Comparative Analysis of Seismic Response of Regular and Irregular Multi-Storey Frame Buildings

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ABSTRACT:
The aim of the paper is to assess the usability of nonlinear simplified methods for practical application for regular and irregular frame structure with different stories. The behaviour of regular and irregular, four and eight multi-storey RC frames, were analyzed using pushover analysis which allows for a more realistic estimation of seismic demands of multi-storey buildings. Nonlinear modeling and analysis allows more accurate determination of stresses, strains, deformations, internal forces and displacements of critical structural components, results that can then be utilized for the final design of the frame components or evaluation of the building global strength capacity and ductility. Numerical modelling of nonlinear behaviour is carried out by applying plastic hinges and the model with inelastic fibers. Estimation of target displacement is performed using capacity spectrum method, equivalent linearization method, coefficient method and displacement modification method. Comparative analysis of pushover curves obtained with plastic hinges model and structural model with inelastic fibers are performed.

Keywords: Seismic demands, multi-storey buildings, pushover analysis, target displacement, plastic hinges

1. INTRODUCTIONS

Existing seismic design procedures are predominantly based on elastic structural models. The capacity of the structure to dissipate input energy during earthquake with inelastic deformation is taken into account indirectly by using the reduced seismic forces. However, the use of the empirically based reduction factor may fail to predict the actual behaviour of the structure. The need for changes in the existing methodology implemented in existing building seismic codes has been therefore widely recognised. The existing seismic design procedures cannot provide an adequate inspection of damage level of building structures in quantitative terms. These methods are based on the assumption of linear elastic structural behaviour and do not provide information about real strength, ductility and energy dissipation (Ladjinovic & Cosic, 2008).

In this paper a simplified nonlinear method for estimation of seismic demands and real response of multi-storey buildings is presented. Two mathematical models are used for the seismic analysis – one mathematical model is a multi degree of freedom (MDOF) system, and the other is a single degree of freedom (SDOF) system. Nonlinear static analysis is used to determine the action effects and the pushover curve of MDOF model, approximated by the bilinear force-displacement relationship to determine the characteristics of the equivalent SDOF system. Developed pushover curve is converted into an acceleration displacement response spectrum (ADRS) format of capacity curve. The ratio of seismic demands and yield strength capacity is determined by comparison of capacity curve and response spectra of excitations. Target displacement is determined using Capacity Spectrum Method (CSM), Equivalent Linearization Method (ELM), Coefficient Method (CM) and Displacement Modification Method (DMM). Target displacement determined in this way is again converted into the corresponding displacement of MDOF system. The whole system is afterwards being "pushed" to the target displacement of the multi storey frame, with the determination of the action effects in structure and monitoring of the plastic hinges formation and propagation of nonlinear deformations.

2. ANALYSIS METHOD

Methods for seismic analysis of structures can be divided into static and dynamic, and structural models into linear and nonlinear. The actual structural behavior under seismic action can be best simulated using nonlinear time history analysis. However, the nonlinear time history analysis is still too complex for practical usage, which led to a recent development of analysis methods based on a nonlinear static analysis (NSA). Results of these researches are implemented into the latest codes for the design of structures for earthquake resistance: (ATC 40, 1996), (FEMA 356, 2000), (FEMA 440, 2005) and EN 1998-1: 2004. Initial structural model for nonlinear static analysis (NSA) of structures subjected to seismic actions is a multi degree of freedom system, for which is necessary to determine the pushover curve, i.e. the relationship between the base shear force and horizontal displacement of the top of the building. Structural strength capacity, as well as the shape of pushover curve, depends on the applied distribution of seismic forces over the height of the building. Different lateral load distributions can be applied: uniform, triangular, according to the first mode shape (modal distribution), the distribution according to the SRSS combination of modal lateral forces, etc.

2.1. Nonlinear structural model of multi-storey frames

Three dimensional multi-storey frame building can be analyzed through the decomposition of structure into certain substructures, which consist of multi storey frames loaded in their own plane. Some codes limit the application of nonlinear static analysis to regular frames in elevation, with the exception to frames with the discontinuity at the ground floor, where the application of nonlinear static analysis is allowed. Plane frames are modelled using beam and column elements of constant cross-sections with two nodes and three degrees of freedom in each node. Structural models with plastic hinges concentrated at the ends of elements are commonly used for nonlinear analysis of multi-storey frame structures. Recently, structural model of multi storey frames with fiber models of beams and columns are also used, which can include propagation of inelastic deformations along structural elements. Frame model with plastic hinges is formed using beam finite elements, "placing" plastic hinges at the ends of elements. Nonlinear effects can occur as a result of material and/or geometric nonlinearity. Geometric nonlinear effects are introduced through P–Δ effects and the incremental displacement determination, while the material nonlinearity is introduced using a nonlinear force-deformation relationship in the plastic hinges. The force-deformation relationship in potential plastic hinges must be previously determined (e.g. moment-rotation, moment-curvature relationship, etc.).

The nonlinear static analysis defines the relationship between base shear force and horizontal displacement at the top of the building through the pushover curve. Overall lateral load is divided into increments, and the whole system is observed through different configurations in which the equilibrium equations are solved for the incremental load. Within each increment, it is assumed that the system of equations is linear, so the solution of nonlinear problems is given as the sum of a series of incremental solutions. As a result of linearization, there are unbalanced (residual) forces, which is the reason why iterations are performed within each increment in order to balance residual load. The distribution of seismic loads over the height of the building is taken to be constant during the several increments (conventional analysis) or with the alteration of the load distribution in the incremental situations (adaptive analysis). In order to evaluate the dynamic response of the buildings, the Incremental Dynamic Analysis (Vamvatsikos & Cornell, 2002) was applied. This procedure consists in performing time history analyses using real or artificial accelerograms, which are scaled each time in order to induce increasing levels of inelasticity in the structural model.

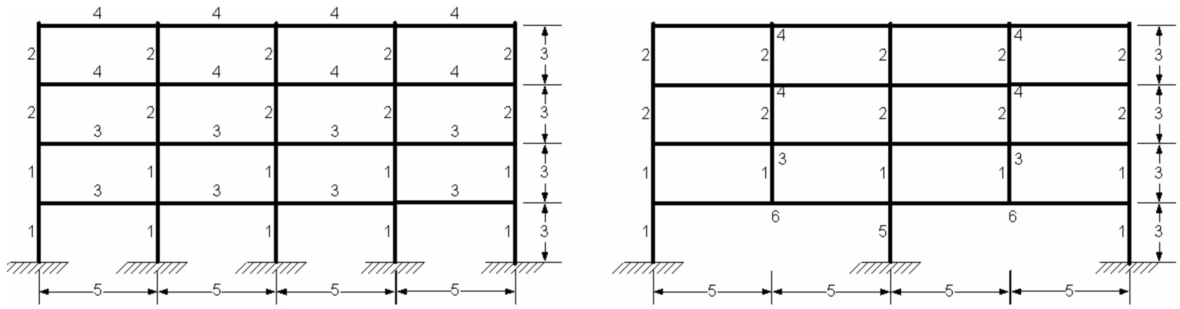
Static analysis is first carried out for vertical load in the conventional analysis. Previously should be defined the system geometry, material characteristics, preliminary cross-section dimensions and amount of reinforcement for all elements, the characteristics of plastic hinges depending on the type of element (beam, column). Afterwards, lateral load is progressively applied and the formation of plastic hinges is monitored with a transition of the system to a nonlinear behaviour range. In slender unbraced frames it is possible problem of stability and divergence of solution due to the second-order effects. Lack of conventional methods is that the lateral seismic load does not change with the occurrence of plastic hinges and propagation of inelastic deformation, but the distribution of loads is constant during the entire analysis. Therefore, according to the codes, e.g. (FEMA 356, 2000) and (FEMA 440, 2005), it is required that the analysis must use at least two different load distributions.

2.2. Estimate of target displacement

Analysis of the target displacement is the second phase of nonlinear static analysis. Estimation of inelastic deformation is based on the analysis of SDOF system, and depends on the procedure applied for the determination of target displacement. In this aim several different procedures are developed. Research in this paper is limited to the analysis verified in practical applications and implemented in technical codes: 1) Capacity Spectrum Method (ATC 40, 1996); 2) Coefficient Method (FEMA 356, 2000); 3) Displacement Modification Method (FEMA 440, 2002); 4) Equivalent Linearization Method (FEMA 440, 2002).

3. NUMERICAL ANALYSIS

Four and eight storey regular and irregular frames have been analyzed (Ladjinovic *et al.* 2009). To determine the required reinforcement in beams and columns, preliminary seismic analysis was made, where the seismic effects were determined using the equivalent static method. The S500 reinforcement and concrete class of C25/30 were used to design. Adopted dimensions of beams and columns, and amount of reinforcement are shown in Fig. 1 and 2. Afterwards, force-deformation relationships were defined for all plastic hinges according to FEMA 356.

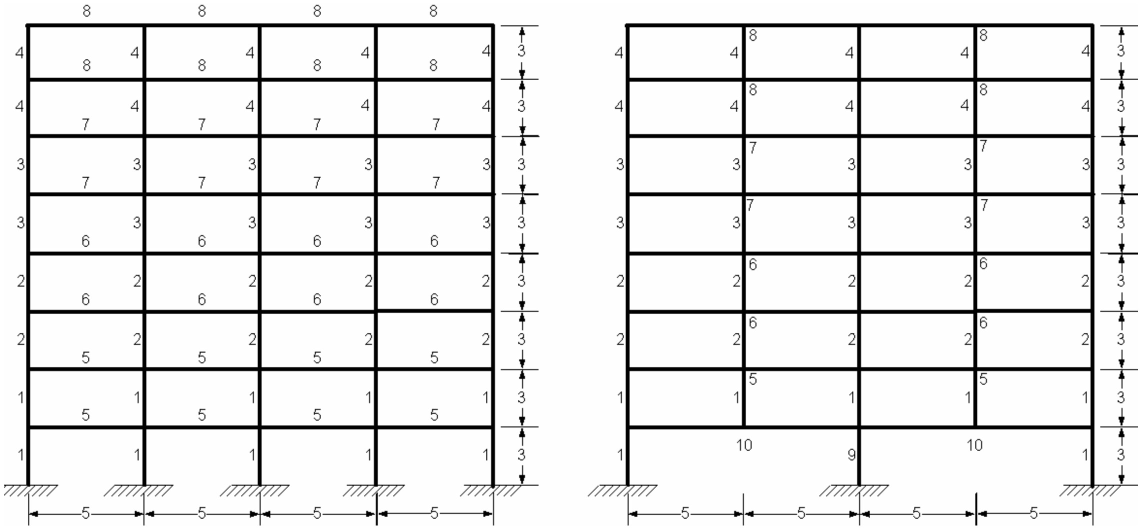


Frame		Regular					Irregular				
Member	Type	Dimensions in [cm]	Reinforcement				Dimensions in [cm]	Reinforcement			
			Ends		Middle			Ends		Middle	
1	column	35×35	2×4RØ19				35×40	2×9RØ19			
2	column	30×30	2×3RØ19				30×30	2×6RØ19			
3	beam	25×40	A_2	6RØ19	A_2	2RØ19	30×50	A_2	11RØ19	A_2	2RØ19
			A_1	3RØ19	A_1	2RØ19		A_1	2RØ19	A_1	6RØ19
4	beam	25×35	A_2	5RØ19	A_2	2RØ19	30×40	A_2	9RØ19	A_2	2RØ19
			A_1	2RØ19	A_1	2RØ19		A_1	2RØ19	A_1	4RØ19
5	column	-	-				40×70	2×3RØ19			
6	beam	-	-	-	-	-	40×80	A_2	15RØ25	A_2	2RØ25
			-	-	-	-		A_1	2RØ25	A_1	12RØ25

Figure 1. Input data for considered four storey frames

Based on the previously described methods of analysis and formed numerical models, pushover curves were developed to obtain the control node displacement in seismic design situation. The static analysis is performed by means of pushover procedures while the dynamic analysis is performed using the Incremental Dynamic Analysis (IDA). The developed pushover curves for regular and irregular structures with plastic hinges at the ends of elements are shown in Fig. 3 to Fig. 8. Results of the nonlinear static and dynamic analysis obtained with fiber models are shown in Fig. 9 to Fig. 11.

Distribution of inelastic deformation over the height of regular and irregular buildings, i.e. interstorey drifts, for various lateral load distributions that are applied and for different design concepts are presented in Fig. 12 to Fig. 14 for 8–storey frame.



Frame		Regular					Irregular				
Member	Type	Dimensions in [cm]	Reinforcement				Dimensions in [cm]	Reinforcement			
			Ends		Middle			Ends		Middle	
1	column	40×60	2×5RØ19				40×75	2×6RØ19			
2	column	40×55	2×3RØ19				40×65	2×4RØ19			
3	column	40×50	2×3RØ19				40×50	2×4RØ19			
4	column	40×40	2×3RØ19				40×40	2×4RØ19			
5	beam	30×60	A_2	7RØ19	A_2	3RØ19	30×60	A_2	10RØ22	A_2	2RØ22
			A_1	4RØ19	A_1	3RØ19		A_1	2RØ22	A_1	7RØ22
6	beam	30×55	A_2	7RØ19	A_2	3RØ19	30×55	A_2	10RØ22	A_2	3RØ22
			A_1	4RØ19	A_1	3RØ19		A_1	2RØ22	A_1	7RØ22
7	beam	30×45	A_2	7RØ19	A_2	3RØ19	30×45	A_2	11RØ19	A_2	6RØ19
			A_1	4RØ19	A_1	3RØ19		A_1	3RØ19	A_1	7RØ19
8	beam	30×40	A_2	6RØ19	A_2	2RØ19	30×40	A_2	9RØ19	A_2	4RØ19
			A_1	3RØ19	A_1	2RØ19		A_1	2RØ19	A_1	4RØ19
9	column	-	-				50×100	2×2RØ22			
10	beam	-	-	-	-	-	40×100	A_2	18RØ25	A_2	2RØ25
			-	-	-	-		A_1	3RØ25	A_1	16RØ25

Figure 2. Input data for considered eight storey frames

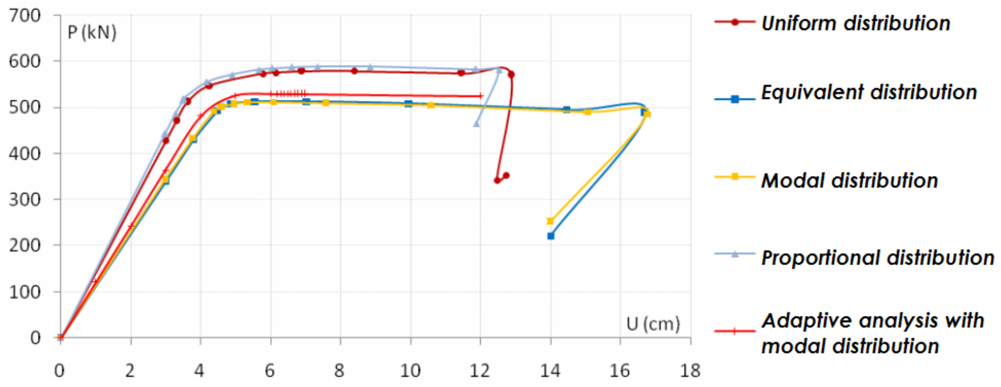


Figure 3. Pushover curves of regular four-storey frame determined for different lateral load distribution

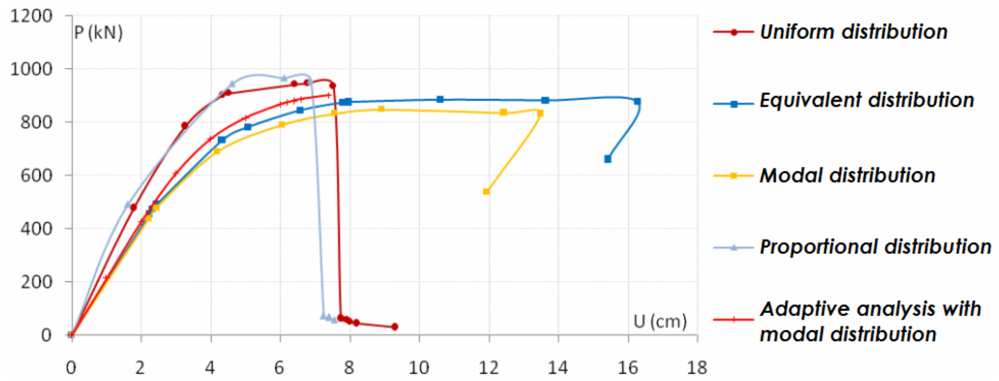


Figure 4. Pushover curves of irregular four-storey frame determined for different lateral load distribution

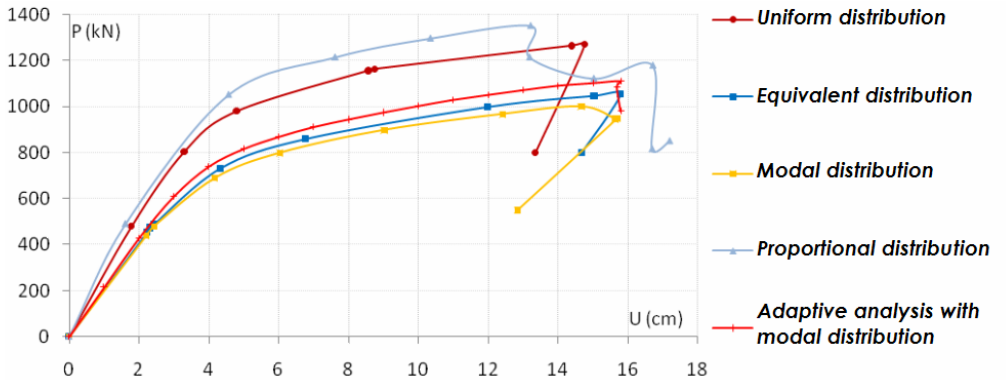


Figure 5. Pushover curves of irregular four-storey frame – capacity design concept

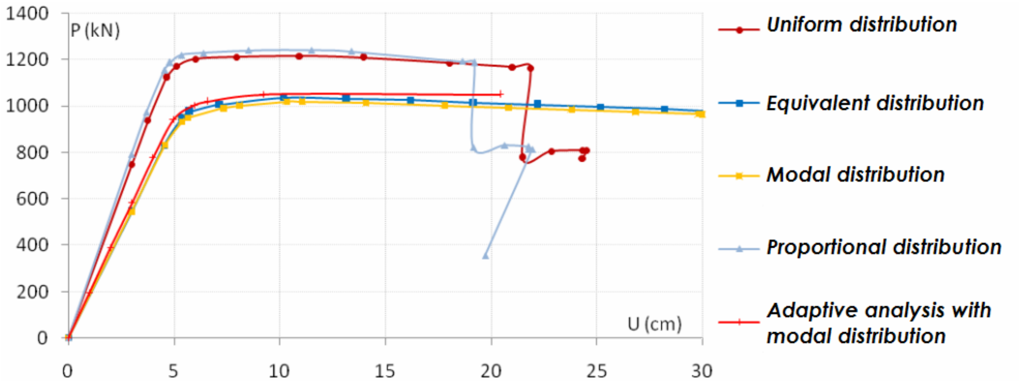


Figure 6. Pushover curves of regular eight-storey frame determined for different lateral load distribution

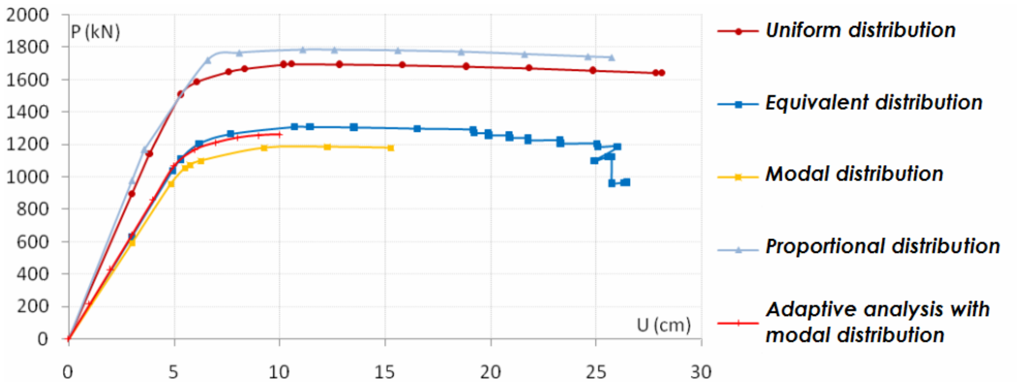


Figure 7. Pushover curves of irregular eight-storey frame determined for different lateral load distribution

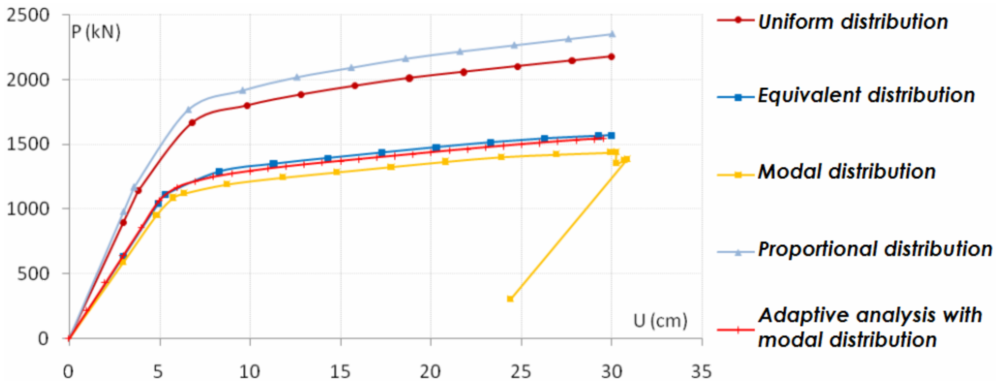


Figure 8. Pushover curves of regular eight-storey frame – capacity design concept

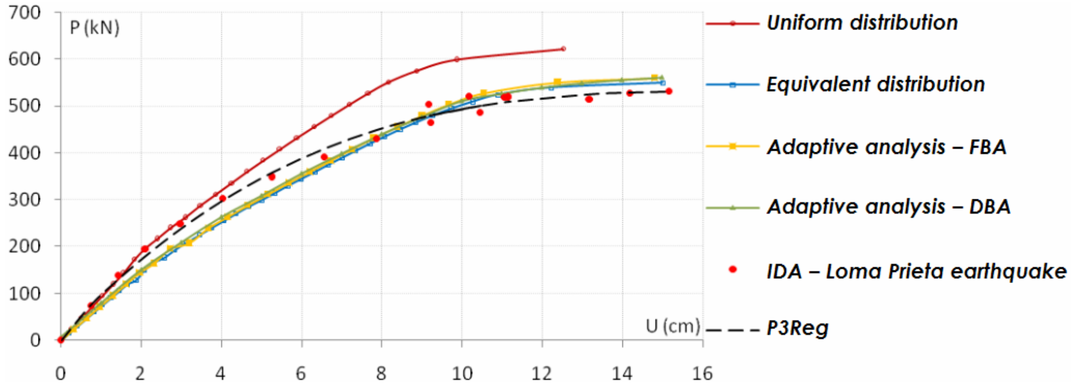


Figure 9. Pushover curves of regular 4-storey frame – fiber models

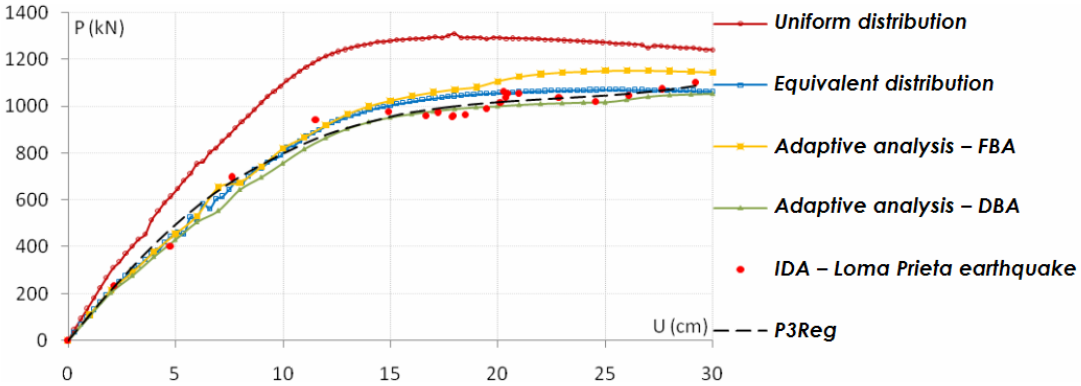


Figure 10. Pushover curves of regular eight-storey frame – fiber models

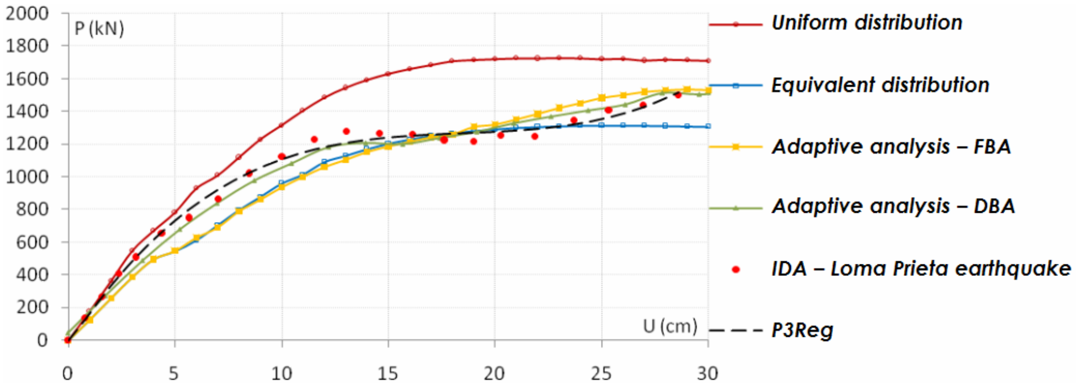


Figure 11. Pushover curves of irregular eight-storey frame – fiber models

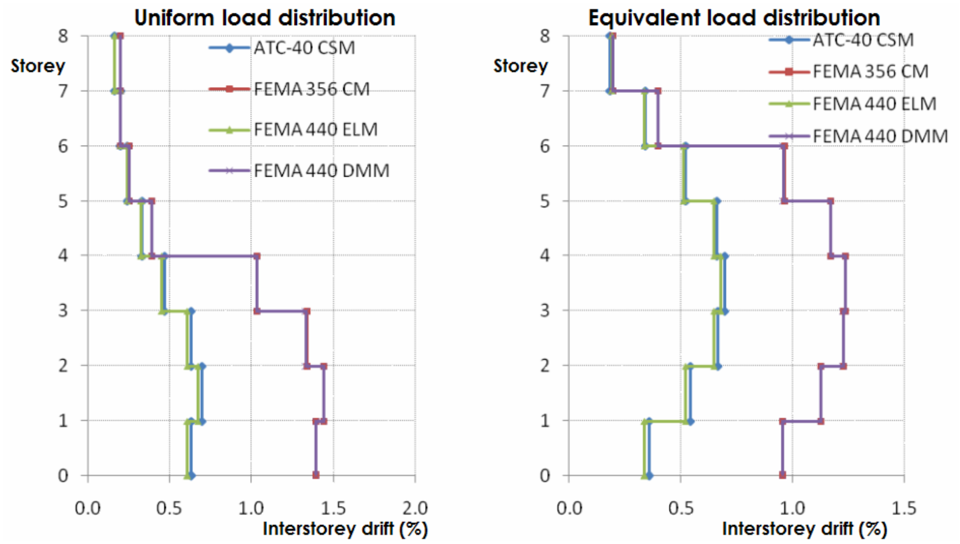


Figure 12. Distribution of interstorey drifts of regular eight-storey frame

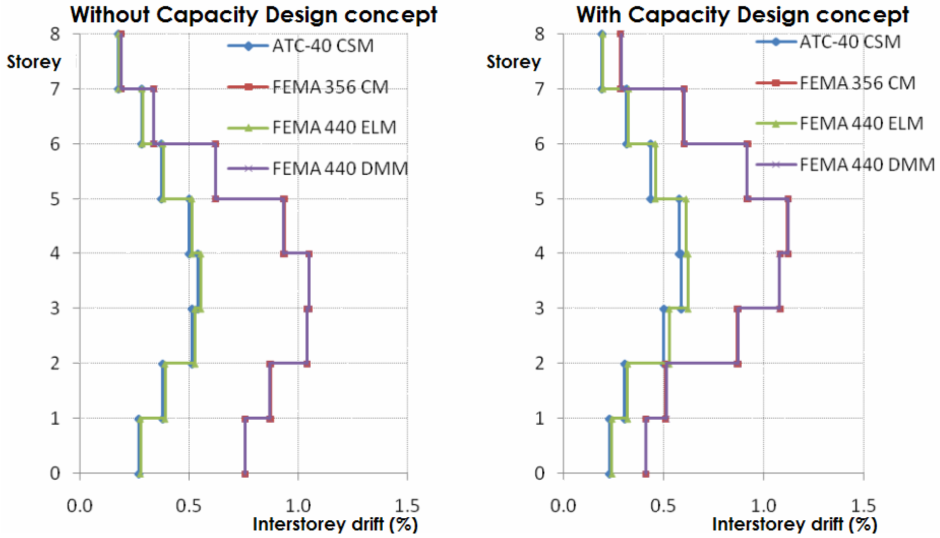


Figure 13. Distribution of interstorey drifts of irregular 8-storey frame – uniform distribution of lateral loads

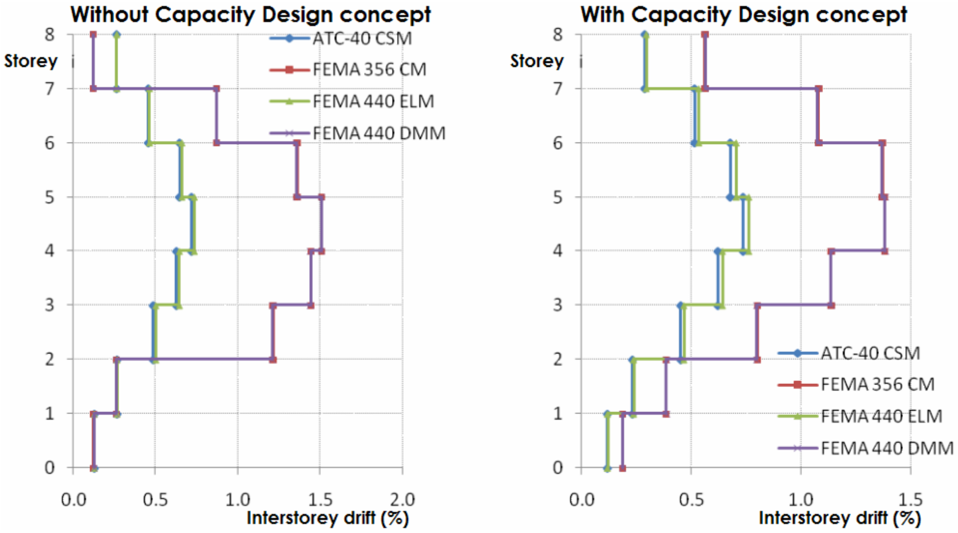


Figure 14. Distribution of interstorey drifts of irregular 8-storey frame – equivalent distribution of lateral loads

4. CONCLUSIONS

The paper presents application of various analysis methods, which are used for the estimation of the structural behaviour under seismic action. They are based on the simplified procedure that combines nonlinear static (pushover) analysis and response spectrum method. Two mathematical models were used for the seismic analysis of multi-storey frames. One mathematical model is a system with multi degrees of freedom, and the other is an equivalent system with one degree of freedom. To calculate action effects of the MDOF model, the nonlinear static analysis is used to develop the pushover curve, which is then idealized to determine the characteristics of the equivalent SDOF system. The target displacements of considered regular and irregular frame structures with different stories are performed using CSM, ELM, CM and DMM.

The most important parameters that can be determined from the developed pushover curves are: stiffness, yield strength and ductility of considered multi-storey structures. Uniform distribution of lateral loads leads to higher values of the base shear force in relation to the equivalent and modal distribution. It is obtained as for four and also for eight-storey frame. However, with uniform distribution less target displacement is obtained than with the equivalent and modal distribution of lateral loads. Also, smaller ductile behaviour is achieved by using uniform distribution in relation to the equivalent and modal distributions – this is particularly expressed in four-storey frame. Adaptive analysis also points to smaller ductile behaviour as for four and also for eight-storey frame.

Comparing methods of analysis for estimation of inelastic storey deformations it can be observed two groups of method according to similarity of obtained results. The first group includes capacity spectrum method and equivalent linearization method, and the second group contains coefficient method and displacement modification method. Methods that belong to the first group provide lower values of the target displacements and distribution of interstorey drifts than when using methods that belong to the second group. The results indicate that the distribution of interstorey drifts over the height of structure significantly depends on the number of stories, regularity of structures, lateral load distribution and applied design concept. Increase of the height of structure leads to highly unequal distribution of inelastic storey deformations along the structure height. Thereby, the distribution of interstorey drifts in tall buildings much more depends on the distribution of applied lateral load distribution than in low-rise buildings (Ladjinovic *et al*, 2009). For all the applied distribution of lateral loads were obtained almost identical levels of strength capacity, stiffness and ductility. This indicates that the regular frames that are sized according to preliminary design using simplified method of analysis can develop favourable plastic mechanisms.

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