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Initiations and Future Directions in the Development of Kinetic Structures for Earthquake Resistance

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Introduction

Currently it is widely acknowledged that buildings subjected to strong earthquake forces have in their design an additional complexity, in avoiding significant permanent damage that may lead to local or global collapse. But also recognizing the economic disadvantages of an exclusive elastic structural response, current earthquake design philosophies, as reflected within national and international earthquake building codes, promote the design of ductile structural systems able to undergo inelastic reverse cycles while sustaining their integrity. Thus capacity design states the aim of proportioning strength and stiffness such that inelastic behavior is localized in a controlled way so that other portions of the structure can respond elastically. This leads to the development of adaptable structures with predefined secondary areas that absorb and dissipate large amounts of the earthquake input energy through enhanced elastic or elastoplastic deformations. Along these lines the performance-based design approach typically accepts different levels of structural damage and consequently repairing costs as unavoidable result of inelastic behaviour depending on the earthquake intensity. Earthquake engineering has borrowed much from other engineering disciplines in its understanding of inelasticity and ductility, in developing probabilistic design approaches and in considering dynamic factors for earthquake structural safety. Such calculation approaches built in parallel on the development of generally applicable analysis methods, such as the capacity spectrum, pushover and displacement-based method [1].

With regard to the development of the structural design strategy for earthquake resistance and specifically, to performance-based design, the contribution made by Nathan N. Newmark and Emilio Rosenblueth with the book publication on 'Fundamentals of Earthquake Engineering' in 1971 cannot be overestimated [2]. The general philosophy of the contents is presented in the introduction of the book: "In this text on earthquake engineering we take for granted that the purpose of design in engineering is optimization, and that we deal with random variables. In the past the orthodox viewpoint maintained that the objective of design was to prevent failure; it idealized variables as deterministic… but when confronted with the effects of earthquakes, we must contend with appreciable probabilities that failure will occur in the near future. Otherwise, all the wealth of the world would prove insufficient to fill our needs: the most modest structures would be fortresses. We must also face uncertainty on a large scale, for it is our task to design engineering systems to resist future earthquakes". Of particular high value in underlying the fundamentals of nonlinear systems response is chapter 11 that addresses criteria for establishing pertinent response bounds of nonlinear systems–elastic, elastoplastic, rigid-plastic, masking-type, stiffness degrading systems and braced structures–and chapter 14 'Basic concepts in earthquake-resistant design' that contains fundamental guidelines for the classification of target failure modes for earthquake resistance.

Beyond the concept of the capacity design of structures, structural dynamics may well be considered to be the topic of the 21st Century, based on modern finite element methods of structural analysis using high-speed digital computers, while more and increasingly accurate records of ground and building motion time histories during earthquakes are been produced. On the other side, even if analytical capabilities in the field have grown highly, contemporary earthquake engineering still relies at first place on the actual control design strategy applied for enabling structural safety. Experimental research, or actual earthquake performance serve for verification of any related computer modelling and calculations. In extension to the capacity design approach currently applied in research and practice, four directions of structural control design for earthquake safety, i.e. damage resisting design, damping control, earthquake isolation and active structural control, shape design strategies for the development of kinetic structures with enhanced capabilities for earthquake adaptation and safety. A brief discussion in the following sections promotes in parallel the significance of further related developments from concept to detail and application.

Damage Resisting Design

While ductility is still central to both, earthquake engineering research and practice, the limits of ductility are also recognized, since the underlying concept of capacity design involves through the development of inelastic deformations, concentrated severe damages of the primary structure itself for avoiding collapse [3]. Currently, the realization of the control method is interestingly traced with autonomous control members properly designed and integrated in series and/or in parallel with the primary structural members to develop an adaptable response behavior for any targeted stiffness and ductility of the system.

The control members comprise cost effective 'external dissipaters', referred to as "Plug & Play", for their capability to be easily mounted and if required, demounted and replaced after an earthquake event [4]. This option would give the possibility to conceive modular systems with replaceable sacrificial fuses at the connection regions of the primary members, acting as the "weakest link of the chain", according to capacity design principles. Plug & Play dissipater solutions may consist of axial, or flexural yielding mild steel short-bar elements, applied on subassemblies configurations of beam-column joint connections, column to foundation connections and wall systems respectively. In terms of material and type of dissipation, metallic, shape memory alloys and viscoelastic systems are used to provide elastoplastic due to axial or flexural yielding, friction and viscoelastic dissipation mechanisms.

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In this respect, self-centering dissipative high-performance systems, referred to as advanced flag-shape systems, combine also alternative energy dissipation forms given by unbounded post-tensioned tendons, mechanical springs, or shape memory alloys with super elastic behavior [5].

Damping control

Back in 1971, Newmark and Rosenblueth note in chapter 15 'Earthquake-resistant design of buildings': "The use of special devices intended to increase damping is not given attention in present building codes. Some codes allow changes in design spectra as a function of anticipated ductility factors and the possibility of having more than one line of defence, making both concepts functions of the structural solution chosen" [2]. Referred to be the transformation of the primary structures into kinetic mechanisms through the integration of damping devices, i.e. energy dissipation devices, which arepassively activated through their own displacement state. Meanwhile passive metallic yielding-, friction, viscoelastic and viscous devices have been developed for this purpose, while current earthquake building codes include at least generic requirements for passive methods of response control, including base isolation and supplemental damping [6].

In principle the damping devices are added in moment resisting frames, attached on steel bracings of relatively large hollow section diagonals, in different configurations. The devices require minimum maintenance and offer a reliable earthquake control solution; the most significant advantage is that the control members enable through their energy dissipation mechanism, the primary structure's elastic response, and if necessary, they can be easily repaired or replaced after an earthquake event. Nevertheless some aspects of the design concept are still disadvantageous: High cost, heavy and stiff bracing members for the devices' integration within the primary system increase of the primary system's stiffness, acceleration and earthquake input energy and residual deformations. In addition the application of relatively stiff bracing members for the integration of the damping devices leads under cyclic loading to a relatively inefficient behavior of the system, since in every half-loading cycle the compression diagonal buckles and it therefore cannot participate in the energy dissipation process.

On the other hand the application of light weight secondary members for the integration of the damping devices seems too often be a promising alternative as regards the avoidance of stiffness interaction with the primary system and optimization of the control system's operation principles in the energy dissipation process. The application of lightweight control mechanisms becomes an attractive alternative, not only for the design of earthquake resistant structures, but also for the earthquake retrofit of existing ones. In principle the implementation of tension-only bracings with damping devices in frame structures is only possible through the development of suitable bracing-damper configurations, whereas all bracing members contribute effectively during the entire load duration, to the operation of the integrated damper. Such optimized control mechanisms in establishing an independent line of earthquake defence to the primary system and enabling maximum energy dissipation are currently been developed, consisting of cable bracings configurations with closed circuit and integrated friction or plastic hysteretic dampers [7,8].

Earthquake isolation

In 1971Newmark and Rosenblueth presented three concepts on earthquake isolation: The flexible first storey, the use of linear rubber pads for partial isolation of the superstructure to the foundation and the use of rollers [2]. Otherwise it is stated, "To the authors knowledge no major applications of any of these alternatives have been attempted". Today isolation-damping devices have almost become standard products, mass-produced with numerous applications worldwide. The basic principle of decoupling the structure from earthquake-induced ground motions is achieved by increasing the flexibility of the system, together with providing appropriate damping. Earthquake isolation aims at first place to shift the building's fundamental period outside the dangerous for resonance, range of periods. As implied in the publication by Newmark and Rosenblueth in 1971, the control approach differs fundamentally from the capacity design and damping control in the method by which the period lengthening and hysteretic energy dissipation mechanism is provided, as well as in the philosophy of how the earthquake induced forces are withstood. Base isolators for example act in an earthquake event as impact transformers to the building body, whereas the earthquake impacts are transmitted from the low tuned bearings to the building as smaller forces, distributed over a longer time span [9]. Acceptable displacements in conjunction with a large degree of earthquake forces isolation is obtained by providing flexibility in the isolator, high damping and force-limitation under horizontal earthquake loads, together with high stiffness under smaller horizontal loads to limit wind-induced motions [10]. In this frame, elastomeric, high-damping rubber, lead rubber, flat sliding, curved sliding, friction pendulum and steel spring bearings have been developed and internationally applied in practice [11].

With regard to the requirements of proper selection, design, manufacturing, installation, protection and maintenance of the isolation-damping devices during the entire life of the isolated structure, further research activities concentrate on the actual development of new materials and prototypes of adaptable bearings that satisfy in compact devices all requirements of rigidity, damping, elasticity and stability. The size and compact form of the isolators ought to make them suitable for an industrialised manufacture and standardisation; the only way for enabling access to this technology also for countries with low technical potential, but with high need for earthquake safety.

As far as the methods of design are concerned, the use of earthquake isolation in countries, where the designers are allowed by the codes to decrease the earthquake forces acting on the superstructure when adopting this technology, requires first of all a reliable definition of the earthquake input, which cannot rely upon simplified routine probabilistic methods, mainly when dealing with displacements definition on which the design of isolated structures is based. The Probabilistic Seismic Hazard Assessment approach is meanwhile been complemented in many earthquake prone countries through the development and application of deterministic models.

Furthermore, lately improvements of isolated systems earthquake responses are been traced with the isolation of multi-storey buildings at single or various elevations over the height [12]. The isolation-damping devices introduced are herewith defined as controllable complex connections that provide in a compact technique different transmission characteristics in accordance with the loading conditions. Conceptually, it is assumed that the structural deformability is influenced decisively by the vertically distributed earthquake isolation, which at the respective storey-levels is alone able to control the partial and overall stiffness, the force transmission and the energy dissipation process. In fact, a partitioned structure with such controllable connections can be looked at as a dynamic adaptable system, which represents in a whole two systems: a primary rigid one for transferring the normal horizontal and vertical loads and a secondary kinematical one, which is activated under dynamic actions. During moderate earthquakes the isolated structure acts as absorber of the kinetic energy at the isolation levels, minimizing thus the displacements of the building. During strong earthquakes the effectiveness of the system in further enlarging the period of the building, compared to the classical method of earthquake isolation at a unique level, is achieved with decreased inter-storey deflections, and without introducing extensive displacements at the building base, which are often limited by practical constraints. In parametric studies conducted most effective vertical distributions of earthquake isolation at various storey-levels are proposed, based on multi-criteria analyses of the isolated systems responses.

Active structural control

By the end of the 20th Century, one of the most advanced and ambitious concepts, active structural control, has been extensively researched but little applied. William Zuk and Roger H. Clark demonstrated already in 1970 with their book publication on 'Kinetic Architecture' the necessity for an architecture that is not static; instead it has the ability to adapt in time changes through systems with embedded actively controlled kinetic mechanisms [13]. As correctly stated by the authors in the preface of the book with regard to the rather conceptual nature of the proposals made within, "The book is a compilation of existing pertinent material on adaptable architecture furthered by some new ideas for the future. The concepts discussed in the book are evolutionary and are based upon reasonable predictions of trends. The newness of many of the applications to architecture has required that we make use of developments in other areas normally placed outside of architecture. However, by its very nature the book is incomplete, as the process of change is ongoing and unending, and technological developments, as well as explorations into adaptable architecture, are multiplying".

The specific publication is considered as a significant milestone for the advancement of the design philosophy of kinetic architecture, aiming at the development of timely adaptable systems as to differing functional or external loading conditions, and leading to buildings and components with variable mobility, location, or geometry. Especially significant in terms of the kinetic operability is the development of the structure in two aspects: The structural mechanism that enables different geometrical configurations of the components through among others, folding, sliding, expanding and transforming in size and shape, and the control system that directs the structure towards specified transformations, through pneumatic, chemical, magnetic, natural or mechanical processes. Of primary concern within the publication by Zuk and Clark was the increased application of high strength materials, but with relatively steadily low elastic modulus that often lead to vibration prone structures. Control concepts for structural deformation control were proposed, such as the 'Variable Controlled Deformation' method, through application of stressing tendons within the structure. The control members should be capable of being variably and automatically tensioned to counteract excessive deformations, based on initial respective ideas by Eugene Freyssinet in 1960 and Lev Zetlin in 1965. The control mechanism was conceptually applied in five control classes: axial, flexural, torsional, instability and vibration and seismic control. With regard to the latter, it was suggested that an active vibration control operates on critical major modes of vibration to oppose the build-up of acceleration, inertia forces, or vibrational energies in the structural system. This could be achieved by the introduction of variably controlled tendons in such locations as to restrain dynamic motion of the major modes. Shear mode control would require a form of X-tendons between floors and flexural mode control would require vertical tendons on the circumferential building structure, on the basis of outrigger systems in high-rise buildings. The principle behind neutralizing the impact motion was thus seen to be a tuned generation of internal energy opposite to the imposed energy of the structure. Along these lines the human body may be considered as the most representative example of dynamically interactive living organisms. The engineer Guy Nordenson describes the phenomenon in active kinetic systems as creating a building like a body: A system of bones and muscles and tendons and a brain that knows how to respond [14]. In numerous applications then, a major part of the structure can be reduced through the ability of a singular system to facilitate multi-uses via transformative adaptability.

The active control concepts proposed by Zuk and Clark, were directly influenced by respective advances in aerospace and mechanical engineering [15]. Active control mechanisms developed primarily in the 70ies and 80ies and applied internationally for earthquake resistance purposes aimed at a mass, damping or stiffness control of the structure [16]. Examples comprise active Tuned Mass Dampers, piezoelectric materials and electro rheological fluids, active friction dampers, impulse control and active bracing tendons. In general, most research conducted on active structural control provided indeed promising results, but was rather based on idealized systems and conditions. In practical implementations critical aspects of the control systems have a direct influence on the selection and development of the active control mechanism. These concerns in most cases time delay effects, as well as the number and placement of sensors and actuators within the structure. Last but not least, practicability issues with regard to the amount of external energy needed for the operation of the control system as to the building's mass favour the development of nonlinear control strategies, such as a variable active stiffness and damping. In such cases the structure's earthquake response is optimized in specific time decrements, or prevented from resonance with the earthquake induced ground motions. Further alternatives comprise control methods of instantaneous passive and active control. Low control forces and higher reliability characterize such hybrid control systems, since the operability of the systems is partly maintained even under energy supply interruption.

From static to kinetic structures

In all structural control directions briefly presented above common is the strategy to design economically affordable and reliable dynamic adaptable systems that can confront to the earthquake induced conditions of the structure, and with less possible inherent damages. An integrative development of material, structure and control mechanism following from early phases nonlinear processes of design and optimization can only provide intelligent solutions of closed-open loop earthquake resistant structural systems, as Newmark and Rosenblueth originally suggested and Zuk and Clark envisioned.

References

1. Reitherman RK (2012) Earthquakes and engineers: An international history. ASCE, Virginia.
2. Newmark NN, Rosenblueth E (1971) Fundamentals of earthquake engineering. Prentice Hall, Englewood Cliffs, NJ.
3. Paulay T, Priestley MJN (1992) Seismic design of reinforced concrete and masonry buildings. John Wiley & Sons, Chichester.
4. Pampanin S (2005) Emerging solutions for high seismic performance of precast-prestressed concrete buildings. Journal of Advanced Concrete Technology 3: 202-222.

5. Kam WY, Pampanin S, Palermo A, Carr AJ (2010) Self-centering structural systems with combination of hysteretic and viscous energy dissipations. Journal of Earthquake Engineering and Structural Dynamics 39: 1083-1108.
6. Symans MD, Charney FA, Whittaker AS, Constantinou C, Kircher CA et al. (2008) Energy dissipation systems for seismic applications: current practice and recent developments. Journal of Structural Engineering 134: 3-21.
7. Di Sarno L, Elnashai AS (2005) Innovative strategies for seismic retrofitting of steel and composite structures. Progress in Structural Engineering and Materials 7: 115-135.
8. Phocas MC, Sophocleous T (2012) Adaptable dual control systems. A comparative parametric analysis. Journal of Safety and Security Engineering 2: 280-296.
9. Skinner RI, Robinson WH, McVerry Gh (1993) An introduction to seismic isolation. John Wiley & Sons Inc., Chichester.
10. Pocanschi A, Phocas MC (2003) Kräfte in Bewegung: Die Techniken des erdbebensicheren Bauens. Teubner, Wiesbaden.
11. Martelli A, Clemente P, Forni FSM, (2012) Recent worldwide application of seismic isolation and energy dissipation to steel and other materials structures and conditions for their correct use. In: Mazzolani F, Herrera R (eds). Behaviour of Steel Structures in Seismic Areas. 3-13.
12. Charmpis DC, Komodromos P, Phocas MC (2012) Optimized earthquake response of multi-storey buildings with seismic isolation at various elevations. Journal of Earthquake Engineering and Structural Dynamics 41: 2289-2310.
13. Zuk W, Clark RH (1970) Kinetic architecture. Van Nostrand Reinhold, New York.
14. Davidson C (1995) Guy Nordenson, Chuck Hoberman, Mahadev Raman: Three engineers (sitting around talking). ANY: Architecture 10: 50-55.
15. Yao JTP (1972) Concept of structural control. Journal of the Structural Division 98: 1567-1574.
16. Miller RK, Masri SF, Dehghanyar TJ, Gaughey TK (1988) Active vibration control of large civil structures. Journal of Engineering Mechanics 114: 1542-1570.

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