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MULTI – LEVEL EARTHQUAKE DESIGN OF STEEL FRAMES: A DESIGNERS' VIEW

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ABSTRACT

Recent unexpected failures have lead to the conclusion that a new design strategy should be developed, in order to mitigate loss of property and to assure life safety. In multi-level earthquake design a structure is sized by achieving performance objectives through predicting the real behaviour of buildings under different seismic actions that could occur. A designers' view is presented in the paper approaching the framework of the implementation of such a strategy in current design practice of steel moment frames.

Key Words: *Multi-level earthquake design, steel moment frames, limit states*

1. INTRODUCTION

Earthquake resistant design has always been in a challenge due to the fact that the loads are not deterministic, the magnitudes are unknown at the process of design, as a consequence having a variable probability to cause failures. From the other part, the society needs safe structures against earthquakes. Furthermore, society expects from designers to provide it with buildings serviceable and economical. Defining the requirements of structures against seismic actions, one can simply describe the followings:

i) no economical losses to frequently seismic events;

ii) no serious damage to the structure and its content during service life of the structure against seismic actions which expected to occur at rare intervals;

iii) no collapse and safety to occupants during extremely rare seismic events.

When we design and construct steel buildings according to a client-required performance level all the aforementioned statements is possibly to be respected. In this way, can be achieved a balance between economic savings and a socio-political criticism after an unexpected earthquake event. However, some problems should be arising concerning the level of performance target and ground motion. It is well known that the seismic design forces are well correlated with the social level of a country. Considering the inherent probable character of earthquakes, today it is difficult to explain or to define in a client what means

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probability of damage or to guarantee the level of damage. When we discuss about constructions, where the money and life "investments" are high, all the people think in a deterministic way. Therefore, in order to design in the spirit of multi-level earthquake design a series of problems should be resolved taking into account structural aspects as well as social aspects. It is very dangerous for the structural engineers the implementation of a multi-level design without obtaining a transparent understanding of the expected seismic performance and the inherent risks of the construction under different earthquake excitations. The introduction of a suitable framework of laws is absolutely necessary.

From the structural point of view, the engineering community makes an attempt to design buildings according to required predetermined objectives, named performance objectives or limit states. The idea of designing based on performance objectives is not new, at this time a great effort is made to quantify the performance targets,[1,2]. Generally, performance targets may be a level of stress not to be exceeded, a load, a limit state or a target damage state. In the last ten years, especially due to damage from Loma Prieta (1989), Northridge (1994) and Kobe (1995) an increasing interest in USA and Japan was marked[3,4,5]. Also in Europe some efforts were made towards this direction [6,7,8]. Generally, US recommendations define four performance levels (fully operational, operational, life safe, near collapse), while European attempts two (serviceability and ultimate limit state) or three performance levels (serviceability, damageability and ultimate limit state). Analyzing all these documents one can observe the divergent viewpoints, the lack of uniform definitions and methods concerning the fundamental definition of ground motions and design criteria. Of course, it should be underlined that the basis of achieving multi-level performance objectives was made.

Learning from recent failures, not only the aseismic design is adequate to mitigate structural damage, but in the same time the structural conformation and structural detailing is very important in order to ensure a level of performance; conventional detailing ("dog-bone" connections, removable shear walls, detached walls, e.t.c.) and innovative detailing (dampers, isolators, energy absorbers).

From the social point of view, firstly, an informational system should be developed in order to clarify the seismic implications in the society and secondly a system that takes into account social policy, users need, structural design practice. So, a multi-level earthquake design is not begins and ends only with a multi-level based structural code.

The aim of this paper is to discuss the implementation of a multi-level design in current structural practice and after that to present directions on the design of steel earthquake resistant frames based one the introduction of fundamental structural properties as stiffness, strength and ductility in order to ensure the multi-level behaviour using the existing codes.

2. INTEGRATED MULTI-LEVEL EARTHQUAKE DESIGN

Multi-level earthquake design needs a multidisciplinary approaching due to great variety of factors affecting the final response of a structure under the probable seismic action. In figure 1 the inter-disciplinary factors for an integrated design is presented. One can observe that in this process the core is the clients' need and expectations. Furthermore, safety levels, social requirements as laws and customs, market values of the buildings, maintenance costs, repair costs after earthquakes, insurance premiums can be well prescribed in order to take the real value of the multi-level earthquake design concept. A research in Japan standing on questionnaires demonstrates that the owners want to suppress hazard severity to a small level, being more interested about " hazard of human life" and "loss of property" than for "function of building". Such researches are useful driving the social policy and the design performance objectives. Once we have resolve the social system framework it is necessary to evaluate the design earthquake. An important factor represents the reliable consideration of probable sources of potential seismic hazard, their selection and representation, in correlation with local site conditions. The contribution of engineering seismology and geotechnical engineering is valuable through macro and micro zonation studies, evaluating the seismic behaviour at the construction site. Unfortunately, there is a lack of such studies. Having all the aforementioned information conceptual conformation design, preliminary design and final design and detailing should be performed. As a function of considered performance targets a more or less sophisticated analysis and design must be made. So, it is easy to understand that the process of multi-level earthquake designs is an iterative one with so many uncertainties, cumbersome and time-consumable for current structural design offices. A solution should be the development of a new multi-level engineering framework composed by laws, open structural codes, insurance and banking support, proper fees for engineering services. Until to obtain such a system in the current design practice, it is important to introduce the spirit of multi-level structural performance exploiting the existing codes and methodologies.

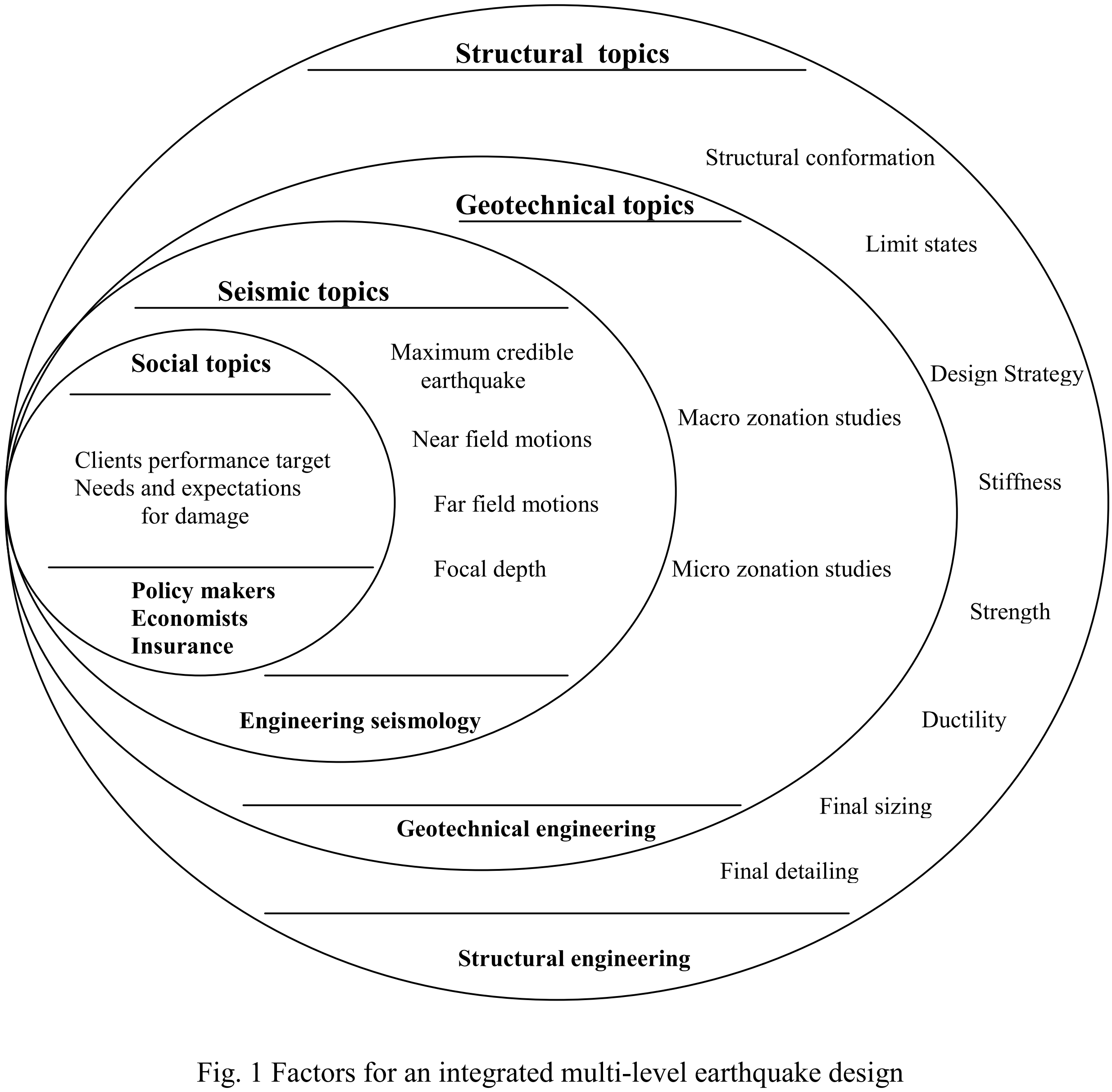

Fig. 1 Factors for an integrated multi-level earthquake design

For a successful implementation of performance based design at the beginning the architect together with the structural engineer and the client need to discuss a wide variety of the project topics including: the use and the importance of the project, users requirements and expectation for damage under minor, moderate and severe earthquakes, life-cycle cost of the construction, clients budget, post earthquake performance associated with repair cost and business interruption, dynamic behaviour of the proposed architectural layout.

An efficient multi-level earthquake design requires the explicit definition of performance objectives, performance requirements and acceptability criteria. As it was mentioned earlier a great debate exists among performance objectives of four, three or two levels[3,7,8]. Another important issue is the definition of the acceptability criteria through suitable performance indexes. It is evident that a single parameter as interstorey drift may not adequately control all the limit states. A methodology that seems to be easy implemented in current design practice is the RSD method which was elaborated by Gioncu and Mazzolani[7]. It is based on capacity-demands verifications of Rigidity, Strength and Ductility for different levels of seismic loads, Table 1. In the followings design directions according to the RSD spirit and existing European Code, EC-8, were presented.

Table 1. Multi-level earthquake design according to RSD matrix

Performance Objective	Limit State	Acceptance Criteria
No damage at structural and non-structural elements under frequent low earthquakes. *"Property Protection"*	Serviceability Limit State	*Rigidity* (Basic) Strength (Secondary)
Minor damage at structural elements under occasional moderate earthquakes *"Function of Building"*	Damageability Limit State	*Strength* (Basic) Rigidity (Secondary)
No collapse of structure under rare severe earthquakes *" Life safety"*	Ultimate Limit State	*Ductility* (Basic) Strength (Secondary)

3. DESIGN CONSIDERATIONS BASED ON RSD METHOD

3.1 Serviceability limit state

The serviceability limit state, under frequent low earthquakes, is considered satisfied if the response of a structure is completely elastic. Such behaviour is necessary for structures with sensitive equipment and high property values. It should be mentioned that the acceleration for each limit state is determined from different spectra due to the fact that ground motion parameters as frequency contents, amplification, and intensity are also different. Simplifying the aforementioned real fact the ν-redaction factor from EC-8 is adopted. The main performance index, characterizing this limit state is the interstory drift. Furthermore, according to RSD method the following acceptance criteria should be respected:

$$\textit{Required Interstorey Drift, } (R_{\delta.req.}) \leq \textit{Available Interstorey Drift, } (R_{\delta.ava.}) \qquad (1)$$

The evaluation of the available drift, $R_{\delta.ava}$, can be made using a linear elastic analysis method, with elastic spectrum, and compared with the required interstory drift, $R_{\delta.req.}$, which is given by EC –8 limitations[6] (for brittle and non-brittle non-structural elements). It is very important if the interaction of structural and non-structural elements may be considered in structural modeling. It is evident that the behaviour factor is taken 1.0. The preliminary and final design of steel elements refer to the interstory drift limitations, as a primary acceptance criteria, and after that the verification of strength and stability should be made, according to EC-8 and EC-3. A general proposal is presented in table 2. Given the experience captured from earthquakes and especially from recent severe ground motions it is demonstrated that is very difficult and uneconomic to design steel frames without taking special detailing measures (e.g. detached non-structural elements from steel resistant elements, base isolation, dampers, e.t.c.).

Table 2. General proposal for serviceability limit state verifications

<table>
<tr><td colspan="4">Performance Objective: No damage at structural and non-structural elements under frequent low earthquakes.</td></tr>
<tr><td colspan="4">Performance requirement: “Property Protection”</td></tr>
<tr><td colspan="4">Structural system: Steel moment frames with non-dissipative behaviour. q – factor equal 1.0</td></tr>
<tr><td colspan="4">Analysis method: Linear static analysis for regular structural layouts or linear modal analysis for irregular layouts using the elastic response spectrum by considering the low return period of seismic action. A possible consideration of both structural and non-structural elements in modeling is strongly required.</td></tr>
<tr><td colspan="4">Performance index: Interstory Drift</td></tr>
<tr><td colspan="4">Acceptability criteria: $R_{\delta.req.} \le R_{\delta.ava.}$ (Basic) ; $S_{(M,N,V)req.} \le S_{(M,N,V.ava.}$ (Secondary)</td></tr>
<tr><td>Elements</td><td colspan="2">Basic acceptability criteria</td><td>Secondary acceptability criteria</td></tr>
<tr><td rowspan="2">Beams
Columns
Connections</td><td colspan="2">$\delta_{el.} \le 0.010h$
(non- brittle elements)</td><td>$V_{tot.storey} / N_{tot.storey\,.} \ge 0.10$</td></tr>
<tr><td colspan="2">$\delta_{el.} \le 0.012h$
(brittle elements)</td><td>$V_{tot.storey} / N_{tot.storey\,.} \ge 0.12$</td></tr>
<tr><td colspan="4">Detailing of structural and non structural elements</td></tr>
<tr><td colspan="2">Conventional detailing</td><td colspan="2">Innovative detailing</td></tr>
<tr><td colspan="2">Steel sections of class 1,2,3
Steel wall plates
Non structural elements isolated from primary structural resistant elements with compressive materials</td><td colspan="2">Base isolation
Hysteretic dampers
Energy absorbers
Memory alloy devices</td></tr>
</table>

3.2 Damageability limit state

The damageability limit state, under occasional moderate earthquakes, is considered satisfied when structural damage can be repaired and global failures cannot occur. The repair cost should be limited according to economical and technical criteria. The non-structural elements are partially damaged. Structural damage in this level of performance is generally presented by local buckling of steel elements or connections component limited damage but without loose of the capacity to carry the gravitational loads. The occurrence of P-Δ global instability phenomena is, also, not permitted. However, this performance level presents the incipient phase of damage. The main performance index, characterizing this limit state is the strength and stability criteria as given from EC-8 and EC-3. Furthermore, according to RSD method the following acceptance criteria should be respected:

$$\textit{Required Strength, } (S_{(M,N,V)req}) \leq \textit{Available Strength } (S_{(M,N,V).ava}) \tag{2}$$

Consequently, the strength acceptability criterion is considered as the basic while the rigidity criteria is considered as secondary. The structure is designed for strength as is done in current design, considering behaviour factors greater than 1.0. This limit state follows the forced based design concept also using the capacity design strategy, in order to minimize and to control damage in predicted locations. Once the final design strength of elements was verified the top displacement of the structure should be respected. It is essential to underline that the proposed damageability limit state is equivalent with the current ultimate limit state due to the fact that elastoplastic mechanisms are defined through strength and stiffness criteria. In table 3 a general scheme for design purposes is proposed. Due to the fact that in damageability limit state the main target is to measure the level of damage, except all the aforementioned verifications a suitable damage index must be considered quantifying the grad of structural elements damage. The Park and Ang[11] damage functional is a proposal, but more research should be done in order to obtain practical formulation for cumulative damage.

Table 3. General proposal for damageability limit state verifications

<table>
<tr><td colspan="3">Performance Objective: Minor damage at structural elements under occasional moderate earthquakes</td></tr>
<tr><td colspan="3">Performance requirement: “ Function of Building”</td></tr>
<tr><td colspan="3">Structural system: Steel moment frames with dissipative behaviour. q – factor greater than 1.0</td></tr>
<tr><td colspan="3">Analysis method: Linear static analysis for regular structural layouts or linear modal analysis for irregular layouts using the reduced elastic response spectrum by considering elastoplastic action through q-factor. For special cases (high structural irregularity, severe ground motions with unsuitable soil conditions) a push-over analysis should be used.</td></tr>
<tr><td colspan="3">Performance index: Strength and stability control (Basic); Top displacement (Secondary)</td></tr>
<tr><td colspan="3">Acceptability criteria: $S_{(M,N,V)req.} \leq S_{(M,N,V.ava.}$ (Basic); RΔ.req. $\leq R_{\Delta.ava.}$ (Secondary)</td></tr>
<tr><td>Elements</td><td>Basic acceptability criteria</td><td>Secondary acceptability criteria</td></tr>
<tr><td>Beams</td><td>§ 6.6.2 / EC-8[6]</td><td rowspan="3">$\Delta_{top} \leq H/500$
Δ_{top} obtained from loads non multiplied with load safety factors</td></tr>
<tr><td>Columns</td><td>§ 4.4.2.2, § 6.6.3 / EC-8[6]</td></tr>
<tr><td>Connections</td><td>§ 6.5.5 / EC-8[6]</td></tr>
<tr><td colspan="3">Damage Index, I_D,: Park and Ang damage index[11]</td></tr>
<tr><td colspan="3">Detailing of structural elements</td></tr>
<tr><td colspan="2">Global conformation</td><td>Local conformation</td></tr>
<tr><td colspan="2">Structural simplicity-continuity
Symmetry and redundancy
Bi directional stiffness
Suitable foundation system</td><td>Steel sections of class 1,2
Avoidance of flexural-torsional buckling
Reduced location with stress concentrations
High redundant connections</td></tr>
</table>

3.3 Ultimate limit state

The ultimate limit state, under severe rare earthquakes, is considered satisfied when no collapse is occurred and life safety is obtained. The non-structural elements are completely damaged and also locally some elements, possibly, don't sustain their dead load. The avoidance of global collapse is the main performance target. Predicted local failures are admitted. Consequently, the determination of expected deformation capacity of elements, failure mechanism, member strength hierarchy and ultimate inelastic deformation is of primary importance. A controlled plastic mechanism should be obtained only using kinematic global analysis and deformation based design concepts, avoiding dangerous concentrations of seismic action[7,10,12]. Despite all these obvious issues, the majority of seismic design codes, in order to assure the inelastic deformation capacity, work with stringent stiffness and strength criteria without an explicit evaluation of the ductility. To achieve the ultimate limit state the basic acceptance criteria that should be respected is:

$$\textit{Required Ductility,}\ \ (D_{\mu\theta.req.}) \leq \textit{Available Ductility,}\ \ (D_{\mu\theta.ava.}) \qquad (3)$$

A proposal towards the evaluation of both the available and required ductility is given elsewhere [7,10]. Once the steel elements obtained from ductility based design, the strength conditions should be checked. In this way it is possible to decouple the domination effect of stringent drift limits in the design of steel moment frames. In current EC- 8 the deformation capacity defined only through general conditions. It is very important to introduce the concept of ductility-based design through an annex format. Table 4 presents a simplified proposal for the verification of ultimate limit state.

As it was demonstrated from past earthquakes, the maximization of the inelastic capacity of a structure is strongly related with the correct structural detailing. Furthermore, in order to mitigate the consequence of the calculation discrepancies more attention must be paid in structural details that enhance energy absorption capacity of steel frames using "dog-bone" connections, high redundant details, only class 1 sections.

4. CONCLUDING REMARKS

The multi-level earthquake design is a promising engineering concept that clearly represents the future progress in earthquake engineering. Certainly, performance-based design from the definition needs a probabilistic reliability format. A structure is protected for specified performance level with a given annual probability of excedence. In order to be implemented such a design it is necessary to be developed a social as well as a new structural framework.

From structural point of view, we have a long way till to introduce in current practice a multi-level earthquake design format, taking into consideration difficulties as the reliable definition of seismic actions, regulations for the different performance levels correlated with corresponding performance indices, a database of structural failures associated with a given probability of excedence or a database of structural details with a prescribed probability of damage, development of construction quality control, feasibility studies and so on. Much research should be done in order to obtain suitable criteria for site performance in terms of acceptable foundation settlements and soil-foundation-structure interaction.

However, it is essential to introduce as a first step, the basic concept of multi-level design through RSD method exploiting the current structural regulations and experience captured from past earthquakes. For this only a ductility-based design is necessary to be implemented in EC-8, and more information about different structural details for the different limit states. Using the RSD method a designer is capable to project structures according to clients performance targets meaning as "Loss of property" (serviceability state), "Function of Building" (damageability state) and "Life safety" (ultimate state).

Table 4. General proposal for damageability limit state verifications

Performance Objective: No collapse of structure under rare severe earthquakes
Performance requirement: " Life safety"
Structural system: Steel moment frames with dissipative behaviour. q – factor greater than 2.0
Analysis method: Equivalent static analysis connected with force distributions obtained from plastic analysis[11] using as seismic actions those obtained from inelastic spectra. For irregular layouts push-over analysis seems to be a good solution. For special cases time-history analysis is necessary.
Performance index: Ductility defined as the rotation capacity of plastic hinges (Basic); Strength and Stability conditions (Secondary)
Acceptability criteria: $D_{\mu\theta.req.} \le D_{\mu\theta.ava.}$ (Basic) ; $S_{(M,N,V)req.} \le S_{(M,N,V.ava.}$ (Secondary);

Elements	Basic acceptability criteria	Secondary acceptability criteria
Beams	A comprehensive methodology presented in [7]	§ 6.6.2 / EC-8[6]
Columns		§ 4.4.2.2, § 6.6.3 / EC-8[6]
Connections		§ 6.5.5 / EC-8[6]

Detailing of structural elements	
Global conformation	Local conformation
Strong column- weak beam concept Avoid soft story mechanism Avoid very short beam spans Provide mass and stiffness symmetry Provide with structural continuity	Steel sections of class 1 "Dog-bone" connections Special fuse elements in predetermined positions High redundant connections

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