Methodology for Seismic Assessment and Retrofitting of RC Building Structures

G. Necevska-Cvetanovska & R. Apostolska
"Ss. Cyril and Methodius" University, Institute of Earthquake Engineering and Engineering Seismology, IZIIS, Skopje, Republic of Macedonia

SUMMARY:
The methodology for assessesment of the seismic resistance of RC building structures developed at the Institute of Earthquake Engineering and Engineering Seismology and the experience acquired in the field of repair and strengthening are presented in the paper in a synthetized form. Presented are two case studies of RC buildings in which the application of this methodology is shown as well as some of the results obtained from comparative analyses of the seismic behaviour of structures prior and after strengthening. A corelation between our national experience in the field of assessment of existing structures and the principles of repair and strengthening on one hand and the European standard EN 1998-3: Eurocode 8: Design of Structures for Earthquake Resitance – Part 3: Assessment and Retrofitting, on the other hand, is also given.

Keywords: seismic assessment, earthquake resistance, retrofitting

1. INTRODUCTION

Most building codes in the World explicitly or implicitly accept the occurrence of structural damage in buildings during strong earthquakes as long as the life hazard is prevented. Indeed, many earthquakes (Haiti, Chile, Japan, New Zealand) caused such damage in the past. Seismic design codes were improved after each earthquake disaster, but existing structures were left unprotected by a new technology. As a consequence, seismic assessment and retrofitting of existing structures has become top priority issue worldwide.

The definition of a method for design and evaluation of the seismic resistance of R/C building structures is a wide and complex problem. On one hand, it is necessary to carry out the most possible realistic definition of the structural system capacity, in terms of strength and deformability capacity of the system, and on the other hand, after having selected the expected earthquake effect on a given site, in terms of intensity, frequency content and time duration, to predict as realistically as possible the nonlinear behaviour of the structure, and on the basis of these results, define the earthquake, i.e., the seismic force or the acceleration that would cause damage to structural elements and the integral structural system. For this purpose, it is necessary to develop a clear and concise procedure that will enable a fast and simple way of achieving the desired results. As a result of the analytical studies, carried out at the Institute of Earthquake Engineering and Engineering Seismology in Skopje, a method and a corresponding package of computer programs (RESIST-INELA) have been developed for fast and simple evaluation of the seismic resistance of the newly designed and existing reinforced concrete buildings of small and moderate number of stories, (Necevska-Cvetanovska, 1992, 2000). In fact, the developed method incorporates the latest knowledge gathered in our country and the world-wide experience from the broad fields of earthquake engineering: determination of strength and deformability characteristics of the building, on one hand, and definition of the nonlinear behaviour of the structure for a given earthquake effect, on the other hand.

The seismic assessment of existing structures and measures for their retrofitting is subject of Part 3 of Eurocode8 (EN1998-3, 2005). It is a modern document, fully aligned with the recent trends regarding performance requirements and check of compliance in terms of displacements, providing also a degree of flexibility to cover the large variety of situations arising in practice. The performance requirements are formulated in terms of the three Limit States (LS): (1) Near Collapse (NC); (2) Significant Damage (SD) and (3) Damage Limitation (DL). The appropriate level of protection against the exceedence of the three Limit States is achieved by associating to each of them a value of the return period (Tr) for the design seismic action. The specific values to be adopted for the Tr's are left for the National Authorities to decide, the suggestions being 2475, 475 and 225, respectively. The compliance criteria consist essentially in checking, for each LS, that the demands, calculated by using the allowed methods of analysis, do not exceed their corresponding capacities, (Pinto & Franchin, 2011).

Presented further in the paper is a brief description of the methodology for seismic assessment and retrofitting of RC structures developed at IZIIS, as well as its application in two case studies.

2. METHODOLOGY FOR SEISMIC ASSESSMENT AND RETROFITTING OF RC BUILDING STRUCTURES

The original methodology and the corresponding package of computer programmes (RESIST-INELA) for optimal design of new and seismic assessment and definition of the most efficient system for repair and/or strengthening of existing buildings were developed by Necevska-Cvetanovska, 1995.

The IZIIS methodology for seismic assessment of RC building structures can be briefly described in the following five steps:

Step 1: Input parameters-definition of the structural system of the building and determination of the quantity and quality of the built-in material for existing buildings

Step 2: Design and determination of strength and deformation capacity for each element, taken separately, and the storey Q-Δ diagrams with determination of the correction factor R (mechanism of appearance of the first cracks)

Step 3: Definition of the seismic parameters and the design criteria. The seismic parameters and design criteria can be determined by complex analyses of the regional and local seismological properties of the building site. On the basis of the local site properties, applying probability methods, evaluation of the seismic hazard parameters is carried out. These enable definition according to which expected maximum ground accelerations are possible to be defined. For this purpose, several time histories with corresponding frequency content are suggested to be used for further dynamic analysis.

Step 4: Nonlinear dynamic analysis of the structural system (INELA- computer program). The mathematical model of the structure is represented by lumped masses at the floor structure levels, connected with springs, expressing the storey rigidity of the structure. The output from the analysis are maximum acceleration, velocities and displacements at the storey level, as well as required ductility and required displacement.

Step 5: Seismic assessment of building structures

In the process of definition of the most optimal structural system for repair and/or strengthening of existing buildings, it is necessary to define, as realistically as possible, the structural system capacity, in terms of strength and deformability capacity of the system on one hand, while on the other hand, after having selected the expected earthquake effect at a given site, one should predict, as realistically as possible, the nonlinear behaviour of the structure, and on the basis of these results, define the earthquake, i.e., the displacement that would cause damage to structural elements and the integral structural system. The process of definition of the mode of repair and strengthening is iterative.

The above presented methodology for assessment and the RESIST-INELA programme package were verified by using the computer programme IDARC2D (Inelastic Damage Analysis of RC Frame-Shear Wall Structures), (Park et al., 1987). Comparative analyses of the results obtained by using these two computer programs for four R/C structures with different structural system and number of stories were performed. From the performed analyses and taking into account the different modeling of the structure and the use of different hysteretic models, it was concluded that the obtained results were satisfactory, (Necevska-Cvetanovska & Petrusevska, 1996).

The presented methodology has widely been applied in design of more than 300 RC building structures in Macedonia, as well as assessment of existing ones. It is based on modern principles and trends for design and assessment of building structures. The results regarding the seismic demands calculated in accordance with this methodology and Eurocode 8 are closely correlated. The obtained seismic demands in accordance with the national regulations are overestimated, (fig. 2.1), (Necevska-Cvetanovska & Petrusevska, 2000).

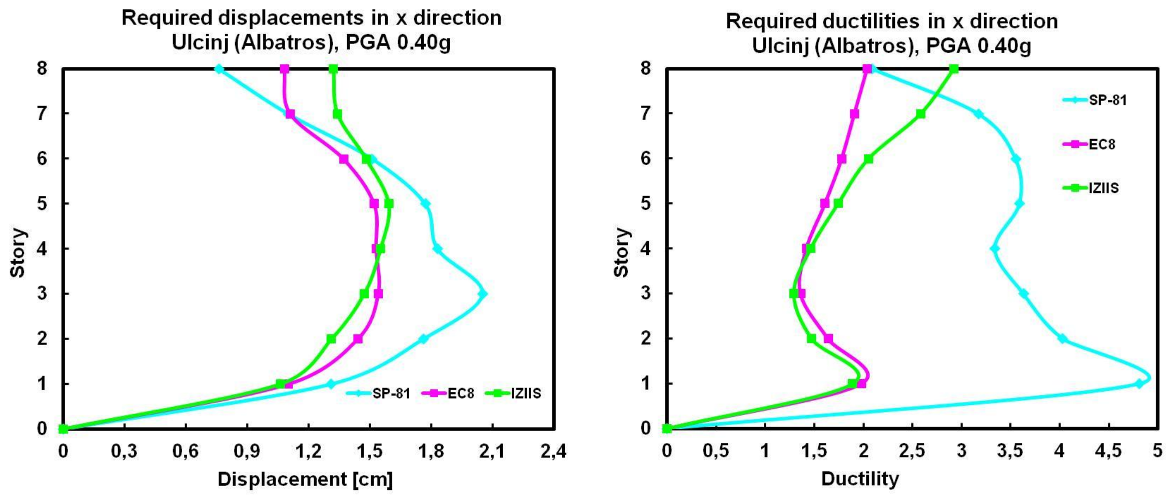

Figure 2.1. Distribution of required displacement and ductilities

3. APPLICATION OF THE METHODOLOGY FOR SEISMIC ASSESSMENT AND RETROFITTING OF RC BUILDINGS STRUCTURES - CASE STUDIES

The application of the methodology described in item 2 is illustrated by two case studies: (1) RC building “Tower 5” in Skopje and (2) Steel building with concrete infill in Kosovo. Seismic assessment of the building structures was performed according to the positive code regulations for reinforced concrete structures, (Rulebook on Construction of Building Structures in Seismic Regions - PIOVS ’81). According to this code, two types of analyses were carried out : (1) linear elastic static analysis and (2) nonlinear time history analysis for expected and/or defined seismic actions on the location.

3.1. Case study # 1: RC building “Tower 5”- Skopje

3.1.1. Seismic assessment

The building structure consists of a basement, a ground floor and ten stories. The load bearing system is designed and constructed as a RC frame system with ribbed floor structure (Fig. 3.1), (Velkov at al, 1991). The structural system was designed in 1968 without dynamic analysis.

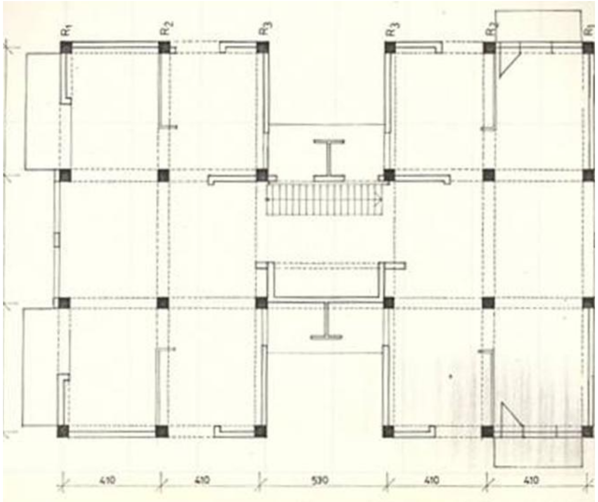

Figure 3.1. The floor plan of the RC building "Tower 5"

Due to the occurrence of deformations in the structural system and extensive damage to the infill walls in the beggining of 1985, detailed investigations of the quality of the built-in concrete were performed by two relevant national institutions. The concrete compressive strength of the extruded specimens was between 10-15MPa. This pointed out the necessity for assessment of the stabililty of the structure under gravity loads, as well as under seismic actions.

Assessment was done based on: (1) study of the original technical documentation of the structural system; (2) visual survey of the building; (3) detailed investigations of the built-in concrete (destructive tests); (4) analysis of ultimate limit state for gravity loads; (5) static and equivalent seismic analysis for design actions and strength of materials and (6) nonlinear dynamic analysis for seismic parameters defined on the basis of seismic zoning of the wider area of the structure location.

The results from the analysis of ULS for gravity loads show that, in most of the columns running up to the seventh story, the normalized axial force factors and safety factors for concrete are bigger than those allowed by the regulations, (table 3.1).

Table 3.1. Selected results (frame R3) from ULS analysis for gravity loads – safety factors

Story	b/d	N	A	Safety factor (PIOVS'81)							
	[cm]	[kN]	[cm^2]	MB10*	MB12	MB15	MB17	MB20	MB22	MB25	MB30
1	60/60	3407	25.13						1.80	2.03	2.39
2	60/60	3109	25.13			BRITTLE FAILURE			1.97	2.22	2.62
3	60/60	2813	25.13						2.18	2.45	2.90
4	55/55	2518	25.13			1.20	1.62	1.87	2.04	2.29	
5	55/55	2231	25.13			1.36	1.83	2.12	2.30		
6	55/55	1945	25.13			1.57	2.10	2.43			
7	55/55	1660	25.13			1.82	2.46	2.84			
8	50/50	1377	16.09	1.55	1.80	2.18	2.44				
9	50/50	1099	16.09	1.94	2.26						
10	50/50	822	16.09	2.60							
11	50/50	547	16.09	3.90							
12	30/30	173	8.04	4.75							

*Note: * concrete compressive strength according to the national code, PBAB'87*

The first three fundamental periods of vibrations were T_1=2.214sec., T_2=1.301sec. and T_3=0.885sec. pointing to the system flexibility.

Nonlinear dynamic analyses were carried out for seismic parameters (intensities and frequency content) defined based on seismic zoning of the wider area of the structure. Two accelerograms were selected: El-Centro with a_{max}= 0.15g and Parkfield with a_{max}= 0.23g. Selected results regarding the ***demands*** in terms of relative story displacements in y-y direction are presented in fig. 3.2.

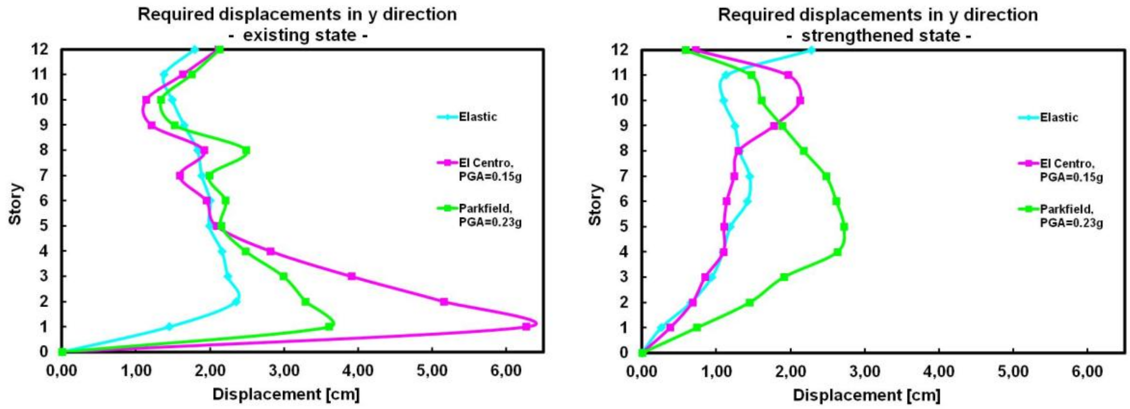

Figure 3.2. Demands in terms of relative displacements

The obtained results showed that the earthquake demands expressed in terms of relative displacements were far beyond the displacement capacity, leading to structural failure. From the analysis of the results, it was obvious that there was an urgent need for repair and strengthening of the existing building structural system as well as measures for temporary support of the first three story heights of the building.

3.1.2. Retrofitting

The strengthening solution anticipated insertion of columns with RC jackets (d=10cm) and concrete compressive strength of 40MPa and incorporation of new RC walls with d=15cm up to the tenth story (2 walls in longitudinal and 4 in transversal direction) (Fig. 3.3).

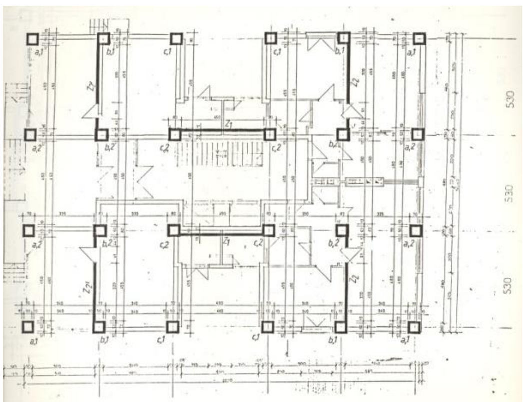

Figure 3.3. Layout of the solution for retrofitting

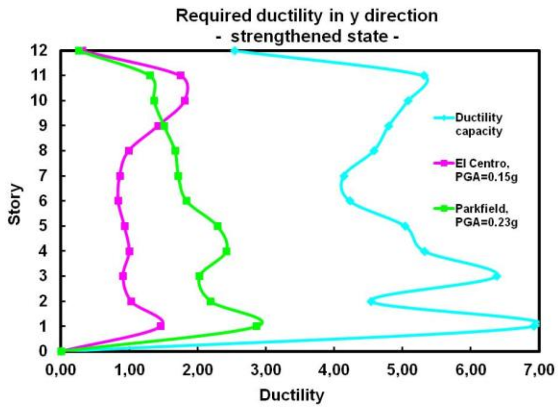

Figure 3.4 Demand versus capacity in terms of ductilities

The selected results from the nonlinear dynamic analysis in terms of displacements and ductilities are given in figs. 3.2 and 3.4. The results from the performed analysis show that the strength and deformability capacity of the strengthened structural elements and of the entire system are greater than the earthquake demands expressed through displacements and ductilities.

3.2. Case study # 2: Steel building with concrete infill in Kosovo

3.2.1. Seismic assessment

The existing steel building with concrete infill is situated in Mitrovica, Kosovo and will serve as an administrative building for the needs of the Investor. The building was built in the late sixties of the last century. It consists of a ground floor and one storey. The structural system is identified as a steel moment resisting frame with a concrete infill, (fig. 3.5).

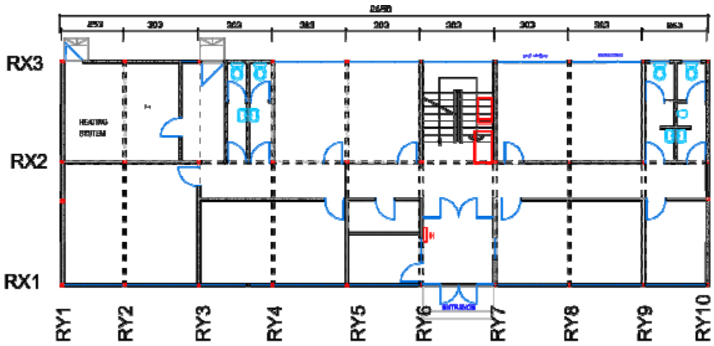

Figure 3.5 The floor plan of the building

For the purpose of re-definition of the building function, assessment of seismic stability and safety of the existing structural system was carried out, (Necevska-Cvetanovska&Apostolska, 2012). Assessment of seismic safety was done based on: (1) detailed on site screening of the building; (2) linear static and equivalent seismic analysis for design seismic actions and strength of materials; (3) assessment of input seismic design parameters on the site and (4) nonlinear dynamic analysis for the identified structural system and quality of built-in materials using the defined seismic parameters.

Since there was no available technical documentation on this building, the IZIIS' expert team visited the location twice to identify the building structural system, the proportions of its structural elements, the quality and quantity of the built-in materials and its dynamic characteristics.

Within the frames of the detailed on site screening of the building, besides visual observations of the existing state, non-destructive investigation of the RC structural and nonstructural elements-infill (identification of concrete strength and location and size of the reinforcement), as well as experimental investigations for definition of the real dynamic characteristics of the structure by ambient vibration method (Krstevska&Taskov, 2012) were carried out.

The linear elastic analysis of the building structural system for gravity loads and equivalent seismic forces was carried out by use of the SAP computer program, (fig. 3.6). The input data for analysis was calibrated using results from ambient vibration measurements. The first two fundamental periods of vibration were T_1=0.230sec. and T_2=0.198sec. The top horizontal displacements in both orthogonal directions due to the code seismic forces, (PIOVS'81) were $\Delta_{top,X}$ = 0.087cm and $\Delta_{top,Y}$= 0.065cm, accordingly. The top horizontal displacements due to the seismic forces defined on the basis of expected real earthquake effects on the location were $\Delta_{top,X}$ = 2.71cm and $\Delta_{top,Y}$= 1.96cm, which are bigger than the allowed ones according to the regulations.

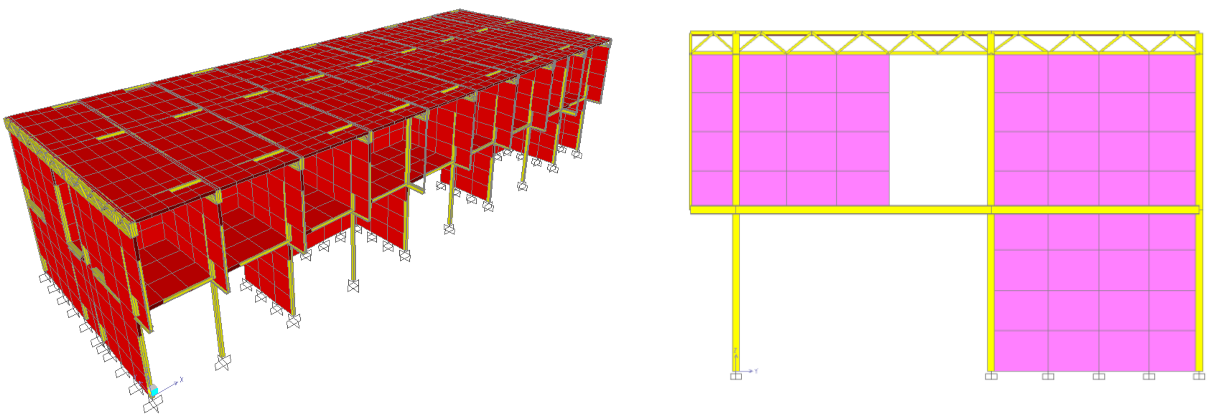

Figure 3.6 3D mathematical model and characteristic frame in transversal direction

Nonlinear dynamic analyses were carried out for seismic design parameters based on the existing data fund from investigations performed in the territory of Kosovo, (Dojcinovski& Olumceva, 2012). Two levels were anticipated: for return period of 95 years, a_{max}= 0.23g and for return period of 475 years a_{max}= 0.26g. The following accelerograms were selected: Bitola N-S, Robic N-S, Ulcinj (Albatros) N-S, Ulcinj (Albatros) E-W and El Centro. Four different states of structural behaviour under seismic actions were analyzed, namely: state 1- steel moment resisting frames with infill; state 2- steel moment resisting frames with reduced infill stiffness for 50%; state 3- steel moment resisting frames with reduced infill stiffness for 75% and state 4- steel moment resisting frames without infill.

Selected results regarding ***earthquake demands*** in terms of relative story displacements in x-x direction are presented in figure 3.7.

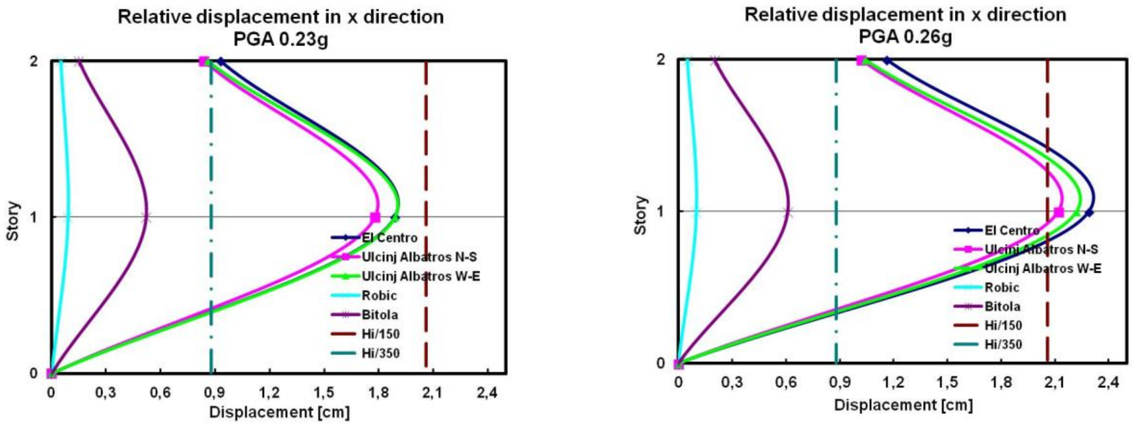

Figure 3.7 Demands in terms of relative displacements (*state 1*)

The results from the analyses show that, for PGA ranging from 0.14g for the Ulcinj Albatros W-E to 0.18g for the Ulcinj Albatros N-S, the ultimate displacement capacity of the infill is achieved. These PGA are less than the expected seismic design parameters on the location. The relative story displacements for the input seismic design parameters are high (ex. for Ulcinj Albatros W-E, PGA=0.26g, they are 2.22cm –state 1; 2.56cm-state 2, 3.63cm-state 3 and 9.15cm-state 4, at the first story, in x-x direction). Such displacements can cause damage to the building structure.

3.2.2. Retrofitting

It is recommended that retrofitting of the existing building structural system be done by insertion of steel braced diagonals in the first and the last span of the steel frames in x-x direction (Rx1 and Rx3), as well as in the first and the third span of the steel frames in y-y direction, (Ry1 and Ry10), (see fig. 3.8). The detailed results from the equivalent static analysis for the real expected forces on site and from the nonlinear analysis of the retrofitted structural system are given in (Necevska-Cvetanovska, Apostolska, 2012), while the selected ones are presented in figure 3.9.

Figure 3.8 Position of steel diagonals in the model

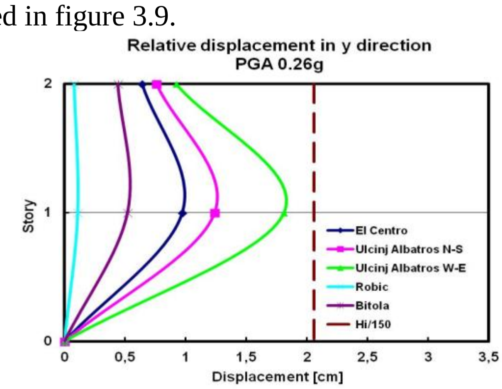

Figure 3.9 Demands in terms of relative displacements

The results from the nonlinear dynamic analysis of the retrofitted model show that, for all input seismic design parameters, the relative story displacements are smaller than those allowed by the regulations (hi/150=2.13cm).

4. CONCLUSIONS

The building inventory including recently constructed structures is generally seismically deficient in terms of both safety and economic protection. It become obvious that seismic upgrading of the built environment would pose a tremendous economic burden and would require a long term planning by the society. Seismic assessment of an existing structure is a difficult task for which an ordinary design engineer is not well educated and trained and was, until recently, without much assistance in the form of normative or pre-normative documents.

The Institute of Earthquake Engineering and Engineering Seismology (IZIIS), Skopje has more than 40 years of experience in the field of assessment, repair and strengthening of existing structures. As a result of this experience, a methodology for seismic assessment and retroffiting of RC building structures has been developed. The methodology is iterative, whereat verification of the earthquake ***"demands"*** versus structural ***"capacities"*** is performed and expressed through displacement and ductility as controlling parameters. This methodology has widely been applied for assessment and retroffiting of building structures in many countries as are Macedonia, Montenegro, Algeria, Mexico, Italy, etc.

Part of the results and the experience gathered from the application of this methodology for seismic assessment of existing building structures in Macedonia were used for definition of NDP in Part 3 of Eurocode8 (EN1998-3, 2005), (Dumova, Necevska-Cvetanovska, Apostolska, Curilov, 2011).

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