Seismic Evaluation And Retrofit of Existing Buildings

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ABSTRACT:
When evaluating and improving seismic capacity of existing buildings 'seismic safety evaluation' and 'retrofitting' are very important tasks. Engineers evaluate structures with different methods. The presented method combines experimental data and engineering knowledge in order to evaluate seismic safety factors and expected structural performance under strong events. Distinction between the structures with and those without problems are made. This is also a quick way to check the response of structures to expected seismic activities. The method could also be used for choosing the optimal strengthening method and to verify the quality of performed strengthening works. Proposed methodology is explained on the example of two buildings with the explanation of performed strengthening methods. The construction price of retrofitted buildings is compared to the price of demolishing the existing and building a new building.

Keywords: retrofitting, seismic safety, strengthening method, non-destructive testing

1. SEISMIC SAFETY EVALUATION

1.1.1. Preliminary Structural Investigation

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.

1.1.2. 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. These characteristics can be obtained by recording just the response of the structure to the ambient vibrations.

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. 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. This obtained data gives us the possibility 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.

1.2. Evaluation of the Structural Safety Factors

1.2.1. Strength Capacity Safety Factor (Iss)

Strength Capacity Safety factor (Iss) is different for each story, and its evaluation is determined by the next equation:

$$Iss=(Veq*G)/Vst \qquad (1)$$

1.2.2. Site Earthquake Parameter (G)

If the measured fundamental frequency of the structure (Ts) and measured fundamental frequency of the adjacent soil are close to resonance:

$$0,8 \leq Ts/Tg \leq 1.2$$

then calculated expected earthquake forces are to be increased by G=1.25, otherwise G=1.00.

1.2.3. Expected Horizontal Forces (Veq)

The expected horizontal forces are calculated on the basis of the measured natural frequencies, forms, damping values and EC8 design response spectra and distributed along the height according to the measured natural forms.

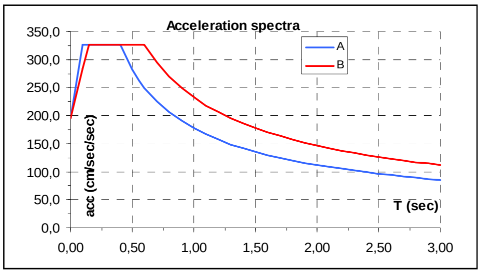


Figure 1. EC8 response spectra for ground type A, B, q=1.5, α=200gal

1.2.4. Shear Capacities of the Story (Vst)

Shear capacity of each story (Vst) is a sum of shear capacities of columns, walls and bracing systems located in the particular story.

1.2.5. The building Strength index Iso

$$Iso = \min (Iss) \tag{2}$$

On the basis of Iso we conclude that if:

Iso > 1.0	the structure is not safe for expected seismic actions.
0.75 < Iso < 1.0	the structure needs more detailed analysis in order to establish its safety.
Iso < 0.75	the structure is safe for expected seismic actions.

1.3. General Overturning Stability Safety Factor

After the expected horizontal forces (Veq) are determined the overall Overturning Stability Safety Index **Ios** is calculated as follows:

$$Ios = Mo/Ms \tag{3}$$

Mo is overturning moment provided by the foundation and Ms is overturning moment caused by earthquake forces.

The building is safe against overturning if its Overturning Safety Index is **Ios>1.5**.

1.4. Displacement Safety Factor (Damage Index Id)

The expected damage in building correlates with displacements and drifts. Therefore, allowable story drift is defined on the basis of accepted performance level as Damage index Id.

1.4.1. Expected nonlinear drift (Δi)

Expected nonlinear drift of the story is calculated by the methodology outlined in (Lepage & Sozen, 1997). They claim that expected nonlinear drifts during earthquake are lower or equal to the drifts calculated by linear spectral analysis for 2% damping.

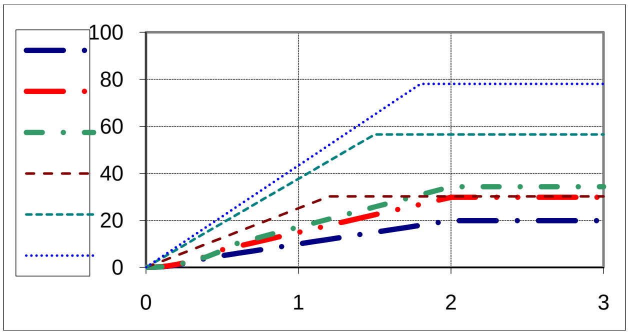


Figure 2. EC8 & Sozen-Lepage nonlinear displacement

1.4.2. Permissible story drift (Δpi)

Permissible story drift is defined in the view of type, contents, function and expected performance level of the structure and suggested values are:

Table 1. Suggested values of permissible story drifts according to the expected performance level

Low damage	Medium damage	High damage	Total damage
Δi<=0,5%	0,5%<Δi<=1,2%	1,2%<Δi<=1,7%	Δi>1,7%

1.4.3. Story and Building damage indexes

The **Story Damage Index (Idi)** for each story is calculated as:

$$Idi = (\Delta i) /(\Delta pi) \quad (4)$$

The **Building Damage Index Ido** is the maximal of the calculated Story Damage Indexes (Idi)

$$Ido=\max (Idi) \quad (5)$$

If $Ido > 1.0$ the structure has an unacceptable performance.
$Ido <=1.0$ the structure has an acceptable performance.

2. EXAMPLE CONSTRUCTION

Three similar buildings were built in Pakrac, Croatia in the 1986. They were prefabricated reinforced-concrete structures built according to the "IMS-Zezelj" building system. Their main structural elements are: r/c columns (b/d=30/30cm) placed in raster of 3.6m and 4.20m and r/c waffle-like slabs connected to columns by post-tensioned cables, shear walls placed between the columns, facades (three-layered sandwich panels) and secondary elements.

Two of the buildings were severely damaged during the war by explosions and fire that came after the war explosions. In order to evaluate their structural state, improve seismic capacity and identify the structure that could be strengthened for a reasonable amount of money 'seismic safety evaluation' was very important. The performed investigations showed that if a suitable testing procedure was adequately combined with common engineering knowledge and finite element software, it was possible to effectively retrofit the structure.

In order to determine the expected dynamical characteristics, and the state of deterioration of the two damaged buildings all three buildings were scanned and examined. To collect all the needed data the investigation consisted of: (a) evaluation of material characteristics; (b) check of the walls homogeneity by non-destructive methods; (c) ambient vibration measurement in both main directions.

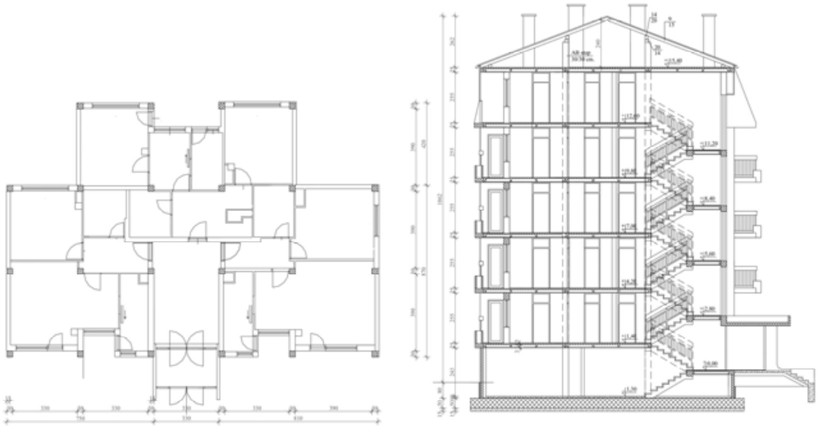
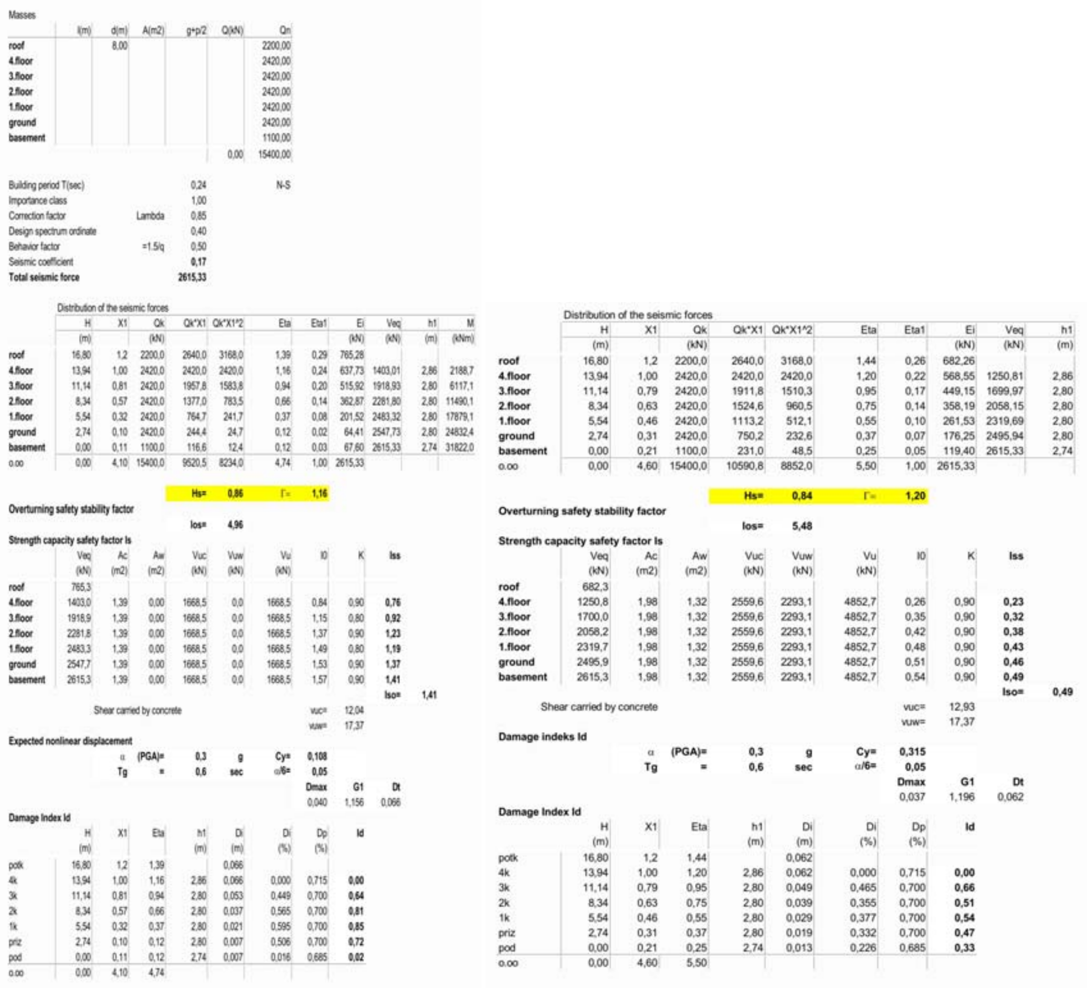


Figure 3. Plan and vertical cross-section of the building in 14 A. Hebranga street in Pakrac

Table 2. Evaluation of the seismic safety for the existing state prior the retrofit (left) and the new state after the retrofit (right)



Masses

	l(m)	d(m)	A(m2)	g+p/2	Q(kN)	Qn
roof		8,00				2200,00
4.floor						2420,00
3.floor						2420,00
2.floor						2420,00
1.floor						2420,00
ground						2420,00
basement						1100,00
					0,00	15400,00

Building period T(sec)		0,24	N-S
Importance class		1,00	
Correction factor	Lambda	0,85	
Design spectrum ordinate		0,40	
Behavior factor	=1.5/q	0,50	
Seismic coefficient		**0,17**	
Total seismic force		**2615,33**	

Distribution of the seismic forces

	H (m)	X1	Qk (kN)	Qk*X1	Qk*X1^2	Eta	Eta1	Ei (kN)	Veq (kN)	h1 (m)	M (kNm)
roof	16,80	1,2	2200,0	2640,0	3168,0	1,39	0,29	765,28			
4.floor	13,94	1,00	2420,0	2420,0	2420,0	1,16	0,24	637,73	1403,01	2,86	2188,7
3.floor	11,14	0,81	2420,0	1957,8	1583,8	0,94	0,20	515,92	1918,93	2,80	6117,1
2.floor	8,34	0,57	2420,0	1377,0	783,5	0,66	0,14	362,87	2281,80	2,80	11490,1
1.floor	5,54	0,32	2420,0	764,7	241,7	0,37	0,08	201,52	2483,32	2,80	17879,1
ground	2,74	0,10	2420,0	244,4	24,7	0,12	0,02	64,41	2547,73	2,80	24832,4
basement	0,00	0,11	1100,0	116,6	12,4	0,12	0,03	67,60	2615,33	2,74	31822,0
0.00	0,00	4,10	15400,0	9520,5	8234,0	4,74	1,00	2615,33			

Hs= 0,86 Γ= 1,16

Overturning safety stability factor

Ios= 4,96

Strength capacity safety factor Is

	Veq (kN)	Ac (m2)	Aw (m2)	Vuc (kN)	Vuw (kN)	Vu (kN)	I0	K	**Iss**
roof	765,3								
4.floor	1403,0	1,39	0,00	1668,5	0,0	1668,5	0,84	0,90	**0,76**
3.floor	1918,9	1,39	0,00	1668,5	0,0	1668,5	1,15	0,80	**0,92**
2.floor	2281,8	1,39	0,00	1668,5	0,0	1668,5	1,37	0,90	**1,23**
1.floor	2483,3	1,39	0,00	1668,5	0,0	1668,5	1,49	0,80	**1,19**
ground	2547,7	1,39	0,00	1668,5	0,0	1668,5	1,53	0,90	**1,37**
basement	2615,3	1,39	0,00	1668,5	0,0	1668,5	1,57	0,90	**1,41**

Iso= 1,41

Shear carried by concrete vuc= 12,04

vuw= 17,37

Expected nonlinear displacement

α	**(PGA)=**	**0,3**	**g**	**Cy=**	**0,108**		
Tg	**=**	**0,6**	**sec**	α/6=	**0,05**		
					Dmax	**G1**	**Dt**
					0,040	1,156	0,066

Damage Index Id

	H (m)	X1	Eta	h1 (m)	Di (m)	Di (%)	Dp (%)	**Id**
potk	16,80	1,2	1,39		0,066			
4k	13,94	1,00	1,16	2,86	0,066	0,000	0,715	**0,00**
3k	11,14	0,81	0,94	2,80	0,053	0,449	0,700	**0,64**
2k	8,34	0,57	0,66	2,80	0,037	0,565	0,700	**0,81**
1k	5,54	0,32	0,37	2,80	0,021	0,595	0,700	**0,85**
priz	2,74	0,10	0,12	2,80	0,007	0,506	0,700	**0,72**
pod	0,00	0,11	0,12	2,74	0,007	0,016	0,685	**0,02**
0.00	0,00	4,10	4,74					

Distribution of the seismic forces

	H (m)	X1	Qk (kN)	Qk*X1	Qk*X1^2	Eta	Eta1	Ei (kN)	Veq (kN)	h1 (m)
roof	16,80	1,2	2200,0	2640,0	3168,0	1,44	0,26	682,26		
4.floor	13,94	1,00	2420,0	2420,0	2420,0	1,20	0,22	568,55	1250,81	2,86
3.floor	11,14	0,79	2420,0	1911,8	1510,3	0,95	0,17	449,15	1699,97	2,80
2.floor	8,34	0,63	2420,0	1524,6	960,5	0,75	0,14	358,19	2058,15	2,80
1.floor	5,54	0,46	2420,0	1113,2	512,1	0,55	0,10	261,53	2319,69	2,80
ground	2,74	0,31	2420,0	750,2	232,6	0,37	0,07	176,25	2495,94	2,80
basement	0,00	0,21	1100,0	231,0	48,5	0,25	0,05	119,40	2615,33	2,74
0.00	0,00	4,60	15400,0	10590,8	8852,0	5,50	1,00	2615,33		

Hs= 0,84 Γ= 1,20

Overturning safety stability factor

Ios= 5,48

Strength capacity safety factor Is

	Veq (kN)	Ac (m2)	Aw (m2)	Vuc (kN)	Vuw (kN)	Vu (kN)	I0	K	**Iss**
roof	682,3								
4.floor	1250,8	1,98	1,32	2559,6	2293,1	4852,7	0,26	0,90	**0,23**
3.floor	1700,0	1,98	1,32	2559,6	2293,1	4852,7	0,35	0,90	**0,32**
2.floor	2058,2	1,98	1,32	2559,6	2293,1	4852,7	0,42	0,90	**0,38**
1.floor	2319,7	1,98	1,32	2559,6	2293,1	4852,7	0,48	0,90	**0,43**
ground	2495,9	1,98	1,32	2559,6	2293,1	4852,7	0,51	0,90	**0,46**
basement	2615,3	1,98	1,32	2559,6	2293,1	4852,7	0,54	0,90	**0,49**

Iso= 0,49

Shear carried by concrete vuc= 12,93

vuw= 17,37

Damage indeks Id

α	**(PGA)=**	**0,3**	**g**	**Cy=**	**0,315**		
Tg	**=**	**0,6**	**sec**	α/6=	**0,05**		
					Dmax	**G1**	**Dt**
					0,037	1,196	0,062

Damage Index Id

	H (m)	X1	Eta	h1 (m)	Di (m)	Di (%)	Dp (%)	**Id**
potk	16,80	1,2	1,44		0,062			
4k	13,94	1,00	1,20	2,86	0,062	0,000	0,715	**0,00**
3k	11,14	0,79	0,95	2,80	0,049	0,465	0,700	**0,66**
2k	8,34	0,63	0,75	2,80	0,039	0,355	0,700	**0,51**
1k	5,54	0,46	0,55	2,80	0,029	0,377	0,700	**0,54**
priz	2,74	0,31	0,37	2,80	0,019	0,332	0,700	**0,47**
pod	0,00	0,21	0,25	2,74	0,013	0,226	0,685	**0,33**
0.00	0,00	4,60	5,50					

3. MEASUREMENT CONCLUSIONS

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 as is shown in Table 1 left. The calculation showed that Strength Index (Iss) was outside the safe region from the 1. to the 3.rd floor. Measured waveforms indicated strength discrepancies at the ground and

2nd floor where structural elements were exposed to fire. The overall state has been rated as possible to strengthen and required strengthening methods have been chosen. The choice of the strengthening works was certified and confirmed after calculations were done, as is shown in Table 1 right.

3.1. Applied Strengthening Methods

Combining structural characteristics for both directions and after several trials, the best strengthening method, from the strength and economic point of view, has been chosen.
Strengthening included:

a) Adding structural walls that are connected to the columns and slabs in both directions
b) Transforming some facade walls into load bearing walls by adding the r/c shell to them
c) Repairing damaged slabs and adding new thin layer of r/c slabs above the basement, ground and 3rd floor that should transfer the horizontal loads to all shear walls.

Strength and Damage Structural Indexes were by these improvements placed within the safe area.
Applicability of the chosen methods and quality of the performed works were checked at two stages: (1) when additional walls were finished at the basement, ground and 1.st floors without the slabs; (2) when complete strengthening has been finished.

In order to complete the strengthening works, several steps needed to be done:

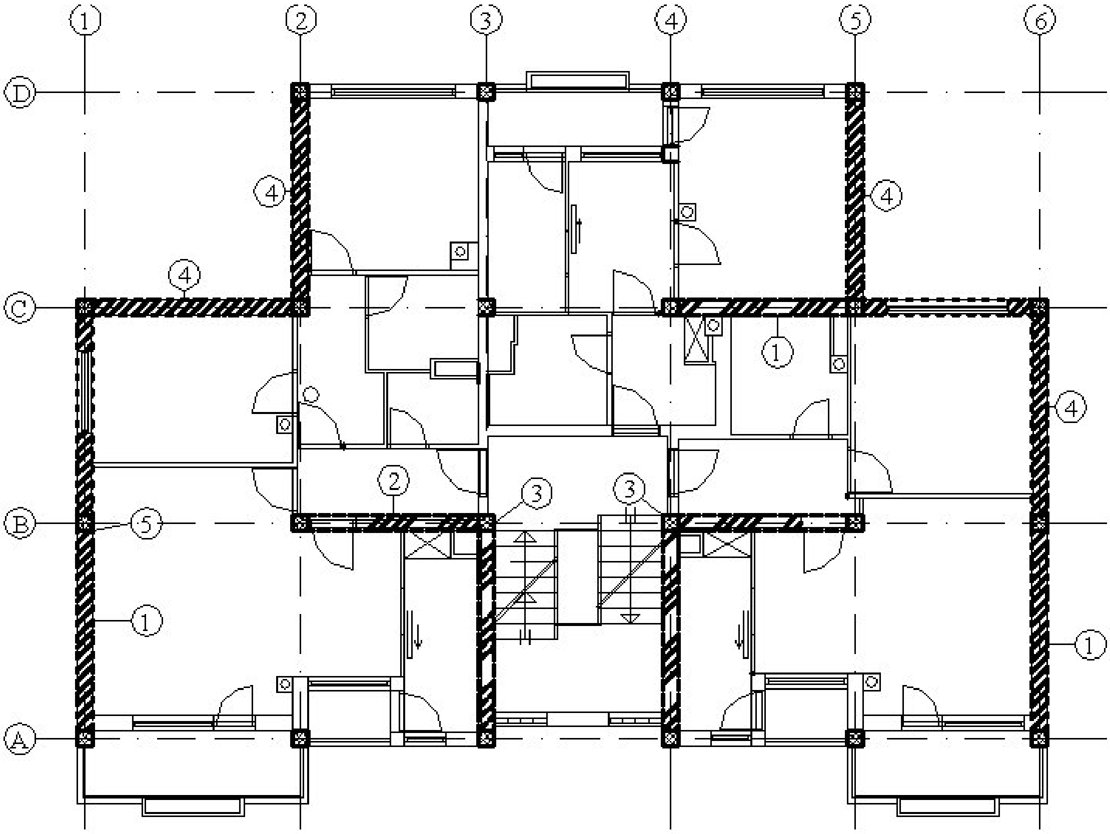


Figure 4. Ground plan of the14 A. Hebranga building with marked details

1) Clearing all damaged concrete of the bearing and non-bearing elements
2) Additionally improving and reinforcing the basement walls
3) Old concrete walls needed to be reinforced and concrete sprayed in order to create a structural bearing walls through the whole height of the building in axes B2-3; B4-5; C4-5; 3A-B; 4A-B (Fig. 5.)

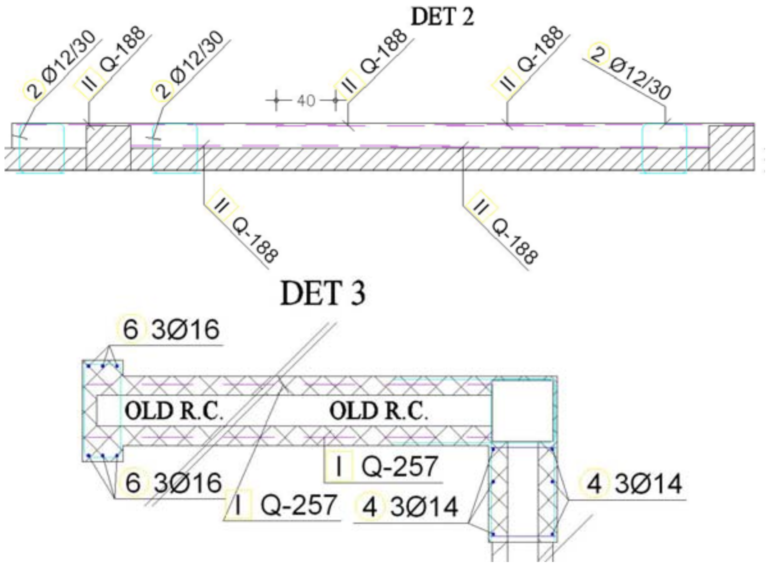


Figure 5. Creating the new load bearing walls from old concrete walls

4) After mortar has been cleared of the old masonry walls a new layer of reinforced concrete has been added and bonded with the old masonry walls at axes 1A-C; 6A-C; C1-2;C5-6; 2C-D; 5C-D (Fig. 6)

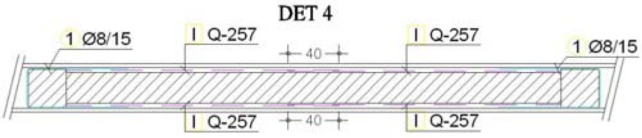


Figure 6. Reinforcing the masonry walls

5) The slabs, that were damaged by fire, needed to be cleared of damaged concrete and renewed. An additional 6 cm thick RC slab layer has been added on the top. This was done on the ground floor, 1st and 2nd floor. (Fig. 7 and Fig. 8.)

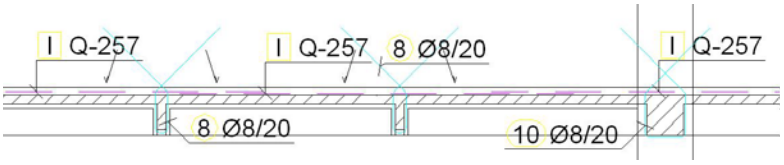


Figure 7. Adding the RC slab layer

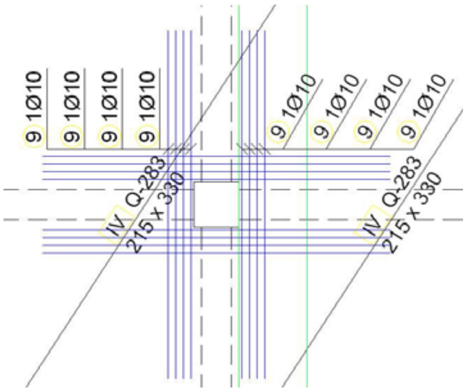


Figure 8. Additional reinforcement around the columns

4. COST COMPARISON

After structural deficiencies have been established the decision had to be made about the value of strengthening the structure. The prevailing idea among the engineers is that the price of strengthening the old and building completely new building sums up to the same. On this chosen example we have compared the construction costs.

Table 3. Comparison of the construction costs in €

	Demolition and new building	**Strengthening**
Demolition, transport, auxiliary support	34500,00	6800,00
Engineering support	26000,00	16200,00
Building	172800,00	35100,00
Total cost in €	**233300,00**	**58100,00**
	100%	**25%**

When we build the new building instead of the old one, required works include: Project of the building demolition and solving problems of demolition in the city; demolition while preserving stability of the surrounding structures, removal of debris, project of the new building and finally construction of the new building.

To strengthen the existing building following works need to be done: Structural evaluation and project of strengthening; cleaning of mortar and poor material from the existing building elements as well as non-structural walls and removal of the debris; execution of strengthening with control measurement that ensures quality of the preformed works.

As can be observed from the shown example, strengthening of existing building is very reasonable and cheaper solution if the functionality of the building is satisfactory. Repair and strengthening of the old structure up to the safety level required today costs only about 25% of the cost of its demolishing and building the similar (calculated on the usable usable area) structure again.

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 very important task.

Described procedure is simple and sound enough as it combines experimental testing with common engineering knowledge and, if necessary, with sophisticated numerical procedures. Good results can be obtained even with a limited number of measurement points.

It is shown that proposed method allows distinction between the structures without problems and those with severe problems and presents a quick way to check the behavior 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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