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NEW HYSTERETIC MICRO-ANALYTICAL MODEL AND ENERGY BASED CRITERIA FOR EARTHQUAKE DAMAGE PREDICTION OF TRADITIONAL AND BASE-ISOLATED STRUCTURES

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ABSTRACT

In this paper are presented the latest results obtained from the recently completed study by the authors as a part of the conducted long-term investigation devoted to development of damage-limiting seismic resistant design concept, at the Institute of Earthquake Engineering and Engineering Seismology, Skopje. The performed integral study actually resulted in the following two principal achievements: (a) Formulated and proposed are a new hysteretic micro-analytical models and energy-based criteria for earthquake damage prediction of both traditionally constructed and base-isolated structures; and (b) Developed is a corresponding special purpose computer software NORA-VUL, which can be very successfully used for advanced design of seismic resistant structures implementing the above mentioned "damage-limiting-design concept". The achieved possibility for refined analysis of progressive seismic damage accumulation in both structural and non-structural elements of the integral structure, along with the full-evidence into time distribution of hysteretic energy absorption, actually represent the most significant advantage of the developed original concept briefly described and discussed in this paper.

KEYWORDS

Hysteretic model; earthquake damage; traditional structures; base-isolated structures; hysteretic energy: damage criteria; damage-limiting design; demand; supply.

INTRODUCTORY REMARKS

During the last two-three decades, a significant progress has been made in the field of earthquake engineering, generally as a result of advanced studies successfully performed in the world leading earthquake engineering centers. However, and unfortunately theoretical knowledge in this field has not been appropriately transferred to practice up-to date. Considering that most of seismic design codes were so much "by default" simplified in the past (from practical applicability reasons), today quite reverse effects are observed: catastrophic damage and total collapse of modern structures during recent strong earthquakes (remember Mexico City, USA, Armenia, Japan, etc.). Knowing this, and considering the present high technological achievements, including sophisticated and low-cost PC computers, the authors have recognized the importance of proposing regular future application of "expert design approach " which should be viewed as a natural qualitatively new step in reliable structural seismic protection with minimized seismic risk level. This goal can be best achieved through adoption and application of new advanced "damage-limiting design concept" based on developed "automated computer simulation procedure". Considering such general target, extensive study devoted to development of "advance damage-limiting design concept" have been carried out at the Institute under the guidance of the first author during the last decade (Ristic, 1988, 1992, 1994; Ristic, et al. 1994). The integral study has been basically concentrated on the following three principal objectives: (1) Development of a consistent methodology for successful earthquake damage prediction of integral structures; (2) Adopting of advanced "damage-limiting design concept" for improved earthquake resistant design of new structures; and (3) Promotion of the same concept as advanced method for optimization of retrofitting measures to be taken for existing structures with full seismic-vulnerability control.

THREE CONCEPTS OF EARTHQUAKE RESISTANT DESIGN

In the light of the conducted up-to date studies and the last earthquake consequences, the authors can propose application of three basic concepts for earthquake resistant design: (1) Conventional design approach, (2) Advanced capacity design approach, and (3) Expert design approach including Structural expertise. The first two concepts are commonly in use today. The third concept should cover the most recent advances in the field, providing reliable structural seismic protection with minimized seismic risk level. This improved method of "damage-limiting" structural design will be more closely discussed in this paper. The most basic proposed steps of this concept are the following: I) Preliminar design of the structure; II) Analysis of section design forces under relevant loads defined on the basis of codes; III) Design of structural components applying the "capacity design approach", and IV) Expert design verification based on application of the following steps: (a) Formulation of totally nonlinear structural model, (b) Selection of representative records or synthetic earthquakes, (c) Computation of nonlinear structural response, (d) Prediction of damage level of structural and nonstructural elements, (e) Structural vulnerability analysis under design and maximum expected earthquakes, (f) Damage-loss assessment and system modification, if necessary.

IMPROVED METHOD OF "DAMAGE - LIMITING STRUCTURAL DESIGN"

Analytical prediction of structural damage is carried out by relating the actual earthquake demands defined from refined micro-model based nonlinear seismic response analysis, and the element supplies defined by appropriate element capacity analysis. It is known that element damage, under dynamic load, is generally produced due to combined effects of the cyclic stresses and large strain or deformation excursions in the nonlinear range (Park, Y.J., et al. 1987). To simulate this, in the present damage criteria separately is considered the cyclic load effect via absorbed seismic (hysteretic) energy combined with calculated extreme section or member deformations during structural earthquake response (see Equation 1).

$$\delta^*_{extr} = \left(\frac{\delta_{extr}}{\delta_{U^*}} + \frac{\int dE}{f_E E_{ref}} \right) \delta_{U^*} = \delta_{extr} + \frac{\int dE}{f_E E_{ref}} \delta_{U^*} \qquad (1)$$

The parameters used in the above equation physically represent the following: δ^*_{extr} - equivalent extreme deformation, δ_{extr} - extreme deformation, δ_{U^*} - deformability capacity of the element or its interface under gradual one-way loading, dE - absorbed hysteretic energy in the element or its interface, E_{ref} - referent energy, f_E - energy capacity factor, $f_E{*}E_{ref}$ - referent energy absorption capacity.

To demonstrate the applicability of the micro-analytical model for prediction of earthquake damage and expected failure mode of a complete structure under earthquakes of variable intensity, the behaviour of an actual nine-storey three-span frame was analyzed. In the first case (model M1), the frame was considered to be composed only of structural reinforced-concrete elements (beams and columns), while in the second (model M2), a masonry infilling was considered to be incorporated in the end spans of the same frame (Zisi, N., 1995).

Nonlinear behaviour of structural RC members (beams and columns) was modeled by developed micro-nonlinear finite element. The distribution of nonlinearity along this element was controlled by specifying a certain number of M-φ relations computed for each of the considered interface elements (Ristic, D., 1988 and Oncevska, S., et al. 1994). By introducing of the appropriate number of interface elements along the finite element, an advanced concept of micro-modeling was introduced (Fig. 1). In the present study for simulation of the hysteretic M-φ behaviour of the interface elements during the dynamic response the following was adopted: (1) Bi-linear model, with excluded tension stresses, simulating σ-ε relationship of concrete under compression which is used for tracing the current axial stiffness of the interface element, and (2) Tri-linear anvelope M-φ relationship defined for a constant level of axial force under gravity loads (Hristovski, V., et al. 1994) and the Takeda's hysteretic model, to simulate current bending stiffness of the interface elements (Fig. 2).

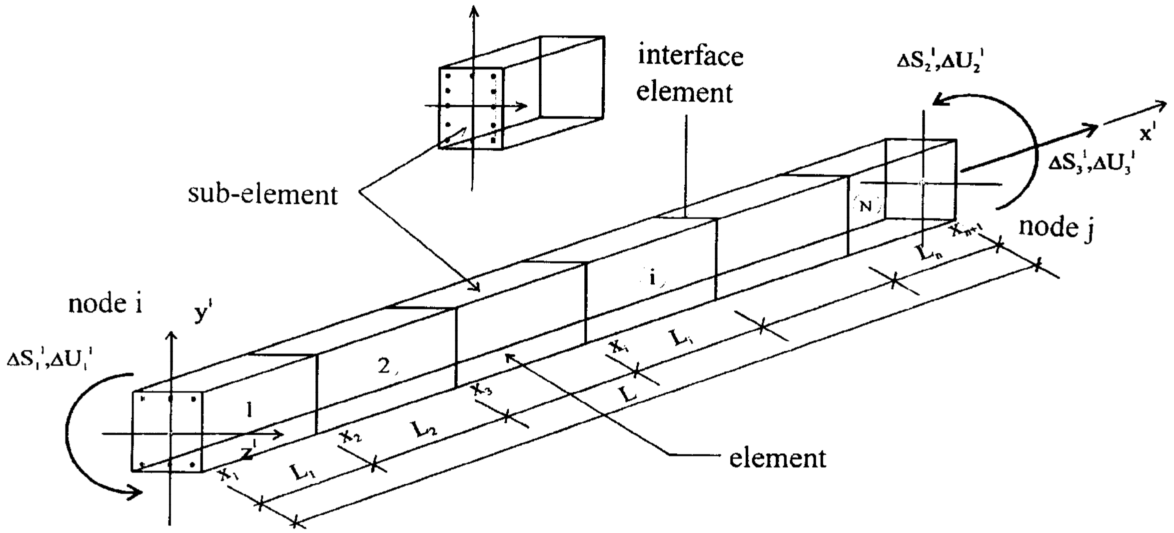
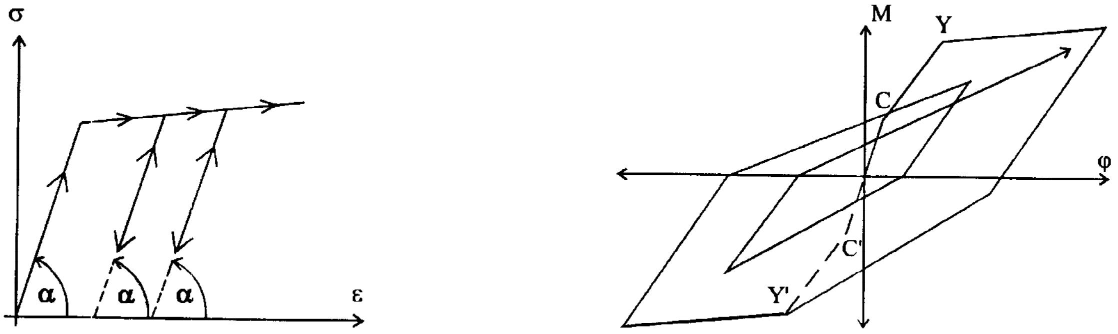


Fig. 1. Non-linear multi-interface finite element (NON-MIFE1) developed for simulation of distributed nonlinearity and prediction of propagated earthquake damage through structural members



(a) (b)

Fig. 2. Family of hysteretic moment-curvature relations implemented for inelastic behaviour modeling of RC, SRC, and steel structural sections. See: a) Bilinear model, b) Takeda model

For modeling of the nonstructural masonry infill, applied was the general nonlinear spring element (Fig. 3). Since masonry infill generally exerts a shear behaviour only the hysteretic relationship between force and relative displacement in the lateral direction of the frame is presently considered in the above mentioned general nonlinear spring element. The behaviour of masonry was assumed by the originally developed hysteretic model 'Infill' (Fig. 4) from which the masonry shear stiffness was defined at each discrete time moment.

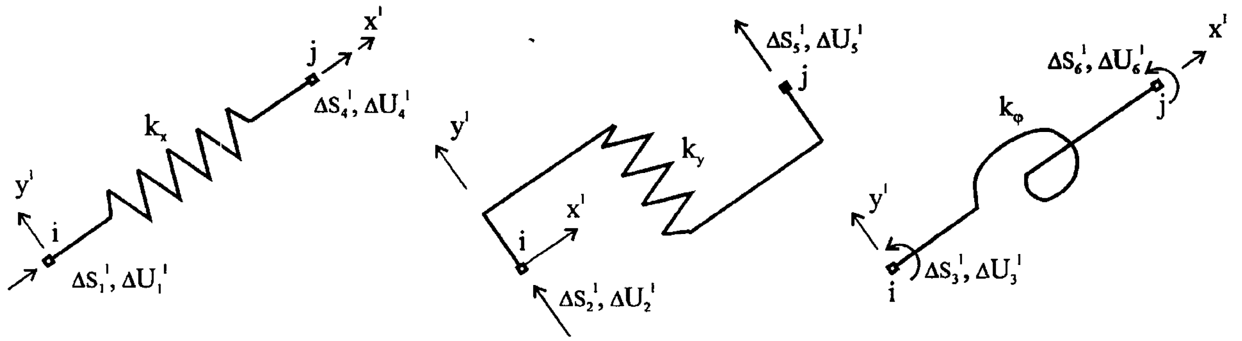


Fig. 3. Non-linear phenomenological spring-type component models developed for inelastic behaviour simulation of special structural, non-structural, base-isolation and vibration-control components

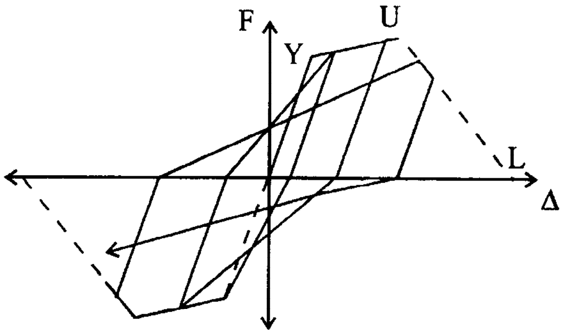
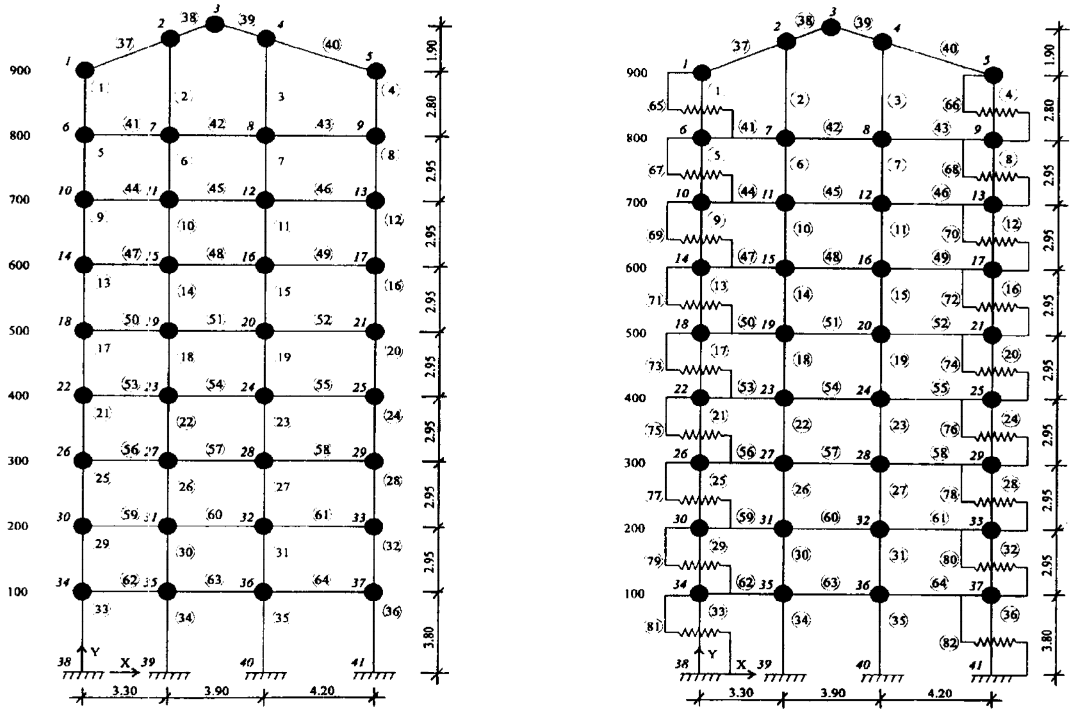


Fig. 4. Hysteretic phenomenological model developed for inelastic behaviour simulation of various constituent infill-type structural components

Using the defined nonlinear finite elements, simulating the behaviour of the structural and nonstructural components, corresponding mathematical models of both frame structures, without and with an infill, were formulated (Fig. 5).



(a)

(b)

Fig. 5. Formulated non-linear earthquake damage prediction models of a conventional structure: a) pure frame system, model M1; b) frame with brick masonry infill, model M2

The implemented mathematical models of both structures actually represent two-dimensional models with a full number of degrees of freedom and masses lumped at the corresponding nodal points at the level of the floor structures. With these evidently complex mathematical models, an attempt was made to present, as realistically as possible, the behaviour of all the constituent structural elements (beams and columns) as well as the behaviour of the used nonstructural elements (masonry infilling), in the second structure case.

For getting an insight into the respective dynamic response characteristics of the models M1 and M2 under different earthquake excitations, both in the elastic and inelastic range, nonlinear dynamic analyses of both structures were performed by using the NORA program (Ristic, D., 1988) and two selected earthquakes: El Centro and Ulcinj-Albatros, scaled to intensities starting from PGA = 0.1g to PGA = 0.5g.

The demands of the elements, or interface elements were obtained in the form of an equivalent extreme deformation calculated by superposition of the extreme deformation reached during the response and the contribution of the cyclic loading effect included based on computed absorbed hysteretic energy (Park, Y.J., 1987 and Zisi, N., 1995).

Knowing the supplies, i.e., the deformability capacity of the elements, or corresponding interfaces and applying the formulated criteria for damage evaluation (Fig. 6), full quantification of damages at each interface element, as well as quantification of damage degree to all nonstructural elements was carried out. Typical distribution of the hysteretic energy absorption in both structural and non-structural elements is shown in Fig. 7. These energy distribution plots can be closely related to the actual structural earthquake damage distribution patterns.

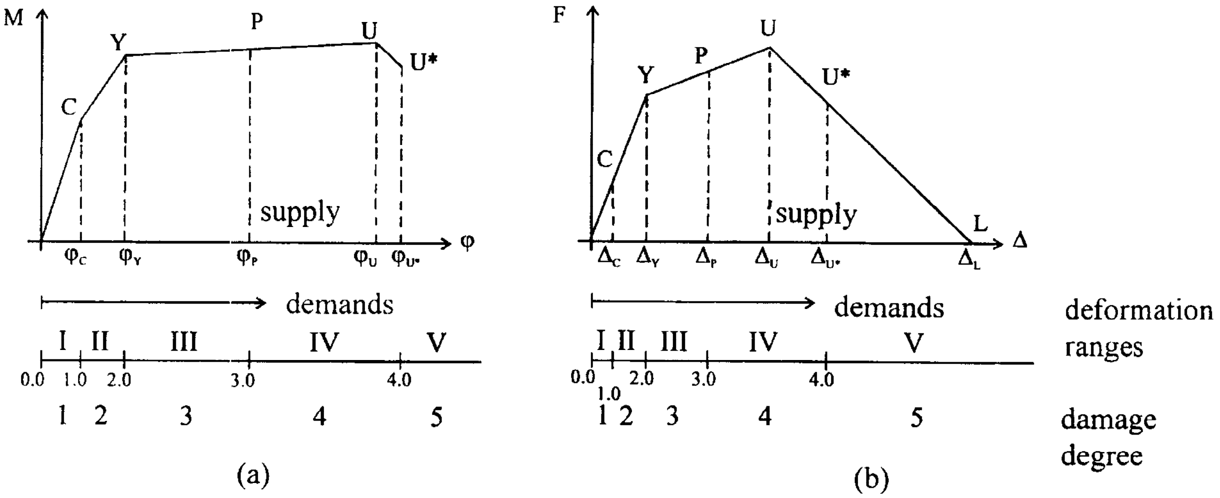


Fig. 6. Energy-based earthquake damage criteria relating the corresponding envelope curve and cumulative hysteretic energy absorption. Typical envelope curves for structural elements (a), and nonstructural infill elements (b)

The analyses performed for the frame model without and with infill under the effect of both the selected earthquakes showed that with the increase of the excitation intensity, the greatest plastic deformations and hence the most extensive damage occur dominantly in the beams in both cases which can be considered as a favorable failure mode for these structures.

However, the infilled frame showed a significant initial stiffness increase. This fact was the main reason to identify a higher level of damage in this frame as well as respective modification of the dynamic characteristics of the structure with progressive element load redistribution.

After the performed nonlinear dynamic analyses and corresponding damage categorization, the analytical vulnerability function was defined for the frame model with infilling (Ristic, D., 1992 and Petrovski, J., et al. 1992) (Fig. 8).

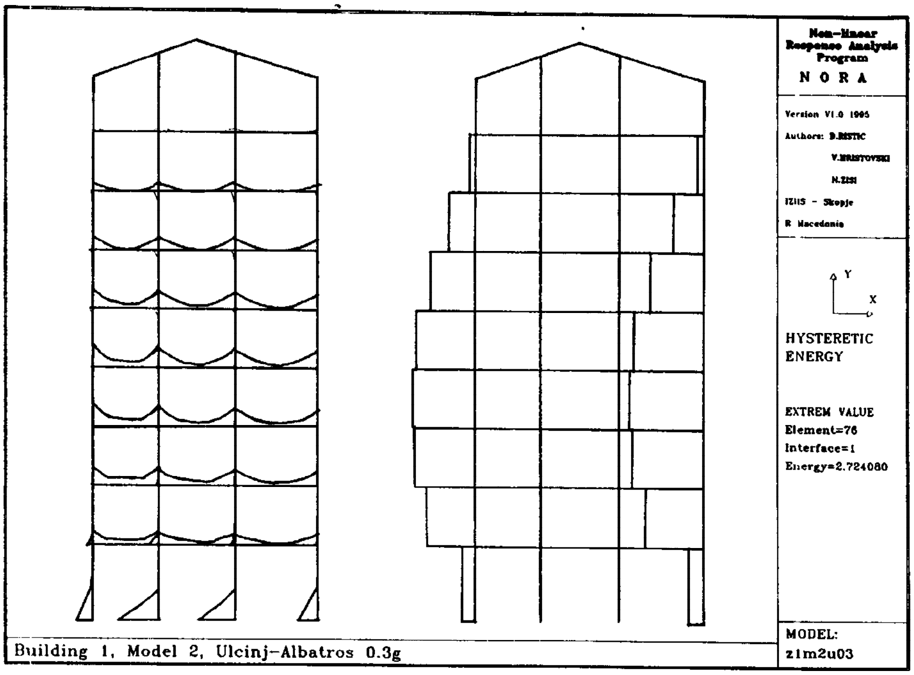


Fig. 7. Typical distribution of hysteretic energy absorption by structural elements (a), and nonstructural infill elements (b) under strong earthquake ground motion (Ulc-Alb eq., comp. N-S, $A_p = 0.3g$)

While defining the vulnerability function, the repair cost of the elements was introduced through the so-called specific loss-functions defined at an element level. The element repair cost was taken as percentage of the original element cost which is defined in advance with full consideration of the type of element, its proportions and location in the structure.

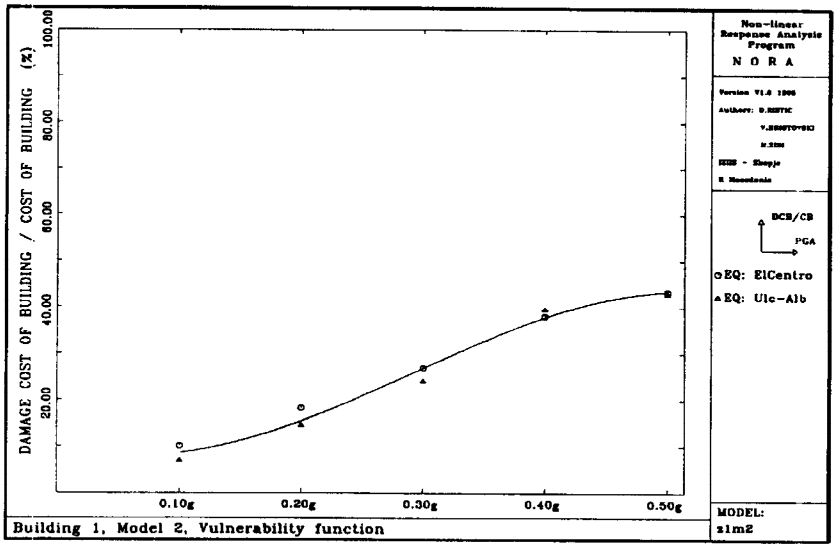


Fig. 8. Predicted earthquake vulnerability function of the analyzed conventional structure with brick masonry infill (model - M2)

The adopted concept capable of predicting structural damage or structural earthquake vulnerability, actually represents an advantageous strategy in reliable structural earthquake resistant design, adopting advanced "damage-limiting design approach". For example, from the shown vulnerability function of the infilled frame, it was observed that the seriously damaged infill actually created a considerably high level of damage repair cost, although the integrity of the structure is preserved, even under the strongest earthquake intensities.

PRINCIPAL ADVANTAGES OF MICRO-MODELING STRATEGY AND CONCLUSIONS

The developed micro-analytical model and energy based criteria for earthquake damage prediction actually represent the key qualitative contribution to the proposed "Advanced Damage-Limiting Design Concept" applicable for successful earthquake resistant design of conventional and base-isolated structures with full damage propagation control. With realization of this long-term study, generally concentrated on application of micro-modeling strategy, the authors have made a significant step forward in modern expert earthquake resistant design of important structures, with the following principal advantages: (1) Developed is an advanced and fully-consistent structural earthquake damage prediction methodology; (2) Developed is an original computer software with confirmed practical applicability; (3) Adopted is an option of advanced generalized methodology applicable for design of conventional structures, base-isolated structures and structures including special antiseismic and vibration-control devices; (4) Generalized is a global structural modeling capability providing application of: (a) Linear models, (b) Partly non-linear models, and (c) Total nonlinear models; (5) Generalized are theoretical analysis approaches including capabilities for: (a) Independent static linear and non-linear analysis; (b) Static linear and non-linear analysis under time-dependent loads, and (c) Linear and non-linear time-history response analysis under synthetic or real recorded earthquakes; (6) Adopted is an advanced and systematic component-modeling approach providing options of both linear and non-linear behaviour simulation of various components: (a) Structural elements, (b) Nonstructural elements, (c) Special in-structure-installed elements, (d) special supporting elements, etc.; (7) Introduced is a generalized modeling concept of inelastic element behaviour at three levels: (a) Simplified P-Δ global-nonlinear models, (b) Macro-nonlinear M-φ models, and (c) Micro-nonlinear σ-ε or M-φ distributed models; (8) Considering "capacity - demand" relation, developed is improved energy-based damage criterion; (9) Generalized is a concept for structural vulnerability prediction with consideration of damage analysis at different levels: at the level of interface elements (sections), sub-elements, structural and nonstructural elements, stories, different structural classes and integral structures; and (10) Achieved is a detailed and full-evidence into required technical measures for effective structural system optimization for earthquake damage reduction.

Finally, based on experience gained form this study, the basic conclusion was that modern earthquake resistant damage - limiting design of important civil engineering structures can be successfully carried out implementing the advances of the proposed expert - design approach and micro-modeling concept.

REFERENCES

Hristovski, V. and D. Rictic (1994). Algorithm for Moment-Curvature and Moment-Axial Force Diagrams for Random Traditionally Reinforced and Prestressed Concrete Cross-Sections (in Compilance with European Standards) and Their Application in Nonlinear Analysis of Structures. Third National Conference on Reinforced Concrete Structures, Sofia.

Micov, V., D. Ristic, et al. (1994). Hysteretic Characteristics of Laminated Rubber Bearings and Modeling of Inelastic Earthquake Response of Integral Bridges. Proceedings 10ECEE, 3, 2001 - 2106.

Oncevska, S., M. Gugulovski and D. Ristic (1994). Verification of MF-NONMIFE analytical model based on results of quazi-static experimental tests of RC columns. Proc. 5th Symp. for Theoretical and Applied Mechanics, Ohrid, Republic of Macedonia.

Park, Y.J., A.M. Reinhorn, and S.K. Kunnath (1987). IDARC: Inelastic Damage Analysis of Reinforced Concrete Frame--Shear-Wall Structures. Technical Report NCEER-87-0008, State University of New York at Buffalo.

Petrovski, J., D. Ristic and N. Nocevski (1992). Evaluation of Vulnerability and Potential Seismic Risk Level of Buildings. Proceedings 10WCEE, 1, 509 - 514, Madrid, Spain, July 1992.

Ristic, D. (1988). Nonlinear Behaviour and Stress-Strain Based Modeling of Reinforced Concrete Structures under Earthquake Induced Bending and Varying Axial Loads. Ph.D. Disertation, School of Civil Engineering, Kyoto University, Kyoto, Japan.

Ristic, D. (1992). "Vulnerability Assessment of Existing Buildings and Development of Analytical Vulnerability Functions", Part-2 of Vol. IV, "Guidelines for Earthquake Damage Evaluation and Vulnerability Assessment of Buildings, Earthquake Protection of Engineered Buildings", United Nation Centre for Human Settlements (HABITAT), UNDP-UNCHS (HABITAT), Project IRA/90/004, Tehran 1992.

Ristic, D., 1994. "New Methodological Concept for Structural Diagnosis and Seismic Vulnerability Analysis of Classical and Base-Isolated Structures" (in Macedonian), Proc. 5th Symp. for Theoretical and Applied Mechanics, Ohrid, Republic of Macedonia.

Ristic, D., M. Popovski, V. Hristovski, N. Zisi, N. Nocevski, 1994. "Seismic Vulnerability Reduction of Reinforced Concrete Buildings and Industrial Halls Using Base-Isolation and Vibration Control Devices", Proceedings 10ECEE, Vol. 1: 755-760, Vienna, Austria, .

Zisi, N., "Formulation of non-linear micro-analytical model for prediction of earthquake induced damage degree of traditionally RC buildings ", Master thesis, IZIIS, Skopje, June 1995.