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SEISMIC STRENGTHENING OF BUILDINGS WITH RC WALLS

R. Folić[1], P. Petronijević[2]

ABSTRACT

The paper presents one of the possible ways of seismic strengthening of existing high-rise structures by adding reinforced concrete (RC) walls. A number of old buildings with RC frame system which were not built in accordance with the contemporary regulations have insufficient resistance to lateral load. Addition of RC walls is a basic strengthening method which can successfully increase horizontal rigidity, bearing capacity, ductility and dissipation capability of seismic energy. A comparison of strengthening variants was performed: by thickening the existing RC walls, closing the openings in the existing RC walls, adding interior infill walls, as well as lateral and external RC walls. Several decades long application of this method has proved its successfulness and efficiency. Application of this method was illustrated by seismic strengthening of the building of new Clinical Centre in Nis.

1. Introduction

Many existing high-rise buildings that are located in seismically active areas fail to meet the current seismic regulations. As a result of a large number of strong earthquakes in recent decades many structures suffered damage and destruction, accompanied by major material damage. Most of the buildings that were built before the adoption of modern codes of seismic construction are highly vulnerable. However, with some corrections to structural system and material properties, their seismic performance can be significantly improved. In recent decades, a considerable research has been dedicated to studying different techniques of strengthening and improving the seismic performance of RC structures. The present paper

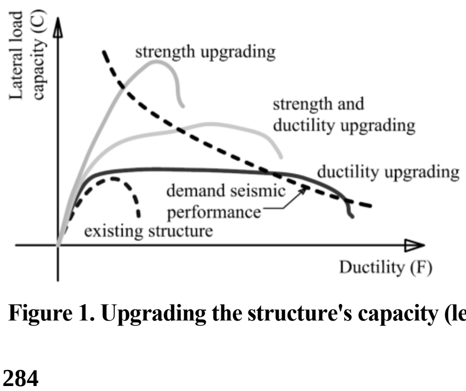
[1] Radomir Folić, Prof. Emeritus, Ph. D., Dr. h.c., University of Novi Sad, Trg D. Obradovica 6, 21000 Novi Sad, Serbia, e-mail: r.folic@gmail.com
[2] Predrag Petronijević, graduate engineer of civil engineering, A. Medvedeva 14, Niš, Serbia, e-mail: predrag.petronijevic@gaf.ni.ac.rs

provides an overview of possibilities for using RC walls that would strengthen the structures. The first attempt to apply RC walls in the rehabilitation and strengthening of skeletal structures was implemented after the Tokachi-oki earthquake in 1968. Due to the lack of guidelines, strengthening was implemented based on the designers' subjective assessment. The first mass deployment of RC walls in the rehabilitation and strengthening was undertaken in Japan after the devastating Miyagiken earthquake in 1978. Until then, experimental and analytical studies on the possibilities of applying different approaches and use of different materials have already been carried out [9].

Experiences after a series of earthquakes in Turkey have highlighted the main causes of bad behaviour of existing frame structures. According to Yakut, these are: structural irregularity in the base and along the height, occurrence of flexible ground floor, combination of weak columns and strong beams, occurrence of short columns, insufficient confinement of columns and walls of edge zones of RC walls (the use of open stirrups), use of low-strength concrete, insufficient and inadequate reinforcement of nodes of frame structures, insufficient anchor length, etc. [10]. In the 1990's the US Federal Emergency Management Agency (FEMA) issues standards for the seismic evaluation of existing buildings (FEMA 310) and their rehabilitation (FEMA 273 and 357). Seismic strengthening of existing buildings is one of the most effective methods of reducing seismic risk. After the 1989 Loma Prieta and 1994 Northridge earthquake in California considerable research in the US has been dedicated to various techniques of strengthening and improvement of seismic performance of RC buildings [8]. During the earthquake in Turkey in 1999 and Chile in 2010, many RC structures constructed as purely framework or mixed systems were destroyed or suffered significant damage. A large amount of research has been carried out on buildings damaged during these earthquakes. The structures were generally unable to ensure the necessary ductility of individual structural elements necessary for meeting the large displacements caused by small lateral stiffness and capacity, [1] and [2].

2. Strengthening methods

In order to select the most effective method of strengthening, it is necessary to assess the seismic performances and condition of the existing building accurately. First, it is necessary to identify the seismic deficiencies by collecting the data on the structure's condition when it was built and perform the control calculations. FEMA 356 (Prestandard and Commentary for the Seismic Rehabilitation of Buildings) provides guidelines for assessing the seismic performances of existing buildings and determining the required method of strengthening for achieving the adequate performances which is usually approved by the investor or the owner.



Earthquake Hazard Level		Target Building Performance Levels			
		Operational Performance Level (1-A)	Immediate Occupancy Performance Level (1-B)	Life Safety Performance Level (1-C)	Collapse Prevention Performance Level (1-D)
	50% / 50 years	A	b	c	d
	20% / 50 years	E	f	g	h
	BSE - 1 10% / 50 years	I	j	k	l
	BSE - 2 2% / 50 years	M	n	o	p

Figure 1. Upgrading the structure's capacity (left), performance levels according to FEMA 357 (right)

The goals of rehabilitation are determined by the investor. According to FEMA 356, there is a wide range of different goals and performance levels that correspond with a certain level of earthquake hazard according to ASCE 41 (2007). The next step is determining the specific parameters and acceptable criteria for the quantitative evaluation of desired performance levels. The required parameters usually contain maximum forces and deformations in supporting and non-supporting elements, ceiling slab displacement and ceiling acceleration. Other required parameters, such as cumulative deformation or energy dissipation can contribute to accuracy of the analysis and/or evaluation of cumulative damage (Figure 2).

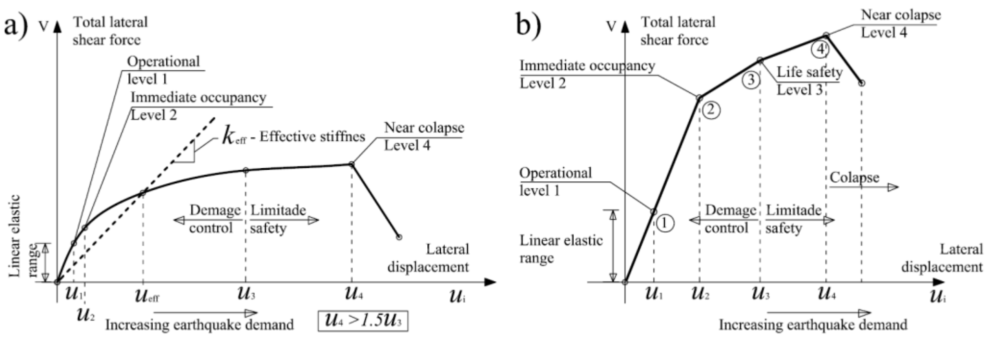


Figure 2. Typical capacity curve of an RC building with the characteristic performance level
a) building with a ductile behavior; b) building with brittle behavior (adapted from FEMA 273, 274)

There are many techniques for improving the seismic behaviour of structures. Selecting the type of intervention is a complex process and involves the consideration of technical and economic possibilities and properties, such as the ratio between the cost of works and the importance of the building, time of termination of the use of the structure, desired performance levels, compatibility of elements to be used for rehabilitation and strengthening with the original structural system, aesthetic requirements, and so on. The method of subsequent addition of RC walls is the most popular and most common among the methods for improving lateral stiffness and capacity. It is applicable with satisfactory results also in cases where the building is already damaged, [6], [7] and [8].

The following are the general methods for improving the seismic performances of existing buildings and preventing significant damage: correcting irregularities in stiffness, reducing eccentricity, reducing the risk of collision of adjacent structures, improving the behaviour of brittle elements and changing their mechanism of fracture to ductile fracture. Generally there are two approaches for increasing seismic capacity of existing structures. The first is a global modification to the structural system by adding RC walls, steel braces, base isolators, etc. These are usually used to improve the structure's lateral capacity. Another approach is at the level of strengthening the elements of insufficient capacity and ductility. It is more cost-effective because interventions are carried out only to elements whose performances need to be improved. This method is based mainly on strengthening the columns and nodes by adding reinforcement, new concrete or gluing FRP fibres [9].

RC walls can be used for strengthening and/or rehabilitating the already damaged structures in several ways. The most preferable method is incorporating the RC walls in the existing RC frames. This is the simplest way of anchoring the RC wall in the foundation structure which allows the partial adoption of gravity load in the second stage of construction work. The RC walls may cover part of a single screen, or run from column to column, which is a more favourable option because in that case the existing columns can be used as edge strengthening of the RC wall.

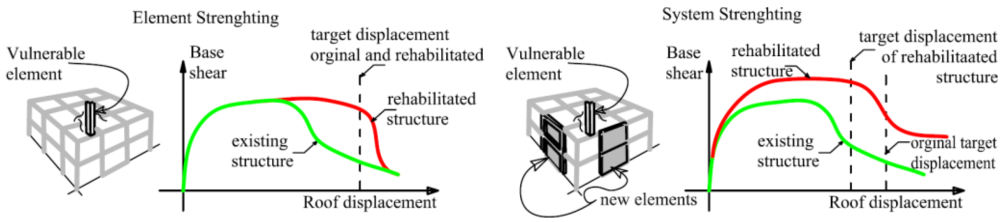


Figure 3

a) Local modification of structural component, b) global modification of the structural system (after Moehle, 2000)

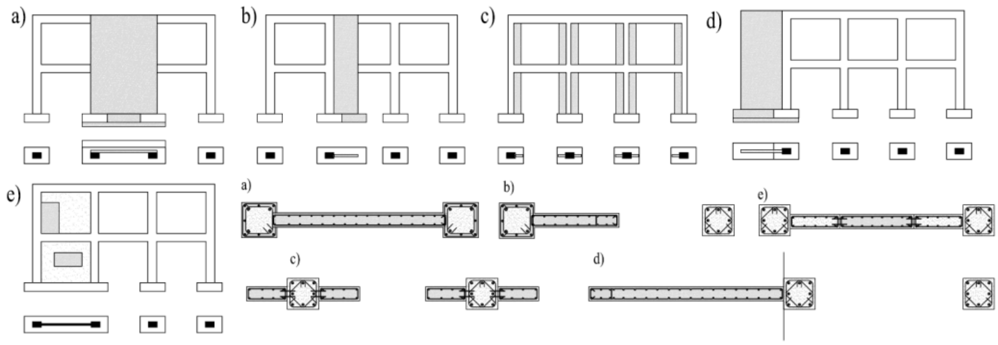


Figure 4. RC frames strengthened with new RC wall

a) external to the frame, b) partial shear walls, c) formation of the end zones-wing walls, d) existing RC wall strengthened with new RC wall

One of the main goals of seismic design is ensuring the proper arrangement of plastic hinges in the load-bearing system. This allows for greater dissipation of seismic energy that enters the system and ensures prevention against the premature failure of one or more vital elements of the system. Constraining the floor mechanism can be achieved by migrating damage from columns and nodes to the beams. Adding wing walls significantly increases the system's ductility but capacity remains the same. The inability of vertical reinforcement of the wing walls to run continually or to be thoroughly anchored significantly reduces the capacity of the strengthened system. The advantage of solution presented in Figure 3*a* is in the fact that it is simple to execute. The behaviour of the wind wall with continuous vertical reinforcement is a more favourable solution, but processing the reinforcement and preparing the column for the realization of the complete coupling are more complex to execute.

Adding external RC walls beyond the building's perimeter is favourable due to small interruption of the structure which leaves the possibility of its continuous use. The problem of executing the foundations of such RC walls is more pronounced, and in many cases almost insurmountable. The high bending moment value due to lateral load and low gravity load opens the possibility for foundation uplift, i.e. high rotation level occurs (Figure 6).

Since they are transferred to the structural element with a disproportionately low gravity load, the strong horizontal forces lead to overturning of foundations. Solution to this problem requires the foundation structure to have robust dimensions, as well as installing a new foundation under the foundation of the existing building or their adequate coupling, engaging thereby to some extent the normal force of gravity load of the existing building already entered in the system. Given the wide excavations required and the high density of roads and structures, this solution cannot be applied in developed urban conditions. This solution is problematic also from aesthetics point of view, but it also can be a torsionally destabilizing factor if interventions to the structure's foundation are not symmetrical.

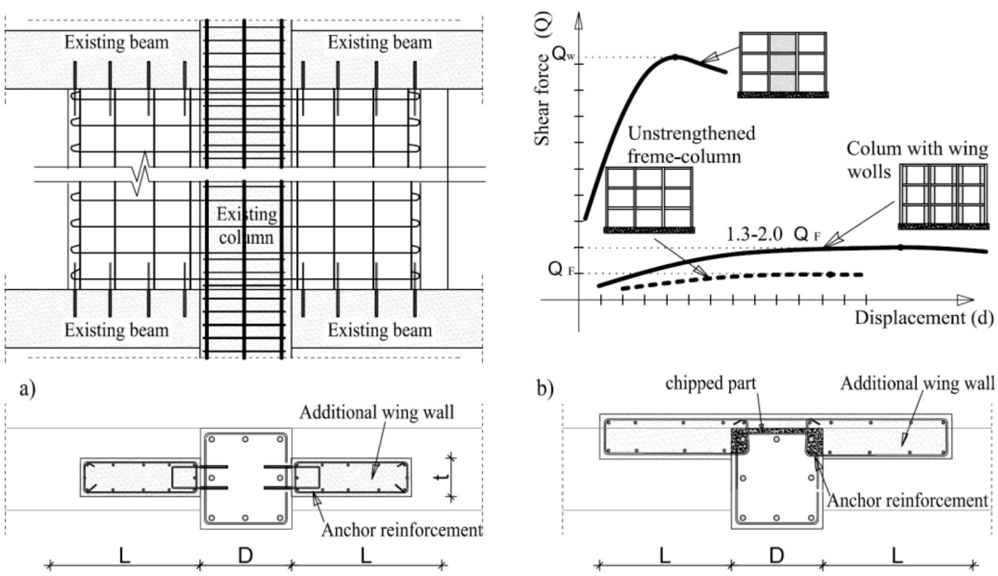


Figure 5. Wing wall with discontinuous and continuous vertical reinforcement

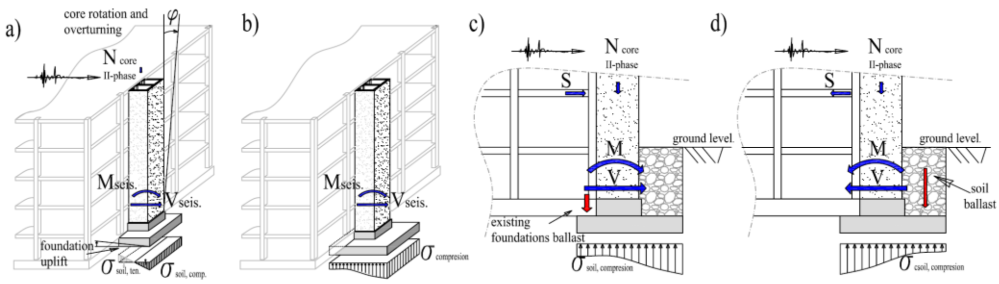


Figure 6. Strengthening with RC core or individual walls beyond the structure's perimeter

Subsequent addition of RC core is a common case when old buildings are reconstructed with the aim of installing elevators. If there is no possibility for incorporating the core inside the very structure and activating the existing gravity load (from the first stage of the construction work), engineers are facing a whole series of problems. If the core is designed to be beyond the perimeter of the existing building, the recommendation is that it should be completely separated (expansion) and prevented from being involved in the acceptance of any horizontal impact. The RC structure of the elevator core is generally able to accept the design horizontal loads, but it requires substantial vertical reinforcement to be installed due to the lack of gravity load. With the separation of the RC core, the building's original torsion regularity and the arrangement of stiffness of vertical elements remains unchanged (Figure 7).

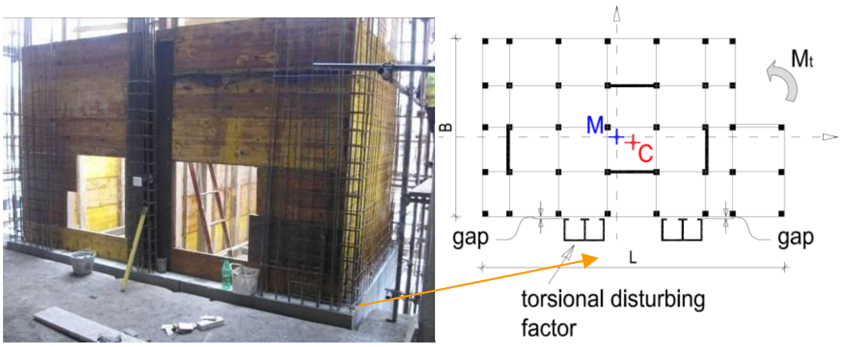


Figure 7. Subsequent addition of RC

RC walls should ensure the controllability of the overall horizontal and relative floor displacement for the design earthquake, the symmetry of stiffness at the foundation, and the building's torsion stability (walls running along the perimeter are more efficient). According to EC8, structural eccentricity (distance between the centre of stiffness and the centre of mass) in each direction on each of the considered floors should be lower than 30% of the torsion radius r_{xc} and r_{yc}.

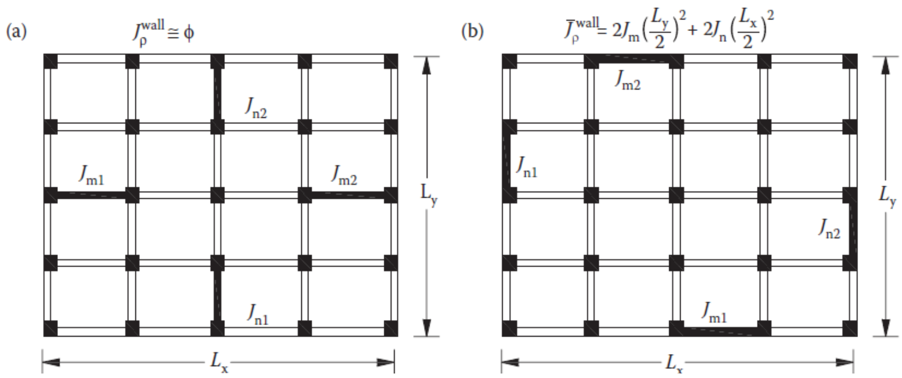


Figure 8. Effect of arrangement of structural wall on the torsional stiffness of the system

Torsional radius with respect to the centre of stiffness C:

$$r_{xc} = \sqrt{\frac{\bar{J}_{TC}}{\sum_{j=1}^{m} J_{jx}}}\,. \tag{1}$$

Torsional radius with respect to the centre of mass:

$$r_{xm} = \sqrt{\frac{\bar{J}_{TM}}{\sum_{j=1}^{m} J_{jx}}}\,. \tag{2}$$

Generally, high RC walls are predominantly subjected to bending load. Under cyclic lateral effect they tend to form a plastic joint at the ground floor. Ductility of the RC wall directly depends on the amount of vertical reinforcement concentrated in the edge zones of the wall, the degree of confinement of the edge zone by stirrups, the level of axial load, the level of shear load, and the amount of horizontal reinforcement in the wall rib. Higher normal compressive stress levels due to gravity load and higher shear force levels due to seismic action reduce the capacity of energy dissipation, as well as the RC wall's ability of ductile bending. In practice, the existing walls are often geometrically regular, but their disadvantage is in the small amount of vertical reinforcement they contain in the edge zones, inadequately confined edge zones (use of open stirrups with large spacing), insufficient horizontal reinforcing of the RC wall rib. Beyond the elastic domain, the deformation ability of these walls is limited. Their dimensions are typically defined using force-based design or displacement-based design.

3. Case study: The building of Clinical Centre in Nis

The old building of Clinical Centre in Nis was built in the late 1970's before the regulations for building structures in seismic zones became effective. It is a prefabricated-type of building constructed according to the IMS system. The prefabricated skeletal structure has been formed using columns of two-storey length, 60x60 cm rectangular cross-section and 6 m axle spacing. The ceiling consisted of 5 cm thick waffled slabs and bearing ribs in two orthogonal directions. The ceiling ribs were prestressed. The joint between ceilings and columns in the IMS structure had been achieved exclusively by prestressing. Between the columns and the ceiling there is no soft reinforcement whatsoever. The load from ceiling to columns is transferred exclusively through pressure and shear stresses. In the stage of assembly, cables running through the columns and the concrete flume have no direct connection with prestressed ceilings. Reinforced concrete walls for the acceptance of horizontal forces are in situ monolithic casts.

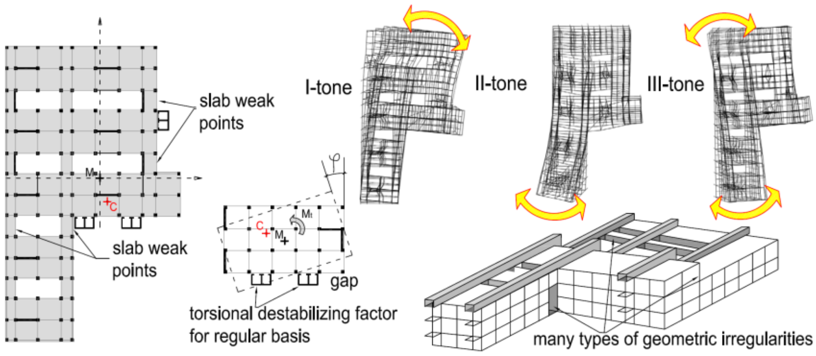


Figure 9. Absence of anchorage of the RC wall to the prefabricated column

The structure's design deviates from all structural regularity criteria. The building's foundation is irregular with a laterally separated "wing" annex. The annex is the major destabilizing factor whose negative effect is manifested in all tones of structural oscillation (Figure 9). The torsion of the entire structure represents an additional load to circumferential frames, as well as the facade walls. Due to the seismic effects, the largest displacements are those of the peripheral points of foundation, exposing the facade frames to increased levels of damage. From the aspect of lateral stiffness and weight distribution, the structure of the building is extremely asymmetrical. There are six atriums in the building's foundation, seriously violating the stiffness of ceiling structures in their plane. The reduced ceiling stiffness influences the irregular redistribution of lateral load between vertical bearing elements. The large distance between RC walls and their arrangement are challenging the full interaction between RC walls and all the frames. The ground floor ceiling even has a notch (contraction) in its corner, i.e. at the junction of the building's main part and the annex. The building is stepped along the height, but the entire structure had been executed a single entity, without expansion joints. This has increased the relative displacement of ceilings in places where the building abruptly narrows. The reduction along the height had been executed asymmetrically at 50% of the foundation area (as opposed to EC8). Originally, RC tunnels were projected on the ceiling of the upmost storey that served as installation corridors, further concentrating the weight at the top of the building. The total building's mass had been significantly increased compared to the original mass due to stricter regulations regarding thermal protection, which required the replacement of original facade made of aluminium panels by brick walls.

All prefabricated columns and the edge strengthening of RC walls were executed without any confinement of cross section (open stirrups with 25 cm spacing) with very low percentage of longitudinal reinforcement in the edge columns, $\mu_c < 0.5\%$. The arrangement of apertures, displacement in the position of openings along the floors, and a significant reduction in the shear surface makes them irregular. All openings in RC walls are without adequate treatment of edges with additional reinforcement. Since the RC walls were cast on site, and the edge strengthening consisted of prefabricated RC columns, they were not vertically coupled.

The strengthening intervention consisted of removing the protective layer from the columns, continuous threading of additional vertical reinforcement, and a quality confinement of edge strengthening using stirrups. The edge zone of the wall rib was chased and anchored in columns. The connection between RC wall and RC prefabricated pillars was made monolith by realization of shear connection on the concrete as well as reinforcement. According to the American ACI 318-08 standard, the horizontal reinforcement in the critical rib area should be fully anchored within the confined core of the edge element, and should contain hooks at its ends bent by 90°. Thus, even after the protective concrete layer is broken off to the depth of stirrups that confine the column, the horizontal reinforcement remains completely enveloped in concrete along the entire length of the edge element of the wall, improving the anchorage of horizontal reinforcement in the edge element.

Figure 10. Strengthening the existing RC walls

Depending on the arrangement of apertures, the building's RC walls can be classified into four types. The total capacity of lateral load is increased by the addition of new, thickening and correcting irregular holes on the existing RC walls. The two newly designed elevator cores on the edge of the building are completely separated and independent structures. Figure 11 displays the pushover curves of individual types of walls and the future strengthened wall. Differences in behaviour, capacity and stiffness are obvious.

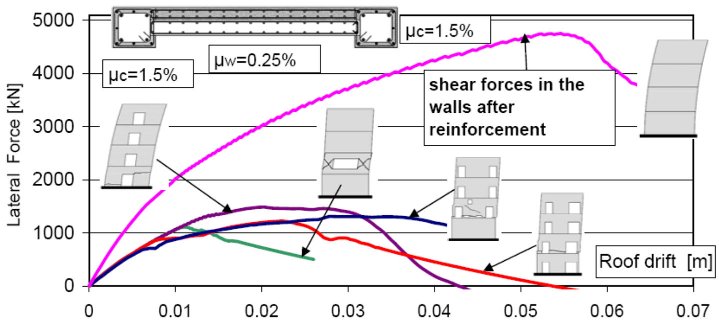


Figure 11. Pushover curves for characteristic types of RC walls

Applying EC 8 and ACI 318 provisions, RC walls are necessary to provide with higher capacity for shear walls than ductile RC frames in structures with similar dynamic properties. The reason for this is that the ductility of the walls is lower, mainly because of the possibility of shear-type fracture where it is more difficult to achieve high ductility levels than in the case where fracture occurs mainly due to bending. Therefore, walls in the y-direction (weaker direction) are duplicated with casting an additional rib, so that a 30cm wall thickness has been achieved.

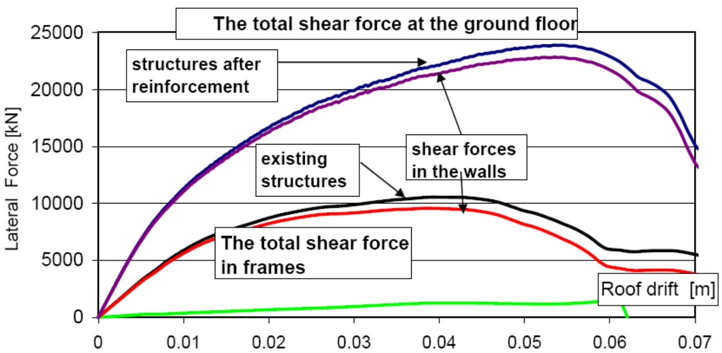


Figure 12. Pushover curves of the entire structure before and after the strengthening of RC walls

Formally, the newly designed structure which is dimensioned using the force base design approach meets the currently applicable regulations which have long been outdated. What remains is the problem of the structure's capacity and non-ductile behaviour of the RC frame (20 – 25 cm spaced open stirrups in columns). The available ductility of displacement of the actual structure depends on the available ductility of element's cross-section curve. For example, according to EC8, the behaviour of the q factor is 1.62, which is close to the minimum value. This requires calculations according to EC8 to the level of 62% of full elastic load. The reinforced structure is significantly below this level of capacity. The intervention of confining all the pillars with additional mantles of RC concrete or carbon fibre tapes is not cost-effective to the investor (over 500 possible positions for remediation). Thus, the building's condition has been left intact. Given the importance of the building and its purpose, the target performance level according to ASCE 41 would have to be the highest, that is level 1-A, which is the level that requires a fully operational building after the earthquake of corresponding seismic hazard (50% of probability in 50 years). In this case, this requirement has certainly not been fulfilled, and the level of damage to structural and non-bearing elements will be much more serious.

4. Conclusion

The present paper provides a brief overview of possible seismic strengthening of RC frame structures by adding RC walls subsequently. Although there are a number of approaches to improve the seismic behaviour of buildings, adding RC walls is the most frequently applied technique. Adding RC walls as global strengthening technique effectively and efficiently resolves the problem of global displacement, capacity and ductility of the frame structure. In addition to cost and ease of implementation, determining and analyzing the efficacy of a specific solution should also be affected by the degree of reliability of the joint. The influence of behaviour of joint elements between the existing structure and the subsequently added elements is decisive for the behaviour of the strengthened system. For this reason, the approach of subsequent strengthening using RC walls proved to be more advantageous than strengthening using steel elements (passive and active). Drawbacks of using RC walls are reflected in the increased volume of construction works and higher price. Methods based on strengthening individual elements are significantly more cost-effective, but they can be applied only to a small number of cases, i.e. when the problem is of local nature on one of the line elements of the structure. Further research should include experimental investigations focused on the behaviour of strengthened structures, as well as methods of establishing connection between the old and newly designed elements.

Acknowledgements

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