INNOVATIVE SEISMIC ISOLATION SYSTEMS FOR BUILDINGS CAPABLE OF FULL SEISMIC ENERGY CONTROL

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ABSTRACT :

Presented in this paper are advanced concepts of the two newly developed innovative seismic isolation systems, applicable for efficient seismic protection of different types of building structures. The first (GVCS-HB2) seismic isolation and vibration control system is applicable for seismic protection of High-rise Buildings (with more than 8 stories). This system is named "Global-Vibration-Compensating System", and now is in development stage of generation-2. The GVCS-HB2 seismically-resistant building system represent qualitatively new strategy for construction of modern high-rise buildings applying classical and new construction materials and providing simultaneously: (1) Full seismic safety of high-rise buildings, (2) Reduction of construction time, and (3) Profitable construction in seismic and non-seismic areas achieved with special system characteristics. The second seismic isolation system, named "Globally Optimized Seismic Energy Balance System" (GOSEB-GB3), is applicable as generation-3 (GB3) for seismic protection of all General types of Buildings (up to 8 stories), based on innovative full seismic energy control. This has been achieved by integration of the advantages of seismic isolation system and the new concept of multi-level seismic energy absorption. The GOSEB-GB3 system enables application of a wide range of seismic isolators. In addition, the developed new multi-level seismic energy absorber has extraordinary features as to adapting its behavior to the actual seismic intensity level.

KEYWORDS: Seismic isolation, nonlinear response, energy dissipation, vibration control, damping, seismic vulnerability

1. IMPORTANCE OF CONSTRUCTION INNOVATIONS

The most recent earthquakes that have occurred around the world generally are characterized with large direct losses including thousands of victims, much more injured people, many thousands of heavily damaged and collapsed buildings, as well as with very serious long-term secondary economical and social consequences. Regarding the permanent need for intensive future construction activities in most world seismically active regions, it is highly important to develop and introduce advanced innovative systems for improved seismic protection of buildings. In this paper presented is long-term creative and innovative work which finally resulted in the proposed new advanced construction technology with qualitatively improved systems for seismic protection of both, high-rise buildings and low-rise buildings. The proposed new construction systems are created based on application of two successful patents. The integral innovative development is further considered for realization of the unique and long-term pilot-innovative project entitled "Seismically Safe Cities of the Future".

2. ADVANCED SYSTEM FOR SEISMIC PROTECTION OF HIGH-RISE BUILDINGS

2.1. Innovative Concept of GVCS-HB2 System

The GVCS-HB2 system is patented under the original title: "Global vibro-compensating structural system (GVCS) for industrialized construction of vibro-isolated and seismo-resistant buildings", Ristic, D., et. all., (1995). The disclosed new building construction technology is actually based on the incorporated structural global vibro-compensating system (GVCS) integrating an optimal combination of: (a) Ductile central core structure incorporating all planned vertical communication systems, (b) An effective base vibration isolation system (BVIS) for the lower ring-shaped building segment around central core (composed of adequate number of building stories, ns1), (c) A specific hanging vibration isolation system (HVIS) for the upper ring-shaped building segment around central core (composed of adequate number of building stories, ns2) and (d) An adjusted interactive vibration isolation system (IVIS) between two globally separated ring-shaped building perimeter segments and ductile central core structure. With created specific building composition the transmitted seismic energy to the structure (building excitation intensity) can be rapidly reduced. This effect is provided by adjustment of the dynamic characteristics of separate structural segments to avoid resonant effects under actual ground excitation originated by strong earthquakes or any other artificial sources. In the adopted globally separated structure, vibration response of the lower building part is basically controlled by the base vibration isolation system (BVIS) possessing advantageous capability for vibration control of stiff low-rise structures. The vibration response of the upper building part is dominantly controlled by the advantageous hanging vibration isolation system (HVIS), while the interactive vibration isolation system (IVIS) serves as a compensation device to transmit positive effects between the two out-of-phase activated isolation systems into the remaining building part, achieving in general vibration reduction of the integral building as well as required safety level under strong earthquakes by effective elimination of unacceptable building oscillations under generated strong ground vibrations.

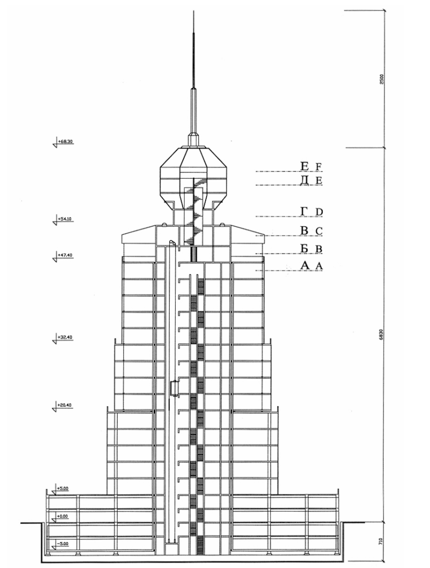

Fig.1. "Sun Tower" Elevation

Fig.2. Created Attractive "Sun Tower" Skopje Symbol Building

The significant advantage of this building system is expressed through created possibility of dominant application of the industrialized building construction technology based on in situ assembling of modular prefabricated elements. The main advantages are disposed in the following: (1) Simplification of structural design process, (2) Reduction of building construction time, (3) Achievement of high construction quality, (4) Implementation of new materials with advanced performances, (5) Elimination of some specific and costly construction phases, (6) Simplification of building finalization phases, and (7) Reduction of the total building construction and maintenance cost during long serviceability period in seismically active regions. Finally, by adopting the developed unified building modules (units), it is made possible to create flexible and attractive architectural building compositions in both, building plane and building elevation.

2.2. "Sun Tower" Symbol Building

Using the approved financial support by the Macedonian Ministry of Science, National Patent Office, and other institutions supporting innovations, realized are specific innovative and development project phases mainly focused on creating conditions for practical patent application. In the initial phase the development research included experimental testing of large-model of the designed first representative GVCS building prototype structure. To provide potentially applicable and attractive prototype structure for this specific scientific and development research created and promoted was by the first author an original and unique "Sun Tower" project.

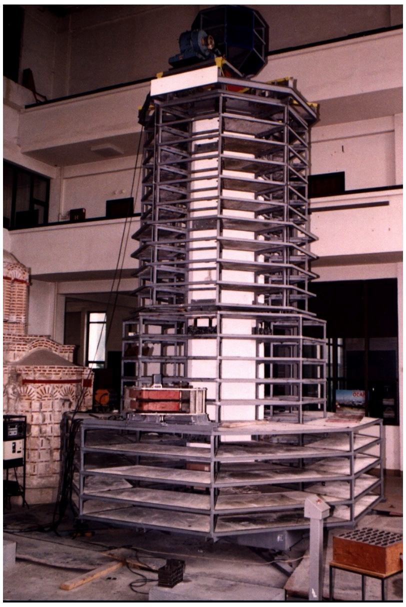
Fig. 3. Large Model Construction in IZIIS Lab


Fig. 4. Experimental "Sun Tower" Model

The adopted "Sun Tower" symbol prototype structure, Fig. 1,2,3 and 4, adequately integrates many of the advanced design features representing unique structural and engineering challenge. With its specific purpose, appearance, grandeur and specific integral structural system, this prototype structure bears the characteristics of uniqueness in both, structural and architectonic sense. During the initial creation of general concept of the prototype structure, the following primary characteristics were basically promoted and applied: (1) The created prototype to be characterized by unique, attractive and representative structural system, expressing positive seismic performances of the patent itself and (2) The created prototype to provide attractive multi-purpose usage, promoting therefore important contents of wider commercial and other specific interests.
The general architectonic appearance of the created "Sun Tower" prototype structure successfully integrates in itself a pronounced symbolic, since the structure of the tower ends with a polyhedron sphere symbolizing the Sun, while the eight cantilever girders of the upper segment symbolize the rays of the Macedonian flag. The structure is therefore called the "Sun Tower". The final and extended goal is focused on construction of "Sun Tower" structure in Skopje, as a structure representing "symbol of our time and world solidarity". Skopje, or so called "city of international solidarity" has particular and noble reasons for this, particularly having in mind the great international assistance and the shown wide world solidarity in mitigation of the consequences of the catastrophic earthquake that struck this town in 1963. Taking into account the obtained integral results from conducted experimental and theoretical investigations, the following most essential conclusions are drawn: (1) The dynamic response of the experimental model is in full compliance with the expected dynamic behavior; (2) The "GVCS" structural system has very large capacity of seismic energy absorption; (3) The frequency characteristics of separate structural segments are fully controlled as different, whereby the main concept of the patent have been confirmed; (4) By adequate interventions in the domain of damping devices, it is possible to efficiently control the effective dynamic characteristics and seismic response of individual segments, providing thereby an optimal seismic energy balance and (5) It has been proved that the proposed innovation named GVCS seismically-resistant system offers great qualitative improvement of the potential seismic safety of high rice building structures, and can be widely and successfully implemented in modern practice

3. ADVANCED SYSTEM FOR SEISMIC PROTECTION OF LOW-RISE BUILDINGS

3.1. Innovative Concept of GOSEB-GB3 System

To provide necessary technical conditions for efficient seismic protection of low-rise buildings, promoted is application of patented efficient "GOSEB" system. The "GOSEB-GB3"- seismically resistant system is based on the concept of global optimization of seismic energy balance by integration of the advantages of seismic isolation systems and the new multi-level seismic energy absorption, (Fig. 5).

Figure 5. Concept of The Invented "GOSEB" Seismo-Resistant System

Seismic isolation devices (isolators) are available on the market. Produced are as different types, with different proportions and with diverse physical characteristics. This enables wide and universal application of seismic isolators in all kinds of structures. The new multi-level "GOSEB" hysteretic seismic energy absorber has extraordinary features as to adapting its behavior to the actual intensity of the input seismic energy. Actually, "GOSEB" - hysteretic energy absorber possess the following features of multi-level earthquake response: If there is no earthquake excitation, the "GOSEB" hysteretic seismic energy absorber enables behavior of the structure analogous to the behavior of any traditionally constructed structure. If a relatively slight earthquake occurs, the "GOSEB" hysteretic seismic energy absorber reacts with an adequate level of dissipation of the input seismic energy, making the structure fully safe and avoiding even micro-cracks. If a moderate earthquake occurs, the "GOSEB" hysteretic absorber reacts with adequately increased level of dissipation of seismic energy, providing complete protection of the structure. Finally, in the case of the most severe earthquake, the "GOSEB" hysteretic energy absorber reacts with its full capacity for dissipation of the increased seismic input energy. The needed capacity of seismic energy absorbers should be defined based on advanced analytical models providing design of optimal seismic performances of the "GOSEB" multi-level seismic energy absorbers. The multi-level response of the "GOSEB" system in compliance with the input seismic energy provides a complete seismic protection of structures, even under the strongest recorded earthquakes.

3.2. Advances of GOSEB-GB3 Seismically Resistant System

To evaluate seismic performances of the invented *GOSEB-GB3* system intensive research have been realized involving comparative inventive design and analysis of 12 representative prototype structures of different usage categories and with different structural characteristics.

Fig.6. "GOSEB" National Patent Center (P-6)

Fig.7. "GOSEB" Children's Education Center (P-7)

Each individual prototype structure has been designed by application of two structural systems. In the first case, the structure is designed applying classical structural system. In the second case, the structure is designed

applying new seismically resistant "GOSEB" system. However the integral super-structure has remained the same in both cases, providing conditions for efficient comparative studies. With the selection of 12 representative prototype structures, a total of 6 different inventive "GOSEB" building construction programs has been created and realized, as follows: ***Programme-1:*** Construction of seismically resistant *family houses* (Prototype-1, Prototype-2, and Prototype-3). ***Programme-2:*** Construction of seismically safe *residential buildings* (Prototype-4 and Prototype-5). ***Programme-3**:* Construction of seismically safe vital *public buildings*: Prototype-6, representing "National Patent Center", and Prototype-7, represents "Center for Education of Talented Children" (Fig. 6). ***Programme-4:*** Construction of seismically safe *modern hotel buildings* (Prototype-8, representing 5-story hotel and Prototype-9, representing 26-story hotel). ***Programme-5:*** Construction of seismically safe *school buildings* (prototype –10). ***Programme-6:*** Construction of seismically safe very important *infrastructure facilities* (post building, Prototype-11 and hospital building, Prototype-12).
Nonlinear seismic response studies of classical and GOSEB-Structure (66 analysis for each prototype, or 12x66=792 nonlinear numerical seismic response analysis) are computed using the special purpose computer program NORA2000. Applying the formulated advanced nonlinear mathematical models (including structural and non-structural elements) for both, classical and inventive GOSEB – Building prototypes, the required comparative nonlinear seismic response analysis were performed. Earthquake response analysis are carried out using 11 intensities of representative set of three recorded earthquakes, as follows: (1) Ulcinj-Albatros, Component N-S, (2) Montenegro Earthquake, 1979, (3) El - Centro, Component SOOE, USA, 1940, and Parkfield, Component N85E, USA, 1966.

Based on integral analytical studies, the following principal conclusions were drawn: (1) Prototype buildings constructed by application of classical system (Case-1), common RC frame (medium strength), generally experience complete failure under relatively low earthquake intensity, a=(0.15 to 0.25)g.

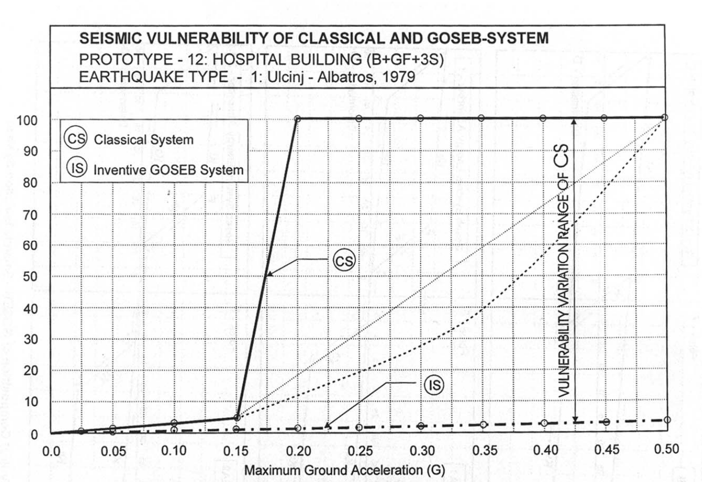

Fig. 8. Comparative Seismic Vulnerability Functions of Classical and Invented GOSEB-System for EQ-1

(2) However, the performed analytical investigations proved that the same buildings do possess a total seismic protection in the case of application of the new "GOSEB" system even under the strongest earthquakes characterized by maximum ground acceleration of 50% of the gravity acceleration. (3) The achieved total seismic protection of all building prototypes may be seen as an extraordinarily accomplishment in the field of seismic structural engineering. (4) This conclusion is particularly important because it was confirmed that "GOSEB" system possesses capability to provide complete seismic protection of building, even in the case when the building superstructure (upper-part or part above the installed GOSEB-System), is constructed with the weaker and lower cost structural system. The above conclusions are directly confirmed by the drawn representative and comparative seismic vulnerability functions, developed based on this study for classical and inventive GOSEB-System, Fig. 8.
Seismic vulnerability functions of all considered representative building prototypes clearly demonstrate very high potential of inventive GOSEB-System for practical application and full seismic protection of low-rise buildings.

4. OVER 20 YEARS OF APPLICATION OF THE COMPUTER PROGRAM "NORA"

This specific and multi-objective study was realized applying special purpose computer program NORA, (presently NORA2000), originally developed by the first author in the year 1985 during his PhD studies at Structural Earthquake Engineering Laboratory, Kyoto University, Japan. The author is particularly pleased to use this occasion to mark over 20 years of the computer program NORA and its very successful application and extension. During past more than 20 years (1985-2008), NORA was permanently used for solution of very specific and innovation's related problems. Computer program NORA was permanently considered as our very flexible and strong computational tool providing advanced options for successful solution of the most complex innovative, scientific, technological and practical structural and/or engineering problems. Up to date, NORA was permanently and mainly used from our research team and close collaborators. However, after more than 20 years of very reach experience, the author's present intention is to prepare public version of NORA computer program. In fact, NORA was "born" in beautiful Kyoto, the city of flowers and place of real inspiration. During extensive application, we never had serious problem with NORA, even computer technology was changed rapidly. It is now moment to express sincere personal appreciations and thanks to Prof. Hirokazu Iemura, Structural Earthquake Engineering Laboratory, Kyoto University, Japan, for his permanent encouragement creating always conditions for the success in our research. Thanks are also extended to my closed collaborators for their efforts and help in various ways.
NORA is special purpose computer program for static and dynamic, linear and nonlinear analysis of large-scale and complex: (1) Classical structures, (2) New and/or innovative seismically isolated and seismically controlled structures, and (3) All types of special structures, applying: (1) Advanced nonlinear micro-modeling concept, (2) Nonlinear macro-modeling concept and (3) Global non-linear modeling concept. NORA was very successfully used in solving large number of different classes of engineering problems such are: (1) Structural state diagnosis problems, (2) Non-linear soil-structure interaction problems, (3) Low-speed, time-dependent nonlinear problems, (3) Reversed-cyclic (quasi-static) non-linear problems, (4) Non-linear problems under moving loads, (5) Vulnerability analysis of complex structures under seismic loads, (6) Non-linear analysis of new structural types, (7) Non-linear analysis of special types of bridge structures, (8) Non-linear analysis of building structures, (9) Non-linear push-over analysis of buildings with or without infill, (10) Non-linear response analysis of infilled frames with unreinforced and reinforced masonry, and many other specific engineering problems. During long period of more than 20 years (1985-2008), we had permanently very intensive research activities and very extensive use of NORA. It is estimated that minimum 40.000 NONLINEAR ANALYSIS have been successfully realized with NORA.

5. ACKNOWLEDGEMENT

To successfully realize the creative and complex research activities in the area of development of this specific innovations, great and highly appreciated support was extended by many experts, individuals, collaborators, institutions and a number of MSc and PhD students of the first author in IZIIS-Skopje, both domestic and from abroad. With particular pleasure, we express our warm thanks to all of them. In addition we are particularly pleased to mention the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) at the University "Ss Cyril and Methodius", Skopje, Macedonian Ministry of Education and Science, Industrial Property Protection Office - Skopje, Ministry of Transport and Communications, Alga S.p.a. - Milano (Italy), Daris Invent –Skopje, Liting - Skopje, Mavrovo - Skopje, Saga Engineering - Skopje, Granit - Skopje, Fadom - Strumica, Pelagonija-Skopje, EIC Management GmbH - Oberhausen (Germany) and many other project collaborators, institutions and individuals supporting these long-term activities in various ways. Finally, my sincere gratitude is extended to Prof. Dr. Jakim Petrovski for permanent support and encouragement.

6. AWARDS RECEIVED

The originality and high potential of the presented inventions are very well and widely recognized. This is confirmed by the received the highest international and national awards in the area of inventions:

- In 1995 the invention was awarded with gold medal, the highest international award for innovations at the 23-rd International exhibition of inventions held in Geneva, Switzerland from 31.03. to 09.04 1995.
- In 1996 the invention was awarded with the highest national award "Patent of the Year" in the Republic of

Macedonia.

- In 1998 the invention was awarded with "Gold metal with mark" the highest international award for innovations at the International exhibition of inventions held in Casablanca, Morocco.
- In 1999 the invention was awarded with the new highest (special) national award "Patent of the Decade" by the Government of Republic of Macedonia.
- In 2000 this innovative project was promoted at EXPO-2000, the greatest world exhibition of inventions and new technologies for the 21st century, held in Hannover, Germany, (June 1 to October 31, 2000). The project was officially nominated by the Government of the Republic of Macedonia to represent new and advanced national achievements in the field of INVENTIONS AND SCIENCE.

During recent years research activities are continued and are more focused to practical application of the developed innovative seismically safe construction technology. The current creative activities are particularly focused to construction of unique “Sun Tower Symbol Building” in Skopje.

7. CONCLUSIONS

The conducted complex long-term research activities toward development of GVCS-HB2 seismically-resistant building system are generally viewed as part of the unique project entitled "From Patent to Application", firstly originated and promoted by the first author. Particular efforts have been made, not only to the original creation and development of the invented GVCS-HB2 system, but also to successful realization of series of important parallel activities and developments including: (1) Patent protection, (2) International promotion of the new system (3) Creation of innovative research program for realization of further development activities, (4) Creation and design of innovative "Sun Tower" prototype structure, (5) Design, construction and testing of experimental model, (6) Realization of unique theoretical developments, including development of special purpose software, (7) Establishment of cooperative national and international collaboration relevant for successful continuation of the overall work, (8) Establishment of important contacts with potential cooperation partners in various technical and application domains of interest including promotion of new construction materials, special vibration control devices, advanced construction technologies, etc. The integral study clearly indicates that consistent practical application of the invented GVCS-HB2 system may be in practice accepted as "a new era in construction of seismically-resistant high-rise buildings (with more than 8 stories)", particularly because it may simultaneously satisfy the three most important construction demands: (1) Seismically safe construction; (2) Cheaper construction and (3) Faster construction. Of course, it is a great challenge to confirm these three "target" conditions in the case of planned construction of the designed "Sun Tower" symbol building in Skopje. In fact, the construction of "Sun Tower" symbol building in Skopje remains one of the principal goals of the general project "From Patent to Application".

Analogously, from the second long-term research activity is concluded that the developed and proposed innovative seismically-resistant GOSEB-GB3-system can be efficiently used for complete seismic protection of buildings (up to 8-stories), based on innovative multi-level seismic reaction and globally-optimized seismic input energy. This is achieved by simultaneous application of the advantages of seismic isolation systems and newly developed innovative “GOSEB” multi-level hysteretic seismic energy absorber. The multi-level response of the “GOSEB-GB3” system in compliance with the input seismic energy provides a complete seismic protection of the buildings even under the strongest recorded earthquakes. A big advantage of the new seismically resistant “GOSEB-GB3” system for seismic protection of structures is its simple application localized only at the base of the structure. The skill of the design engineer is generally used for correct determination of an optimal number, optimal physical characteristics and optimal position of the seismic isolators and multi-level seismic energy dissipaters to achieve the optimized seismic energy balance for each specific structure. This innovation opens a wide field of practical application of the patented globally optimized system of seismic energy balance and realization of the creative vision of the authors for construction of seismically resistant structures in the 21st century and realization of the project “Seismically Safe Cities of the Future”.

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