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Prediction of necessary framed or independent walls for the strengthening of existing building

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Abstract:

Framing walls within the framework of the structure of a building aims at: (a) the receipt by them of a large part of the seismic loads and (b) a drastic reduction of seismic displacements of the 3D frame system. Both indirectly contribute to the effective protection of the existing supporting structure with the most economical way. In pursuit of a pre-estimation of the walls' cross-sections, a strengthening methodology is proposed based on the displacements of existing spatial system. According to this methodology, using linear analysis and the spectral response method, seismic stresses (corresponding to the admissible performance) of the vertical components of the existing supporting structure are determined. Then based on these stresses and *their corresponding strength using a certain procedure, loads and safety displacements of the supporting structure are determined. If the displacements of the existing supporting structure for the aforementioned loads, as typically happens, are larger than the safety displacements of the structure, then the reduction of the displacements of the existing supporting structure is aimed through the construction of walls inside existing frames at locations specified according to technical and economic criteria. The amount of the walls to be constructed is proportional to the gap between safety displacements and design displacements. The methodology is applied in the case of a building designed according to the Greek Seismic Code of 1959 and for two expected performance levels according to ΚΑΝΕΠΕ (Greek Retrofitting Code).*

Key words: Walls, strengthening, safety displacements, linear analysis, spectral response method.

1. Introduction

A large percentage of Greece has buildings built before the earthquake regulations of 1985 (Ministry of Public Works 1985) which is the landmark and the forerunner of a new generation of regulations and also, a significant proportion of these buildings have been built earlier than the first earthquake regulation of 1959 (Ministry of Public Works 1959). Based on the most recent census of the National Statistical Service of Greece, 33% of the country's buildings are built before 1959 and another 47% between 1959 and 1985. Therefore the majority of Greek buildings has been designed either without anti-seismic regulations or under rudimentary seismic regulations (Ministry of Public Works 1959), which on one hand underestimated the size of seismic actions and on the other hand calculated seismic stresses incorrectly because of, comparatively with the current, very weak computational media available. The aforementioned

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have resulted to buildings of decreased strength. Also designers were unaware of the importance of ductility, which is currently considered as the most important attribute of earthquake engineering construction in combination, of course, with the capacity design, which includes the rational, in terms of seismic resistance, hierarchy of strength either between different components or in the same structural element. However, the seismic safety of old buildings is threatened, perhaps more, by the quasi scattered weak links of the 3D frame which are related either to deviations from normality ("soft" floors, short columns), or due to human factors (ignorance, irresponsibility) or, finally, to the in-situ method of construction of the structural system (nodes, incomplete juxtaposition lengths, anchorages) (Penelis and Kappos 1996). And it would not be a great exaggeration if these weak links in the chain of individual strengths in some cases were characterized as time bombs threatening with devastating results if triggered by a powerful earthquake. In that case, the seismic safety relies on existing reserves led by the computationally neglected masonry infill body. The last observation raises the sensitive issue of uncertainties, which in the case of strengthening existing structures is understandably of much larger scale than that of new constructions (Fib 2003a). This observation gives special value to the Aristotelian principle according to which "a reasonable person seeks no greater accuracy than that allowed by the nature of the problem that studies".

Another observation, which should be taken into account when designing strengthenings of structures is that, according to statistical evaluations, the seismic damage from the ground floors of multistory structures has the biggest participation in total damage (Fib 2003b). The phenomenon is not difficult to interpret since the devaluation of computational seismic stress was greater in the bottom floor of the seismically active floors. Also regarding the importance in contributing to the safety of the building, in accordance with the spirit of capacity criteria of modern regulations (Fib 2013), (Ministry of Environment, Planning and Public Works 2000a), (Standards New Zealand 2006), (European Committee for Standardization 2004), there is an unquestioned supremacy of the importance of vertical members, namely the columns and walls against horizontal ones. Again, the statistical results on seismic failures show that while walls fail generally from shear, columns, depending on the shear span ratio, sometimes fail due to bending and sometimes due to shear (Penelis et al 1995).

During an extreme earthquake, successive failures of cross-sections take place, which means at best, that their contribution to the assumption of seismic stress takes place no more. If, however, the component after the displayed seismic damage is unable to bear the gravity loads, then the spatial system presents local collapse and if the neighboring components cannot replenish the assumption of gravity loads through any available overstrength, then there is a general collapse of the building.

The issue of local or general collapse refers to levels of performance of modern regulations and in particular to their fundamental objectives, among which is the avoidance of collapse, the repairable damages, the protection of human life and the almost full functionality after the design-level earthquake (see Table 1) (Earthquake Planning and Protection Organization 2011).

Table 1. Performance levels converted at the current Regulations

Exceedance probability of seismic activity in the conventional life	Performance Level of Structural System		
	Almost full functionality after the earthquake	Protection of life and property of tenants	Quasi collapse
10%	A1 [2.00]	B1 [1.00]	C1 [0.70]
50%	A2 [1.00]	B2 [0.55]	C2 [0.40]

2. Description of the Proposed Strengthening

Methodology

It is known that seismic inertial loads, seismic movements and seismic stresses are in interfering relationship with each other, and one is affected and fed from the other. Therefore, if the existing spatial system is loaded according to the provisions of Greek Seismic Code 2000 (Ministry of Environment, Planning and Public Works 2000b), it is possible to determine the loads and movements that correspond to the limit state (in terms of safety) of the critical, in accordance with the preceding remarks, vertical members of the ground floor. Because depletion of resistances of these components does not in any way take place simultaneously, a process is required like that described in Fig. 1 for determining the seismic failure loading of the bottom floor. In the coordinate system of Fig. 1, each vertical element of the ground floor is depicted by a point whose abscissa represents the load of the group of actions including the earthquake loading and its ordinate represents its homologous strength. If for the design loading of the chosen strengthening performance all vertical elements simultaneously exhausted their strength, then their corresponding points would be situated on a straight line passing through the beginning of the coordinate system, while if their seismic stresses were equal to their strengths, then the chosen load would be the safety limit load. As this is not the case, points over the bisector of the system of axes correspond to structural elements which have safety margins against the seismic action corresponding to the intended performance, while points below the bisector correspond to structural elements which, theoretically, have failed for the design loading. Following the above, some degree of personal crisis is required for drawing a correlation line corresponding to the generalized failure of structural elements of the ground floor. The slope (direction factor) of this line represents the correction (normally reductive) coefficient of seismic actions, having in mind that the corrected loads represent the failure load of the structural system.

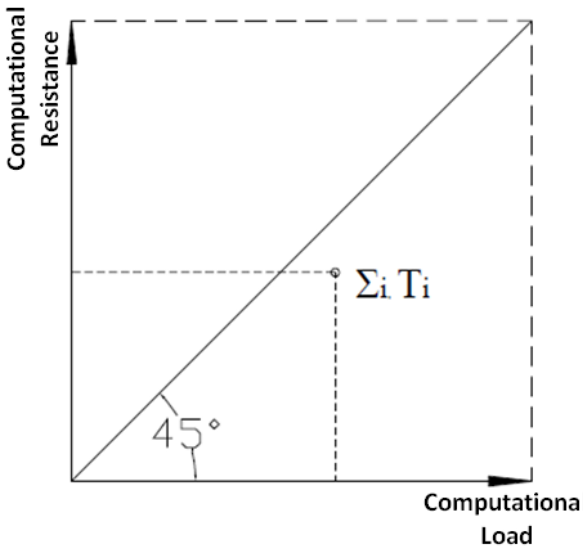

Figure 1: Process of determining the actions and safety displacements.

Any doubts about whether indeed the ground floor is the critical floor can be clarified by repeating the process for any suspected floor. Note that the decision on which elements may need to be strengthened, it may arise for those elements whose representations are below and far away from the fixed position of the drawn line, or for those elements whose strengthening would result in a drastic improvement of the direction factor value having as a criterion the economy of the strengthening method. Regarding starting load this could be, as mentioned, the load corresponding to the intended strengthening performance. The behavior factor for the old structures is reasonable to be assumed depending on each case as q = 1.50 or q = 1.0.

Displacements arising for seismic failure loading in combination with the value q that was deemed appropriate for the case under consideration are characterized as "safety displacements" of the existing structural system. In the sense that these are the maximum displacements that can be safely borne by the structural system. Consequently, in the framework of a strengthening strategy that relies on indirect access, the type and amount of strengthening are sought, since as far as strategy is concerned, it is known that many times the zigzag way is the shortest way. A compliance key criterion set is the restriction of displacements of the strengthened system for the seismic actions of the chosen performance to the same level as the safety displacements which have been identified for the existing structural system.

3. Application

The proposed methodology is applied in the case of a building which was studied under the Greek Seismic Code of 1959 (Ministry of Public Works 1959) and is included among the teaching examples of the manual titled "Reinforced Concrete Structures" (Penelis et al 1995) given in Aristotle University of Thessaloniki. The formwork of the ground floor slab of the existing building is given in Fig. 2 while the vertical section of the existing building is shown in Fig. 3.

In the example of the book (Penelis et al 1995), columns of the first floor are studied, however, based on the current practice at that time and for the purposes of this study the calculations were extended to the vertical elements of the ground floor. Then, it was attempted to determine the necessary strengthening of the structural system for seismicity I and two levels of performance, according to Table 1: (a) the protection of life and property of residents and (b) almost full functionality after the earthquake, with 10% possibility of exceeding the design earthquake for a life expectancy of the building after strengthening equal to fifty years.

The existing spatial system is examined for the loading of the above performance case "a" (α_0 = 0.16 and q = 1.50). For the two horizontal principal directions of the floor plan, cross-sectional loads are calculated; bending moments for columns and shear loads for the walls of the ground floor. Subsequently, homologous strengths of these components are identified and their points are placed in axis systems of Fig. 4.

Based on the dispersion of points, the following conclusions arise:

(a) In the case of ordinary performance, strengthenings are required for the columns S5, S15, S18, S19, as shown in Figs. 4a and 4b, and for the core walls of the stairwell, taking into account their points on the diagram, so that they are on or above the bisector of the system of axes. Certainly, a core strengthening, if it is possible, results to an additional relief of all columns including the four columns that need strengthening. Fig. 5 shows the new state of the structural system and Figs. 6a and 6b display the modified representations of the vertical elements.

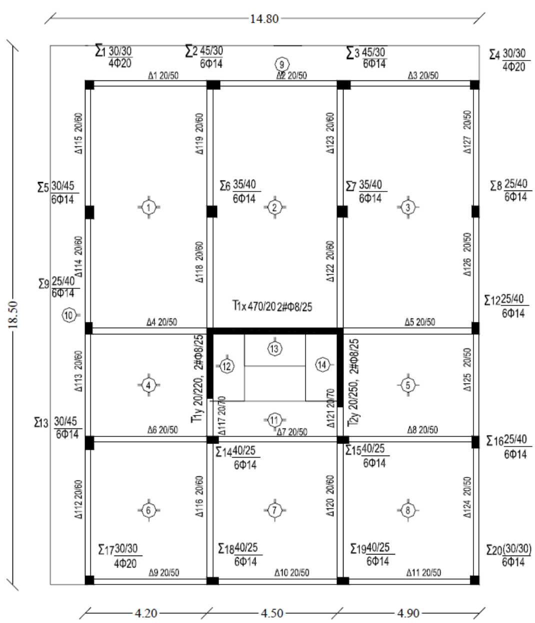

Figure 2: Formwork of ground floor slab of the existing building.

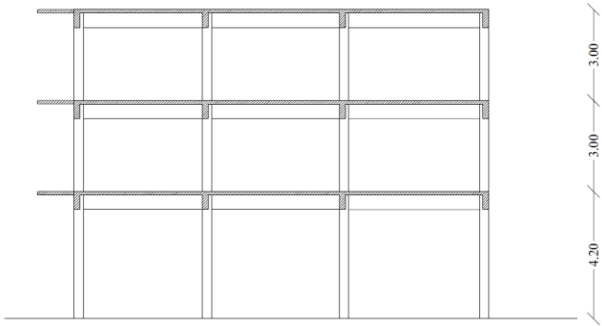

Figure 3: Vertical section of the existing building.

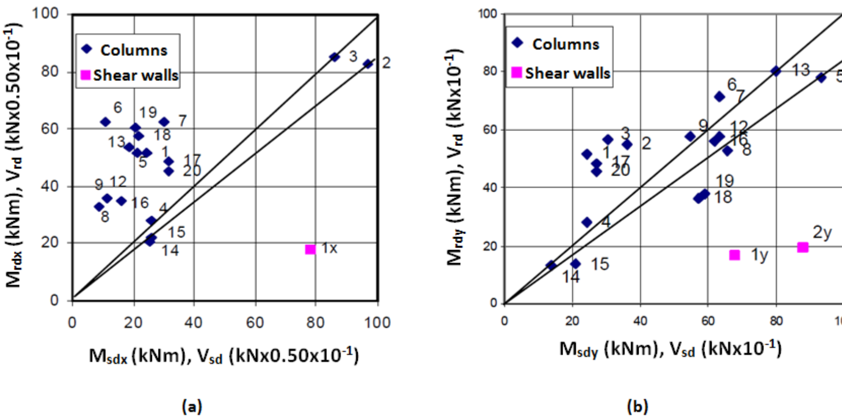

Figure 4: Correlation diagrams: (a) for x-x direction, (b) for y-y direction.

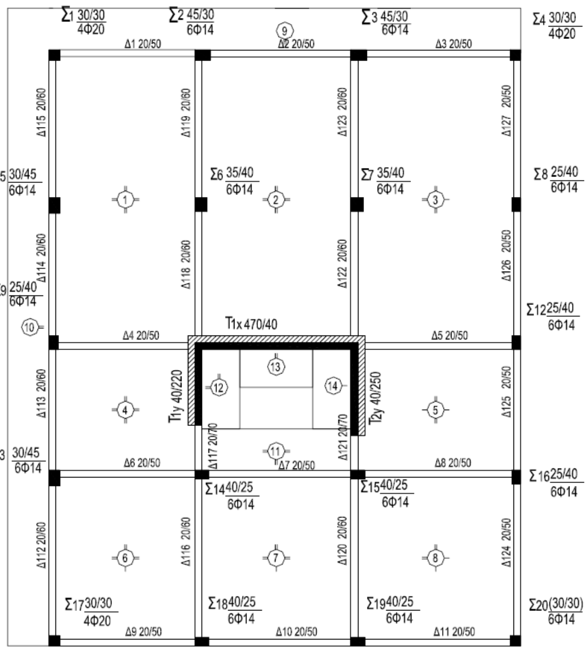

Figure 5: Formwork of strengthened structural system for performance case "a".

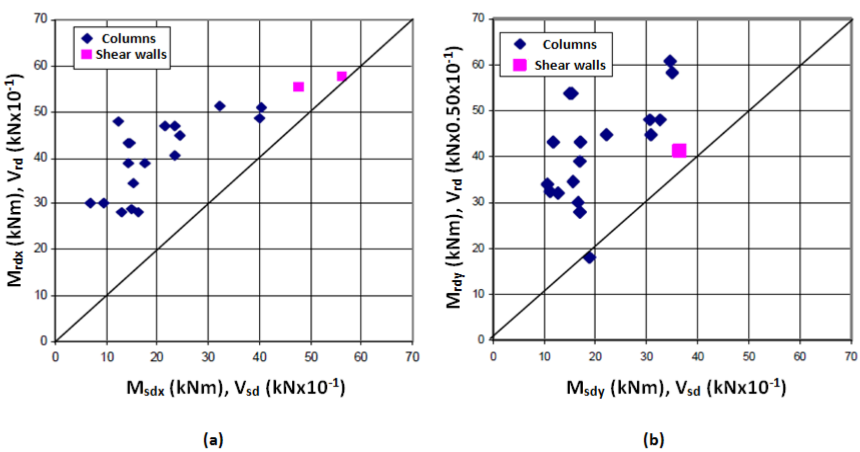

Figure 6: Correlation diagrams (a) for x-x direction, (b) for y-y direction for the strengthened building of case "a".

(b) For the second case of higher degree of performance, correlation lines determining the seismic safety loads are drawn in the initial diagrams of Figs. 4a and 4b. Based on these lines, it is decided to strengthen the walls of the staircase core. Because loads of the performance case "b" are twice than loads of performance case "a" examined previously, a further strengthening of the system is required. The solution selected is placing walls inside frames as shown in Fig. 7.

The requested seismic safety actions are determined by means of the slopes of these correlation lines, which have the value $\lambda = 0.83$ coincidentally on both principal directions. Then the computational safety seismic displacements d_E are derived from the displacements d_{E0} found using the method of spectral response linear analysis by multiplying with the behavior factor $q = 1.5$ and the resulting value of λ for each direction:

$$d_E = \lambda \cdot q \cdot d_{E0} \quad (1)$$

The resulting strengthened system is studied then under the corresponding seismic actions ($a_0 = 0.24$ and $1.50 \leq q \leq 3.50$ according to the designer's discretion) and its resulting displacements are compared to the safety displacements previously encountered. The solution is characterized sufficient when the required compliance criterion is fulfilled, according to which, displacements of the strengthened system should be equal to or smaller than the safety displacements of the existing system. Based on the conservative value $q = 2.50$, correlation results listed in Figs. 8a and 8b arise.

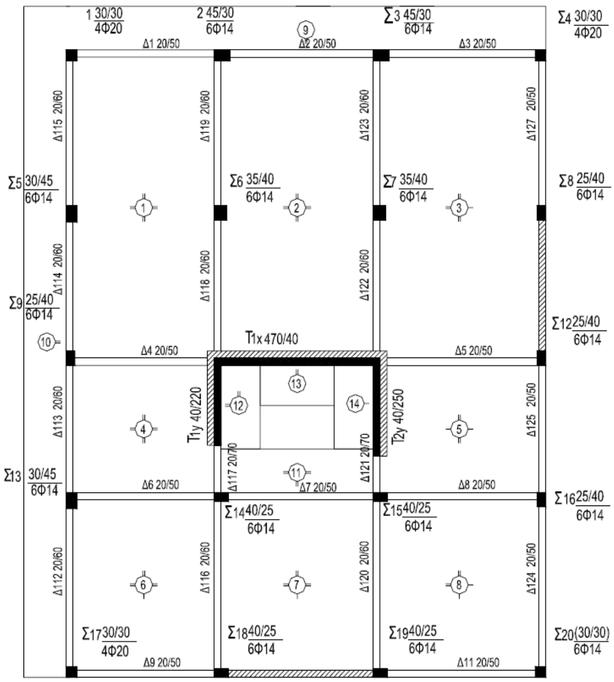

Figure 7: Formwork of strengthened structural system for performance case "b".

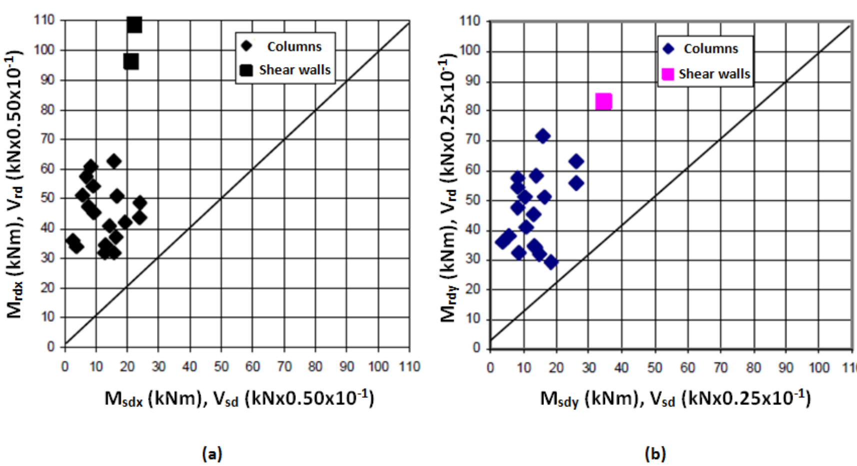

Figure 8: Correlation diagrams: (a) for x-x direction, (b) for y-y direction for the strengthened building of case "b".

4. Epilogue – Conclusions

The present work proposes a methodology of indirect access to the problem of determining the elements to be strengthened in a structural system of a reinforced concrete structure. The methodology is simplified due to the plurality of the problem's uncertainties. It consists in, for a given degree of performance, a controlled displacements restriction of the strengthened system having as a term of compliance the protection of the existing system, for which safety displacements are initially identified.

The methodology was applied for two expected performance levels in the case of a building designed seismically according to the Greek Seismic Code of 1959 (Ministry of Public Works 1959).

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