METHODOLOGY FOR SEISMIC DESIGN OF R/C BUILDING STRUCTURES

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SUMMARY

Two methodologies for aseismic design of R/C buildings are presented in the paper: Displacement-based design-DBD [Kowalsky, Priestly and MacRae, 1994] and RESIST-INELA [Necevska-Cvetanovska, 1992]. DBD is a new procedure for aseismic design where the input design parameter is the target displacement and the strength and the stiffness of the structural system are not variables but end results in the iterative design process. The methodology and RESIST-INELA computer package, (developed at IZIIS), which are used for design and seismic evaluation of the R/C buildings is also iterative until the definition of optimal seismic forces and optimal structural system. In the paper are present the details of the both methodologies and their advantages in relation to the traditional design procedures.

INTRODUCTION

The definition of a method for design and evaluation of the seismic resistance of R/C building structures is a wide and complex problem. 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 to 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 for coming to 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 a fast and simple evaluation of the seismic resistance of the newly designed and existing reinforced concrete buildings of small and moderate number of stories. In fact, the developed method incorporates the latest knowledge gathered in our country and the world-wide experience from the broad fields of the earthquake engineering: determination of strength and deformability characteristics of the building, on one hand, and definition of the nonllnear behaviour of the structure for a given earthquake effect, on the other hand.

The idea of using displacement in the design process is not a new one. In 1974, Gulkan and Sozen discussed that the design of the structure could be modelled as a single degree of freedom system. That work formed the basis of the so-called "substitute structure approach". The substitute structure is an elastic structure that has the same peak force and peak displacement characteristics as the inelastic structure. This modelling is required because Displacement -based design (DBD) procedure used an elastic response spectra for the design of a structure that is expected to have inelastic deformation in the design level earthquake. DBD procedure is alternative seismic design procedure that designs the structure for the requirements based on the displacements rather than forces. The only initial design input parameter is the maximum allowable displacement. Design forces, stiffness and reinforcement details all become dependent on the target displacement. Presented in the paper are the main characteristics of these two methodologies for seismic design of R/C structures.

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METHOD FOR DESIGN AND EVALUATION OF THE SEISMIS RESISTANCE OF REINFORCED CONCRETE BUILDINGS, DEVELOPED AT IZIIS - SKOPJE

The method for design and evaluation of the seismic resistance of reinforced concrete buildings, developed at IZIIS [Necevska-Cvetanovska,1992], consists 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 1a: Determine the geometry, weight and masses of the structural members

Step 1b: Determine the vertical and seismic loads

Step 1c: Performed the elastic analysis of 3D structural building system

Step 2: Design and determination of the Q-Δ diagram for each element, separately, and the storey Q-Δ diagrams

Step 2a: Design of the structural elements, (RESIST-computer program)

Step 2b: Determine M-ϕ for all structural elements

Step 2c: Determine the correction factor R (mechanism for appearing of the first cracks)

Step 2d: Determine Q-Δ diagram for each element

Step 2e: Determine storey Q-Δ diagrams for the building structure

Step 3: Definition of the seismic parameters and the design criteria.

Step 4: Nonllnear 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.

Step 4a: Determine the period of the building structure

Step 4b: Determine the maximum acceleration, velocities and displacements at the storey level for different earthquakes and different hysteretic modelling of nonlinear behaviour of the system

Step 4c: Determine the required ductility and the required displacement

Step 5: Evaluation of the seismic resistance for the designed or existing structure

Step 5a: Compare the required displacement with the displacement capacities of the structural members

Step 5b: Compare the required ductility with ductility capacity of structural members

Step 5c: Check of bearing capacity of structural members to shear forces

Step 5d: Evaluation of the seismic resistance for the given building

Step 5d-1: if it is good the procedure is finished

Step 5d-2: if it is poor that the procedure starts again with Step 1, (correction of geometrical characteristics and/or strength characteristics of structural members and repeating the procedure until the optimal structural design is performed)

Presented further are the detail explanation of this methodology as well as an example of the R/C building design according to this methodology.

Step 1

The initial step for design and evaluation of the seismic resistance of a building is the definition of the structural system of the building as well as the quantity and the quality of the built-in material of the existing building.

On the basis of the defined schemes of frames and walls distribution with the proportions of the elements and the defined vertical loads and seismic forces, elastic analysis of the structure is carried out applying TABS computer program.

Using a special REINF.DAT database, the quantity and the quality of the used steel reinforcement for each structural element cross sections (columns, walls and beams) are entered. By the related computer programs, developed by the author for each cross section for the whole building, the internal forces M, Q and N are arranged for each structural element, i.e., frame-wall, in the columns and beams and for each loading pattern. The databases, prepared in this way, are ready to be used with the RESIST computer program for step 2.

Step 2

The strength and deformability characteristics of each element of the building can be determined applying the RESIST computer program (Golubka Necevska-Cvetanovska), by which, starting with the elastic analysis of the structure performed applying the TABS program and the known quantity and quality of the built-in steel reinforcement and the attained compressive strength of the concrete in all the cross sections of the elements (columns, beams and walls), for each storey element, separately, it is possible to obtain the yield displacement δy, the shear force at yielding Qy, the maximum displacement δu, the shear force at maximum displacement Qu. At the same time, the shear strength of each element of the building is determined, according to the Arakawa and Ohno method taking into consideration that no shear failure of the element occurs. Having the Q-Δ diagrams for each element and storey, applying the QD.FOR computer program summarising of the Q-Δ diagrams is carried out and the storey Q-Δ diagrams are obtained.

It should be mentioned that the method for determination of the displacement at yield point is based on the known fact that the curvature diagram of the column corresponds to the shape of the bending moment diagram, since the moments are still in the initial linear range of the moment-curvature relationship. The curvature of the column differs for different stories due to the different properties of the cross sections and the level of the axial load. The horizontal displacement of any storey can be determined as a sum of the moments of the areas of the curvature diagrams in respect to that level. Using the RESIST computer program it is possible to follow the moment diagram obtained by the TABS computer program for each storey and it is possible to determine the correct inflexion points at each column line, thus defining the failure mechanism at each joint, separately. Thus, the correction factor Ri can be determined in the following way (Figure 1):

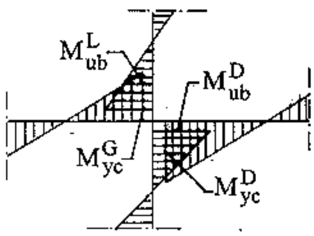

Figure 1. Moment diagram at the joint

$$R_i = \frac{M_{ub}^{L} + M_{ub}^{D}}{M_{yc}^{D} + M_{yc}^{G}} \tag{1}$$

Ri - correction factor for i-th storey

Mub - ultimate moment of beam left and right

Myc - yield moment of column up and down.

In the case of development of a plastic hinge in the beams (Ri<1), it is necessary that ϕy and My of the columns experience adequate corrections (i.e., be decreased since after the development of plastic hinges in these cross-sections, full moment and yielding rotation are not possible to develop in the column).

By correct definition of the inflexion points and the corrected ϕ-values (where necessary) the known procedure for determination of ϕy and Qy in the elements should be continued During the determination of the horizontal displacements of reinforced concrete walls bending and shear deformations are taken into consideration.

The storey Q-Δ diagrams represent the basis for further nonlinear dynamic analysis of the building.

Step 3

The seismic parameters and design criteria can be determined on the basis of the seismic parameters of the earthquake effect, which in turns can be determined by complex analyses of the regional and local seismological properties of the building site. On the basis of the actual and the local site properties, applying probability methods, evaluation of the seismic hazard parameters is carried out according to which expected maximum ground accelerations for 50, 100, 200 and 500 year return periods are possible to be defined. For this purpose, several time histories with corresponding frequency content are suggested to be used for further dynamic analysis.

After having defined the Q-Δ diagrams for each storey of the building and the seismic parameters of the site of the building, dynamic analysis of the structural system of the building can be carried out.

Step 4

In addition to have studied a large number of experimental and analytical investigations aimed at more realistic definition of the capacity of the structural system of the building, and more realistic selection of corresponding seismic parameters for the given site, intensive investigations have been performed aimed at defining different hysteretic models through which it is possible to carry out the most realistic presentation of the behaviour of the structural system under a given earthquake effect.

The computer program INELA (INELastic Analysis by Golubka Necevska-Cvetanovska) is used for nonlinear analysis. 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 response analysis of such an idealised structural system, for an arbitrary ground motion is brought to a solution of a second order differential equations, with time variable coefficients. The input data of the mathematical model are: the masses, storey rigidity, yielding point and plasticity line (obtained by step 2), then the damping and record, in terms of ground acceleration time history. As a result or the storey displacements, the velocities and the accelerations for the required portion of a second during the earthquake effect are obtained.

The application of these computer programs makes possible selection of different hysteretic models depending on the structural type and obtaining responses for a large number of ground acceleration time histories, due to the relatively short computer time requirements and the satisfactory accuracy of the analysis for practical purposes.

The storey drifts, the storey shear forces, the relative velocities and the absolute accelerations, obtained as a result of the analyses, represent the basis for step 5 for evaluation of the seismic resistance of the considered structure.

Step 5

The results obtained by step 4 (relative storey drifts) are entered in the storey Q-Δ diagrams, i.e., in the Q-Δ diagrams for each structural element, and then it is obvious which earthquake record and which intensity can cause the occurrence of initial cracks, yielding and even failure of the structural elements of the building. The evaluation of the seismic resistance of the considered building can be defined by comparison of the nonlinear response "requirements" of the building to the earthquake effect with the ultimate "capacity" of the building.

During the design of new structures if the results satisfied the required criteria for strength and defomability the analysis is finished. If not the geometry, strength and /or stiffness characteristics of structural elements are changed and the procedure is repeat from step 1 to step 5 until the optimal structural design is performed.

Application of the IZIIS methodology for design of R/C building structure - example

The methodology developed at IZIIS is used for design of new building structures as well as for evaluation of the seismic resistance of the existing building.

To conceive the individual aspects and requirements prescribed by Eurocode-8 (EC8) and compare the requirements and criteria to the national seismic codes (SP-81) and methodology developed at Institute of Earthquake Engineering and Engineering Seismology-IZIIS, Skopje, several structures were analysed. Presented in the paper will be the results from the analysis of a structure (a frame structural system - eight storeys) constructed in the territory of the town of Skopje, [9]. First the structure was designed only in accordance with our existing regulations (results SP - 81) and then it was designed in compliance with EC8. The results from both analyses were compared to the results obtained during the design of the structure in 1993, using the presented methodology.

Table 1 shows the forces obtained according to SP - 81, EC8 and the optimised forces obtained in IZIIS (by using this methodology) and considered in the design of the structure.

Table 1. Seismic forces [kN] obtained according to SP-81, EC-8 and IZIIS

Storey	SP-81		EC-8		IZIIS	
	x-x dir.	y-y dir.	x-x dir.	y-y dir.	x-x dir.	y-y dir.
8	645.5	825.3	823.5	970.7	700.0	700.0
7	313.3	400.5	727.7	857.8	700.0	700.0
6	270.4	345.7	628.1	740.5	700.0	700.0
5	227.5	290.8	528.6	623.1	600.0	600.0
4	184.6	236.0	428.9	505.7	500.0	500.0
3	141.7	181.2	329.3	388.3	400.0	400.0
2	98.9	125.4	229.8	270.9	300.0	300.0
1	59.2	75.8	137.9	162.5	100.0	100.0
Sb=ΣQ/W	7.65%	9.78%	15.1%	17.8%	15.8%	15.8%

The design results show that the seismic forces defined by the methodology developed at IZIIS by prof. G.N.Cvetanovska are very closed to the results obtained according to EUROCODE 8, (table 1).

DISPLACEMENT-BASED DESIGN PROCEDURE

Application of DBD procedure for the design of single degree of freedom system

Displacement -based design (DBD) procedure is an iterative process where the end results is the required strength and stiffness of the structural system. In the DBD procedure, the substitute structure approach is used to characterise the response by the equivalent stiffness to maximum displacement response. An equivalent damping is used based on the expected hysteretic characteristics and ductility level. The response is than based on final secant stiffness and hysteretic damping rather than initial stiffness and elastic damping.

DBD procedure for seismic design of single degree of freedom system, [Kowalsky, Priestly & MacRae, 1994] is summarised in the six steps as follow:

Step 1: Choose Initial Parameters

Step 1a: Establish column axial load and column height

Step 1b: Choose material properties

Step 1c: Establish the target displacement, Δu

Step 1d: Choose effective damping relationship

Step 1e: Choose a displacement response spectra

Step 2: Calculate Parameters Leading to Effective Stiffness

Step 2a: Select the starting value for the yield displacement, Δy

Step 2b: Calculate the initial ductility, μ

Step 2c: Determine the effective damping, ξ

Step 2d: Determine effective period, Teff

Step 2e: Determine the effective stiffness, Keff

Step 3: Determine the Ultimative and Design Forces and Moments

Step 3a: Determine the ultimative force, Hu and ultimative moment, Mu

Step 3b: Determine the design force, Hd and design moment, Md

Step 4: Design the Column

Step 4a: Estimate the initial column diameter

Step 4b: Design the column rebar

Step 4c:Estimate moment of inertia of the cracked section

Step 4d: Calculate stiffness of the cracked section

Step 5: Optional Steps

Step 5a: Calculate the period of the cracked section, Tcr

Step 5b: Calculate the post yield stiffness and period, Keo and Teo

Step 5c: Determine problem status

Step 6: Obtain Revised Yield Displacement and Check convergence

Step 6a: Calculate the yield displacement, Δy

Step 6b: Check convergence

Application of DBD procedure for the design of multi degree freedom system

Extension of the DBD methodology to MDOF buildings, [Calvi&Pavese, 1995] is based on assumed deformation shapes in height. Another method within the DBD procedure [Fardis&Panagiotakos, 1997] considers DBD as a part of the overall structural design, including also an ultimative limit state design versus gravity loads and high probability seismic event. DBD procedure for design of MDOF buildings are summarises in 7 steps:

Step 1: Beams and walls are dimensioned in bending for a) gravity loads ($\gamma gG+\gamma qQ$) and b) for a high probability seismic action Es, associated with quasi-permanent loads $G+\psi 2Q$ (equivalent lateral seismic force method)

Step 2: Columns are dimensioned in bending for a) as above and b) from capacity-design calculations, whichever is controlling

Step 3: Shear dimensioning of beams and columns via capacity method (end-moments from Steps 1,2). Design shear forces for walls: From Step 1, magnified by the capacity ratio of the base cross-section

Step 4: Calculation of the fundamental period T of the building, based on the secant-stiffness at the yield of all members, Ky=l*My/6*θy, where θy is estimated according to Park&Ang (1985)

Step 5: For this T-value, spectral displacement values du are read from the 5%-damped elastic response spectrum corresponding to the "life safety" seismic action. (The method relies on the "equal displacement" rule for relatively large T-values, and avoids the use of rather uncertain inelastic spectra)

Step 6: Chord rotation demands θu=du/l at critical regions are now calculated for each structural member ("l" denoting appropriate member length depending on the failure mechanism observed) and compared to the values of θu,av (available rotation capacities from conservative empirical formulae)

Step 7: Final dimensioning and detailing to satisfy Step 6. Member dimensions may be adjusted, compressive reinforcement may be increased, web reinforcement will be finalised. Normally, an iteration to Step 4 is not needed

CONCLUSIONS

- Methodology for design of seismic resistance buildings (RESIST-INELA) is based on the modern principles and trends for design of seismic resistance buildings.
- The results present in the Table 1 show that the seismic forces defined by the methodology developed at IZIIS are very close to those defined according to Eurocode 8.
- Mathematical model for nonlinear analysis with RESIST-INELA methodology is shear -type model with "n" concentrated masses and input design parameter is time history of acceleration. In the displacement-based methodology the input design parameter is displacement response spectra.
- In the both methodologies the parameter for evaluation of seismic resistance of the building is displacement so the advantages of these methodologies over the traditional design practice is obvious:
    - displacement are the better indicators of damage than forces
    - behaviour of non-structural elements are control by structural displacement
    - better control of P-Δ effect
    - direct information for design of transverse reinforcement
    - control of the plastic deformation

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