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CONSTRUCŢII. ARHITECTURĂ

PERFORMANCE BASED DESIGNED – STATE OF THE ART

BY

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Abstract. Natural disasters from the past 20 years lead to significant human and financial losses all around the world. The increased building density and also that of the population, in seismic areas, lead to higher losses along with the aging of the building stack and financial losses in case of business interruption. In order to reduce these losses the performance based design concept was introduced. The main objective of this innovative approach refers to optimizing the design process so that in case of natural disasters, damages are reduced to minimum. The paper presents main characteristics of this concept, some differences with the classical approach and some limitations that could be improved. The performance based design approach is owner oriented.

Key words: natural hazard; performance based design; vulnerability.

1. Introduction

The effects of Northridge (1994) and Kobe (1995) earthquakes highlighted the inadequacy of old design codes that considered the seismic response of structures for only one limit state. The bases for the modern seismic design were made in FEMA documents (Federal Emergency Management Agency in the USA), developed in 1990...2000, which was declared as the decade to combat disasters. Performance Based Design (PBD) idea started to be

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used in countries with tradition in Earthquake Engineering (Japan, New Zealand) and also the EU (SEAOC, 1995).

Performance-based approach is the way of thinking and working in terms of purpose, above means. It is based on what a building or a building element must be, and not on how to build it (Gibson, 1982). Two main characteristics are at the base of the performance concept: the use of two languages, one for the demand performance and one for the supply performance and the need for validation and verification of the results with the performance requirements (Szigeti & Gerald, 2005).

These features were included in the “Hamburger Model” proposed by Ghielingh in 1986, in the Netherlands and shown in Fig. 1 (Gielingh, 1988).

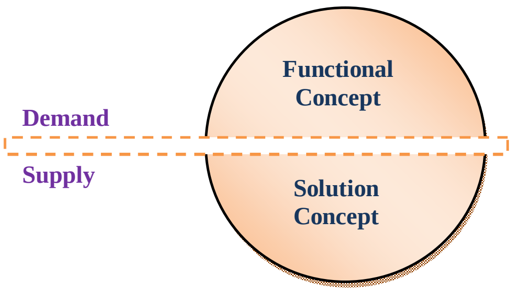

Fig. 1 – Hamburger Model.

The solution concept must fulfill the requirements of the functional concept. The difficulty comes from the fact that the two concepts are expressed in different languages. The functional concept expresses in the “owner language” WHAT and WHY the requirenents are important for the owner. The solution concept expresses in “technical language”, HOW the owner’s need will be fullfiled (Atanasiu, 2009).

Functional and solution concept are two different views of the same court. Finally, the owner must be able to verify that what he receives to move and during the life of the building is according to what he asked and what he paid. Moreover, the checking whether the solutions satisfies the requirements, are difficult because of the different languages used.

A comparison between the two concepts can be realized as soon as the functional and the solution concepts are translated into the "performance language” (Spekkink, 2005).

The performance concept may be applied to various levels of decomposition and aggregation for a structure. Housing needs expressed as a demand can produce a solution concept for the complete construction by elements of the supply. Once accepted, the solution concept for the building can be decomposed into building blocks, each of which can represent functional needs and performance requirements.

Performance-based approach does not exclude the requirements based on design rules, on the contrary is recommended to combine them. Codes regulations will be used when justified by efficiency, speed and low cost, especially if are regularly updated. PBD (Performance Based Design) is important because beneficiaries are more and more demanding when it comes to their money and expect the construction industry to focus more on the customer. To meet customer requirements, it is essential that: clients really know and understand what they need, express their requirements clearly, and also, the participants in the execution process must understand what is necessary in order to be able to provide optimal solutions to meet these requirements.

2. Performance Based Design Aproach

PBD was not introduced in order to replace the traditional design codes. Instead, it can be seen as an opportunity to consolidate and adapt building design, with the purpose of fulfilling easier the customers' interests.

PBD was first introduced in FEMA 273/274, published in October 1997, which was later re-edited in November 2000 as FEMA 356. It is generally accepted that these efforts represent the first generation of regulations for the Performance Based Seismic Design (PBSD). ASCE 41-06 replaced both versions of the FEMA regulston (Tang *et al*., 2008).

Performance based norms define acceptable or tolerable risk levels for a variety of public health, safety and well-being problems. The current list of these norms include: *International Code Council Performance Concept for Buildings and Facilities* (ICC PC) written by the International Code Council (ICC, 2009) and *NFPA 5000. Building Construction and Safety Code* (NFPA, 2009) and *NFPA 101: Life Safety Code* (NFPA, 2008), produced by the National Fire Protection Association (NFPA).

Within ASCE 7-10, "Performance-Based Procedures" represent one of three approaches for design. Under the performance based approach, both structural and non-structural components, as well as their connections must be conceived so that they fulfil also the constraints from the strength based approach. A combination of testing and analysis may be used in order to demonstrate the achievement of requirements described in the Commentary that accompanies ASCE 7 (ASCE, 2010).

In 2006, FEMA published FEMA 445, *Next-Generation Performance-Based Seismic Design Guidelines. Program Plan for New and Existing Buildings.* This document includes guidance for developing detailed modelling, simulation of building's response to extreme loading, as well as estimation of possible damages due to natural disasters. (FEMA P-424, 2010).

ICC PC defines PBD as "an engineering approach to design building elements based on agreed performance levels and objectives, engineering analysis and quantitative assessment of alternatives against the design goals and objectives using accepted engineering tools, methodologies and performance criteria".

A significant difference between the classical design method and PBD is related to objectives (Fig. 2). If, by using the classical method, the designers intend to obtain the best ratio between requirements and capacity, in PBD the purpose is to reach a certain performance level, correlated with different effects. Both methods require repeated iterations until the optimum result is obtained (Tang *et al*., 2008).

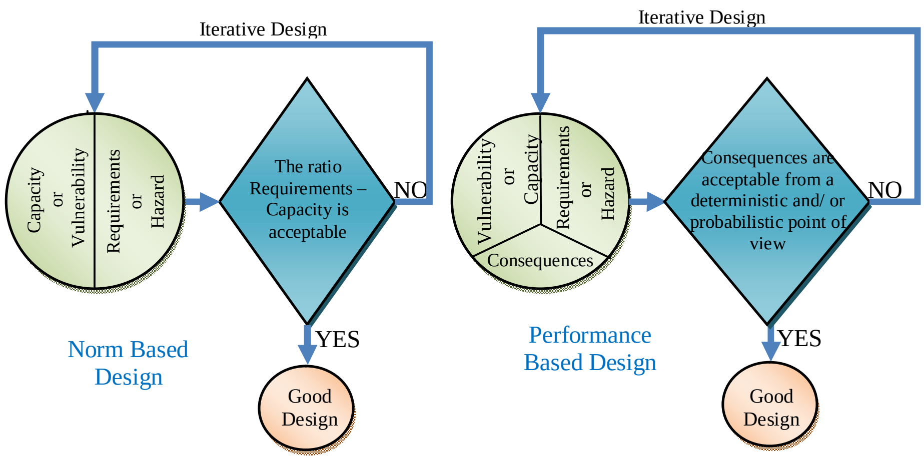

Fig. 2 – Differences between norms based design and PBD.

Another difference between the two approaches is represented by the computation bases. In the classical method, the computation is based on requirements and capacity, using structural computational methods. PBD is based on risk methods, taking into account the location hazard, building's vulnerability and their consequences. The equivalence between risk and vulnerability can be done, as well, as between requirements and capacity. However, PBD takes into account also the consequences related to hazard and vulnerability (Goel *et al*., 2010).

A third major difference refers to the steps made in the design process. In the classical design methods, the seismic hazard level and the acceptable level of degradations inside the structure are determined based on norms. In PBD, both levels are approached during the design process, together with the prediction of consequences and uncertainties from the design and analysis process. Decisions are made based on the intended performance level and not on a set of rules from the design norms.

In PBD, the decisions related to design are based mainly on the customer, who establishes the initial investment in design and construction, which leads towards the assessment of performance level and related consequences. PBD requires a greater effort in the first design stages, but it has the following advantages: long-term financial economies, the possibility of functioning immediately after seismic events and a clear image on the building's behaviour under a natural disaster/ earthquake (Tang *et al*., 2008).

PBD takes into account the uncertainties related to destructive events and evaluates the building's response. The performance capacity identification of a built system is included in the design process and it directs the decisions which must be taken.

PBD begins with selecting design criteria connected with the performance levels. Each performance level represents the accepted risk of producing different damage levels and indirect losses which can be seen as consequences. The losses can be at structural or non-structural level and can be expressed in terms of deaths, direct costs or service cost.

PBD begins with the assessment of the acceptable risk and of the appropriate performance levels for a building and its systems. The acceptable risk represents the maximum degradation level of the building, which can be accepted for a realistic risk scenario (Priestley, 2000). In ICC PC, four performance levels are formulated which correspond to four degradation levels of the building:

a) *Mild impact*: the structure is not affected and can be occupied without restrictions. The number of injured people is very low. Non-structural systems are fully functional. Inside damage is minimal and the repairing costs are small.

b) *Moderate impact*: the structural system develops minor damages and some delays are expected in the building's reoccupation. Non-structural systems are completely functional, although some repairs may be required. Emergency systems remain fully operational. Some injuries may occur, but not significant human losses. Some dangerous materials are released in the environment, but the risk for the community is small.

c) *High impact*: significant damages are produced to structural elements. Repair is possible, but significant delays in re-occupancy are expected. Non-structural systems are significantly damaged and inoperable. Emergency systems may be damaged, but remain operational. Moderate injuries can appear, and the number of human life-loss is also moderate. Dangerous materials are released in the environment and local relocation is required.

d) *Severe impact*: important structural damage is expected and their repair is not justified. The building is not considered safe for living. Non-structural systems are not functional, and the emergency ones can be substantially damaged. Occupants can suffer severe injuries, and their number could be high. Important quantities of dangerous materials can be released in the environment and their relocation beyond the affected area is needed (FEMA P-424).

The three essential elements in PBD are: risk assessment, vulnerability evaluation and outcome computation, as they are presented in Fig. 3.

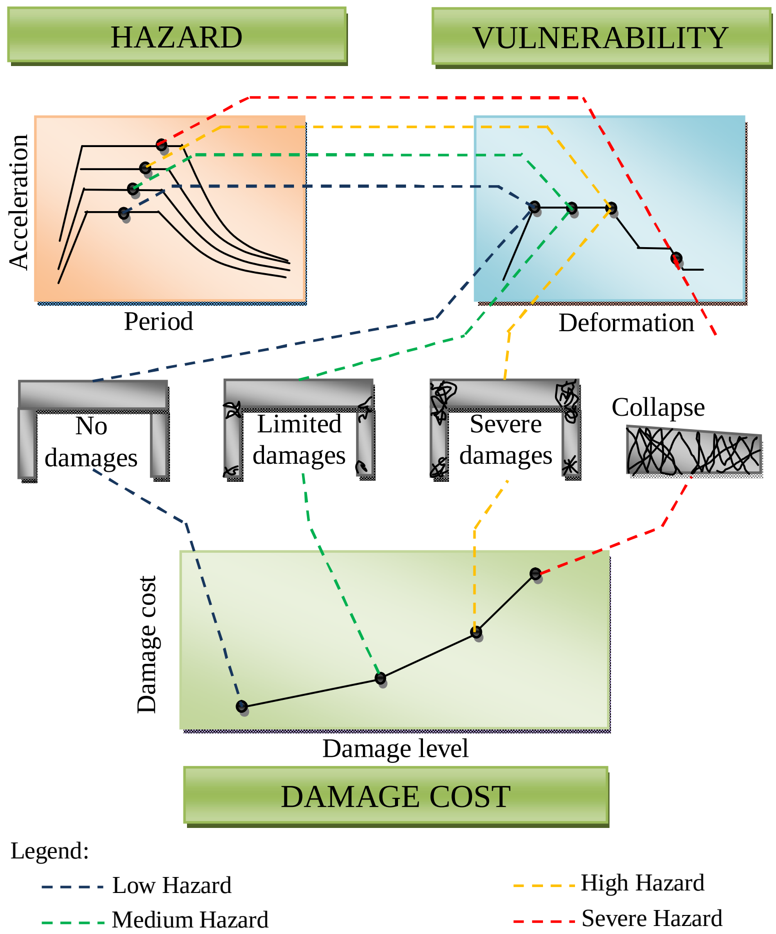

Fig. 3 – Steps in PBD used in constructions.

In PBD, assessment of the design risk level requires an evaluation of the seismic event and the occurrence probability. The complexity of this assessment can vary from the election of a certain hazard level and the design response spectra shape, to a more complicated method, like generating time-history accelerograms. The designer must consider parametres such as the recurrence period and the peak ground acceleration.

A more complex approach can be obtained by considering a higher number of seismic action levels and more recurrence periods (Fig. 4). The time needed for this analysis is longer, because computation must be made for each scenario (Olteanu *et al.*, 2011). However, the advantage of this approach is that it gives a more detailed image on the structure's behavior for its life span (Tang *et al.*, 2008).

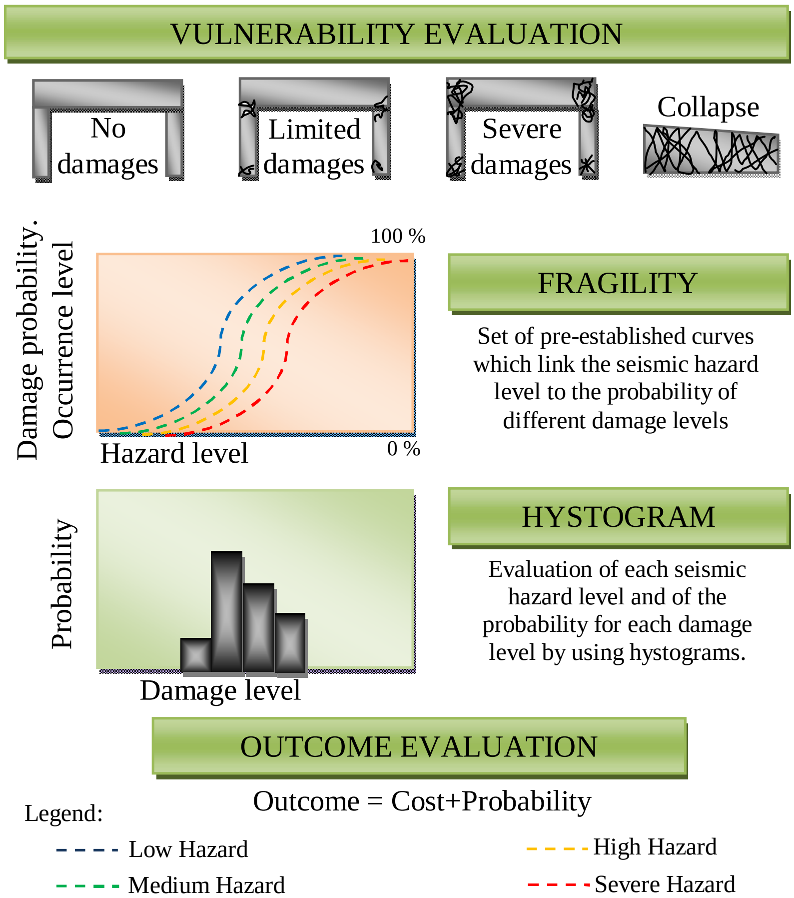

Fig. 4 – Risk evaluation.

After defining the input data refering to the seismic action, the design process can begin. If in the case of classical design, the acceptance criteria are defined so that they ensure life safety, in case of PBD, a variety of acceptance criteria are considered, which target the assessment of an acceptable damage level which can be endured by the structure after an earthquake. While linear analyses are the most used in classical design, in PBD are preferred the non-linear analyses.

Intensive research is developed nowadays with the purpose of simplifying the way in which the earthquake is defined in PBD. A developing technique which links the damages caused by earthquake to the loss uncertainties' evaluation is the use of fragility curves. Fig. 4 presents the way in which fragility curves are used in PBD.

In PBD, the outcomes are generally referred to the customer. According to FEMA, they can be quantified depending on the repairing costs or on the casualties. For evaluating the outcomes, the probability for different damage types (expressed, for example, under the shape of fragility curves) is combined with the pre-established relation between the degradation level and the associated costs. The estimated earthquake cost can be computed afterwards as is indicated in Fig. 4. Cost computation, based on uncertainties, is one of the many risk definitions, proving that PBD is a risk based method.

After the outcomes of a certain seismic event have been quantified, based on the chosen performance levels, the parts interested in building (customer, architect, engineer, users, insurance companies, etc.) must decide if this is an acceptable cost. If the costs are too high, performance levels may be modified, and the whole procedure is repeated until an acceptable outcome level is reached (Tang *et al.*, 2008).

3. Limitations and Positive Aspects for the Performance Based Design Method

The main barriers for the PBD Method in the construction field are considered to be (Spekkink, 2005):

a) the traditional culture of the building process;

b) the suspicion felt by building designers that the application of PBD will further undermine the design profession;

c) the believe of people in the design process, that the most important quality aspects of buildings cannot be translated into performance specifications;

d) the conviction of the same people that the responsibility for the functional and architectural design on the one side cannot be separated from the responsibility for the technical design on the other;

e) the segregation and fragmentation of design, engineering and construction;

f) the guilds mentality in the industry.

PBD is a mean to reach 'higher' goals, not a goal itself. The Performance Based Approach requires a different attitude, a different way of thinking about designing buildings than in the traditional design process. In the followings ten reasons to prove that PBD is better than the traditional approach are presented (Spekkink, 2005):

a) is more client oriented;

b) PB thinking helps clients and designers to gain bette r knowledge about how a building operates or should operate;

c) leads to cost effectiveness;

d) curent building regulations are more and more performance-based;

e) prevents designers from tumbling into solutions from the very beginning without proper understanding of the real client and user needs;

f) provides architects with the tools to be the integrator in the design process again;

g) offers better conditions for creativity;

h) offers the opportunity to make better use of knowledge and expertise of contractors and suppliers, allowing them to come up with innovative, cost effective solutions;

i) helps to fill in the building industry’s responsibility for the environment;

j) is common practice to some extend already.

4. PBD in P100-2013

In FEMA 356 four levels of performance are described, Fig. 5. However important practical application difficulties, mainly due to high volume of operations involved and the difficulty of establishing simple specific design criteria, associated with the four performance levels, the standard EN 1998-1 considers only two performance requirements: the no collapse Requirement (SV) and the limit damage requirement (LD).

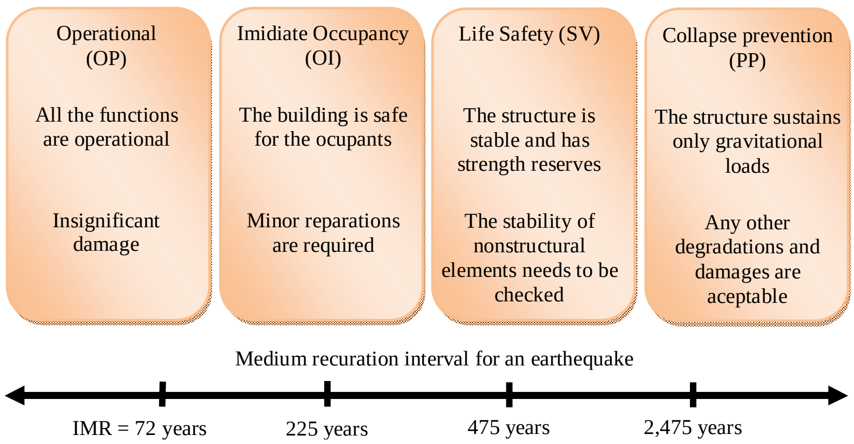

Fig. 5 – Performance levels according to FEMA 356.

This approach was also considered in P 100-1/2006, with some differences because IMR values for SV, respectively for LD were only 100 years and 30 years, in comparison with 475 years and 100 years considered in the european regulation (Postelnicu & Zamfirescu, 2000).

In the new version of the seismic code, P100-2013, the following basic requirements need to be satisfied: *life safety requirement* – in this case the seismic action corresponds to a mean recurrence interval of 225 years (20% probability of exceedance in 50 years) and *limited degradation requirement* – in this case the seismic action corresponds to a mean recurrence interval of 40 years (20% probability of exceeding in 10 years).

Two checkings are used to fulfill the above requirements: ultimate limit state (ULS), which is associated with structural damage and other failure modes that may endanger human safety and service limit state (SLS), which ensures the developing of degradation to a level beyond which specific operational requirements are not met anymore.

In the ultimate limit state the structural system will be have a specific strength and will fulfill all the restriction from the seismic code in order to obtain the necessary energy dissipation capacity (ductility). The displacement will be limited in order to: provide a sufficient safety margin to lateral deformation of the structure in comparison with the collapse deformation and to avoid the risk that it may present to people the collapse of nonstructural components.

In the service limit state a checking if the drift displacements under seismic actions are lower than those that protect non-structural elements, equipment, valuables, etc. (Postelnicu & Zamfirescu, 2001).

Besides explicit limit states checks specific measures should be taken to reduce uncertainties related to good behavior of the building in case of earthquake:

a) apropiate construction sites will be choosen, with minimum seismic hazards;

b) the design will pursue a general favourable conformation for seismic action;

c) sufficient stiffness will be provided for the structure to limit displacement;

d) the design will tend to generate favourable structural mechanism for energy dissipation for the seismic action;

e) foundations and the foundation subsoil will take the efforts transmitted from the superstructure without substantial permanent deformation;

f) the soil interaction with the structure and neighboring buildings will be taken into consideration;

g) in the execution the materials used are those mentioned in the project;

h) during the life cycle of the construction, operation and maintenance measures will be considered to preserve undiminished the strength capacity of the structure.

5. Conclusion

It can be concluded that the Performance Based Design approach is among the modern design tools and that can lead to more efficient results. Comparing with the results obtained through a traditional approach, the results that the PBD method leads to better performance and more economical buildings. This approach is being used currently, with minor differences in the entire world.

Even though the method is still under development and further research is needed in order to obtain the fastest and easiest methodology for the optimum results.

REFERENCES

Atanasiu G.M. *Managementul riscului seismic urban utilizând IIS*. Edit. Politehnium, Univ. Tehn. „Gheorghe Asachi", Iaşi, 2009.

Gibson E.J., (Coordinator of the CIB Working Commission W060), *Working with the Performance Approach in Building. CIB State of the Art.* Report no. *64*, CIB, Rotterdam, 1982.

Gielingh W.F., *General AEC Reference Model (GARM)*. Report No. IBBC – BI-88-150. Delft, 1988.

Goel S.C., Liao W.C., Bayat M.R., Chao S.H. *Performance-Based Plastic Design (PBPD)Method for Earthquake-Resistant Structures: An Overview.* The Struct. Design of Tall and Special Build., **19**, 115–137 (2010).

Hamburger R.O., *A Vision for Performance Based Earthquake Engineering*. Unpubl. white paper for the ATC-58 Project, Framework for Performance-Based Design of Nonstructural Components, Appl. Technol. Council, Redwood City, CA, 2003.

Olteanu I., Vargas Y..F, Barbat A.H., Budescu M., Pujades L. *Vulnerability and Risk Evaluation For a Reinforced Concrete Frame*. Bul. Inst. Politehnic, Iaşi, **LVII (LXI)**, *3*, s. Constr. Arhit., 9-20 (2011).

Postelnicu T., Zamfirescu D., *Towards Displacement – Based Methods in Romanian Seismic Design Code. Earthquake Hazard and Countermeasures for Existing Fragile Buildings.* Eds. D. Lungu & T.Saito, Bucureşti, 169-142, 2001.

Postelnicu T., Zamfirescu D., *Towards Performance – Based Seismic Design*. Bul. of the Techn. Univ. of Civil Engng., Bucharest, *1*, 19-29 (2000).

Priestley M.J.N., *Performance Based Seismic Design.* Bul. of the New Zealand Soc. for Earthquake Engng., **33**, *3*, 325-346 (2000).

Spekkink D., *Performance Based Design of Buildings.* Pebbu Domain 3 Final Report, Rotterdam (disponibil online la www.pebbu.nl), 2005.

Szigeti F., Gerald D., *What is Performance Based Building (PBB): in a Nutshell.* Articol in cadrul proiectului PeBBu (disponibil online la www.pebbu.nl), 2005.

Tang M., Castro E., Pedroni F., Brzozowski A., Ettouney M., *Performance-Based Design with Application to Seismic Hazard.* Structure Magazine, owned by Nat. Council of Struct. Eng. Assoc., 2008.

* * * *Action Plan for Performance Based Seismic Design*. FEMA 349, Prepared for the Federal Emerg. Manag. Agency by the Earthquake Engng. Res. Inst., 2000.

* * * *Building Construction and Safety Code.* NFPA 5000, Quincy, MA, 2009.

* * * *Cod de proiectare seismică* – Partea I. *Prevederi de proiectare pentru clădiri.* P100-1/2006.

* * * *Cod de proiectare seismică* – Partea I. *Prevederi de proiectare pentru clădiri.* P100-1/2013.

* * * *ICC Performance Code for Buildings and Facilities*. Internat. Code Council, Inc. (ICC PC), Country Club Hills, 2009

* * * *Minimum Design Loads for Buildings and Other Structures.* ASCE 7-10, Struct. Engng. Inst., Reston, VA., 2010.

* * * *Life Safety Code.* National Fire Protection Association (NFPA), 101, 2009 Edition, Quincy, MA, 2008.

* * * *Risk Management Series.* FEMA P-424, Design Guide - for Improving School Safety in Earthquakes, Floods, and High Winds, 2010.

* * * *Vision 2000 a Framework for Performance-Based Engineering.* SEAOC, Struct. Eng. Assoc. of California, Sacramento, CA., 1995.

PROIECTAREA BAZATĂ PE PERFORMANȚĂ – STADIUL ACTUAL AL CERCETARII

(Rezumat)

Dezastrele naturale din ultimii 20 de ani au condus la importante pierderi umane şi materiale în întreaga lume. Creşterea densității clădirilor şi a populației în zonele seismice a condus la mai multe pierderi odată cu îmbătrânirea clădirilor şi la pierderi financiare în cazul întreruperii afacerilor. Pentru a reduce aceste pierderi a fost introdus conceptul de *proiectare bazată pe performanță*. Principalul obiectiv al acestui concept inovativ se referă la optimizarea procesului de proiectare, astfel încât, în cazul dezastrelor naturale, pagubele să fie reduse la minim. Se prezintă caracteristicile principale ale acestui concept, câteva diferențe față de abordarea clasică si câteva limitări care ar trebui îmbunătățite. Proiectarea bazată pe performanță este orientată pe proprietar.