, and afterwards the dynamical screening of the whole object was conducted. The vibrations screenings were conducted with accelerometers (see **Fig. 4**) specifically designed to screen the velocities of the vibrations in areas from 0.007 μm to 100mm/sec for frequencies from 0 to 315 Hz.

Figure 4. Accelerometers for the building screening

3.2 Measuring of the dynamic characteristics

Ambient vibrations or micro-tremor measurements are performed for obtaining the fundamental dynamic characteristics of the structure: fundamental frequencies, mode shapes and damping values. Its advantages are that they do not require heavy and expensive equipment to introduce the excitation forces can be conducted without traffic interruption and enable identification of vibration modes with frequencies bellow 1 Hz. The disadvantages are related to the lack of control and quantification of the excitation forces. That brings difficulties in the evaluation of damping factors or in the identification of the dynamic properties associated with vibration modes poorly excited by the ambient vibration.

Dynamic response of the structure, excited with low intensity forces with flat amplitude spectrum, contains vibrations in all their modes. Each mode is presented with peak in the amplitude response spectrum. Amplitude response spectra at each measuring point are averaged (minimum 32 times) in order to decrease the variance caused by the FFT, to increase deterministic part of the signal (structural response) and thus decrease the accidental part (noise). We obtain natural forms by measuring the response at various places and normalizing them to take into account different excitation levels. Dynamic experiments performed on the structure give us the insight into its state. By knowing dynamic characteristics (natural frequencies, forms and damping values) we are able to exactly determine structural stiffness, masses and to take into account such problematical things as torsion, stiffness changes, wall-slab stiffness, accumulated damage, ground-structure interaction, etc. Measured frequencies and mode shapes (horizontal and vertical) define horizontal and vertical distribution of earthquake forces. Their intensity is determined on the basis of estimated mass intensity and code defined response spectra for particular building location. Modal participation factor (γ =

participation factor for the first-mode shape normalized so that the value at the top level is unity) and modal ordinates at each level (φ_I) are obtained by measurement.

4. RETROFITTING THE CONSTRUCTION

Structural evaluation was performed as describe in the paper (Sigmund, Brana et al. 2010) and obtained Capacity and Damage indexes for both directions were as shown in Table 2 for the direction E-W (longitudinal) and in Table 3 for the direction N-S (transversal).

Table 2. Capacity and Damage indexes for the longitudinal (E-W) direction

Capacity Index Is		E-W		hs	Γ		
				0,880	1,136		

Wall shear forces control

	force (kN)	Ax (m2)	Wx	tauX (kN/m2)	Vu (kN)	I0	K	Is
roof	4564,8							
2. floor	8368,8	190,2	35,1	44,0	28530,0	0,29	0,80	0,37
1. floor	11488,0	233,8	35,1	49,1	35070,0	0,33	0,80	0,41
ground	13161,8	241,3	35,1	54,5	36195,0	0,36	0,80	0,45
basement	14721,4	289,2	35,1	50,9	43380,0	0,34	0,80	0,42

	Allowable base shear stress					Vu1=	150	
Damage Index Id	α	(PGA)=	0,2	g	Cy=	0,160		
	Tg	=	1,2	sec	α/6=	0,033		
						Dmax	G1	Dt
						0,05367	1,136	0,08596

	H (m)	X1	Eta	h1 (m)	d (cm)	DR (%)	DRd (%)	Id
roof	17,8	1,20	1,36		10,32			
2. floor	13,4	1,00	1,14	4,40	8,60	0,391	1,100	0,355
1. floor	8,9	0,82	0,93	4,50	7,05	0,344	1,125	0,306
ground	4,1	0,44	0,50	4,80	3,78	0,681	1,200	0,567
basement	0,0	0,41	0,47	4,10	3,52	0,063	1,025	0,061
o.oo	0,00	3,87	4,40					

Table 3. Capacity and Damage indexes for the transversal (N-S) direction

Capacity Index Is		**N-S**		hs	Γ		
				0,875	1,143		

	force (kN)	Ax (m2)	Wx	tauX (kN/m2)	Vu (kN)	I0	K	**Is**
roof	5369,5							
2. floor	9844,1	85,3	35,1	115,4	12795,0	0,77	0,80	**0,96**
1. floor	12752,6	112,3	35,1	113,6	16845,0	0,76	0,80	**0,95**
ground	14050,2	121,0	35,1	116,1	18150,0	0,77	0,80	**0,97**
basement	14721,4	125,3	35,1	117,5	18795,0	0,78	0,80	**0,98**

	Allowable shear stress					Vu1=	150	
Damage Index Id	**α**	**(PGA)=**	**0,2**	**g**	**Cy=**	**0,143**		
	Tg	**=**	**1,2**	**sec**	**α/6=**	**0,033**		
						Dmax	**G1**	**Dt**
						0,07604	1,143	0,12251

	H (m)	X1	Eta	h1 (m)	d (cm)	DR (%)	DRd (%)	**Id**
roof	17,8	1,20	1,37		14,70			

2. floor	13,4	1,00	1,14	4,40	12,25	0,557	1,100	**0,506**
1. floor	8,9	0,65	0,74	4,50	7,96	0,953	1,125	**0,847**
ground	4,1	0,29	0,33	4,80	3,55	0,919	1,200	**0,766**
basement	0,0	0,15	0,17	4,10	1,84	0,418	1,025	**0,408**
o.oo	0,00	3,29	3,76					

As Capacity index was very high (indicating the need for strengthening) we decided to add reinforced-concrete shells to the walls in that directions and to add additional reinforced-concrete slab above the second floor. Addition of the r/c shells lowered the Capacity index into the acceptable range and addition of the slab enabled homogenous behaviour of the whole structure and distribution of the horizontal loads to all walls.

First evaluation was done initially in order to determine the state and see if it is possible to strengthen the existing structures. Measured waveforms were used for calculation of structural indexes, and the analysis showed that:

1. The building has eigen forms and frequencies which could be expected for the buildings with masonry walls longitudinally, but transversally the flexibility of the building is obvious, and therefore some transversal walls should be strengthened.
2. The high damping values of the building is pointing the conclusion that the masonry bearing structure is damaged. The damage should be identified and repaired.
3. On behalf of measured horizontal frequencies it can be concluded that the behaviour of the building is not equal throughout the whole length of the building. The building wings are showing higher oscillation values then the middle part of the building. This is due to the soft floors on which behalf the walls are not unified, and the reaction to horizontal forces is dispersed on the walls unequally. The walls should be unified in order to increase the bearing capacity of the walls for horizontal forces.
4. The non-destructive tests showed that the wooden floor structure is still in good shape, but in order to achieve the unification of the vertical bearing structure can only be achieved by increasing the shear strength of the floors, which can be achieved by constructing a RC plate on top of the existing wooden bearing structure of the floors. This would also solve the complaints on unpleasant floor vibrations within the offices.

In order to test the results of the strengthening prior and after the application another round of tests were done especially for the transversal (N-S) direction of the building as presented in the Table 4.

Table 4. Capacity and Damage indexes for the transversal (N-S) direction after the strengthening

Capacity Index Is			**N-S**		hs	Γ			
					0,875	1,143			
	force (kN)	Ax (m2)	AxB	tauX (kN/m2)	Vu (kN)	I0	K	Is	
roof	5369,5								
2. floor	9844,1	85,3	1,2	115,4	14605,4	0,67	0,80	**0,84**	
1. floor	12752,6	112,3	1,2	113,6	18655,4	0,68	0,80	**0,85**	
ground	14050,2	121,0	1,2	116,1	19960,4	0,70	0,80	**0,88**	
basement	14721,4	125,3	1,2	117,5	20605,4	0,71	0,80	**0,89**	
		Allowable shear stress				masonry	Vu1=	150	
						concrete	Vu1=	1508,63	
Damage Index Id		α	**(PGA)=**	**0,2**	**g**	**Cy=**	**0,143**		
		Tg	**=**	**1,2**	**sec**	**α/6=**	**0,033**		
							Dmax	**G1**	**Dt**
							0,076038	1,143	0,12250758

	H (m)	X1	Eta	h1 (m)	d (cm)	DR (%)	DRd (%)	**Id**
roof	17,8	1,20	1,37		14,70			
2. floor	13,4	1,00	1,14	4,40	12,25	0,557	1,100	**0,506**
1. floor	8,9	0,82	0,94	4,50	10,05	0,490	1,125	**0,436**
ground	4,1	0,50	0,57	4,80	6,13	0,817	1,200	**0,681**
basement	0,0	0,30	0,34	4,10	3,68	0,598	1,025	**0,583**
o.oo	0,00	3,82	4,36					

5. CONCLUSION

In order to evaluate and improve seismic capacity of existing buildings and to distinguish between the structures that could be strengthened for a reasonable amount of money 'seismic safety evaluation' is a very important task. Described procedure is simple and sound enough as it combines experimental testing with common engineering knowledge. Good results can be obtained even with a limited number of measurement points.

The proposed method allows distinction between the structures without problems and those with severe problems and presents a quick way to check the behaviour of structures against seismic demands. It can also be used for a choice of the optimal strengthening method and for verification of the quality of performed strengthening works.
The strengthening method applied on the shown building could be described as standard one using the reinforced concrete elements for adding strength and ductility to masonry elements. It has been proved as structurally and economically efficient one as it uses standard materials.

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