A CODE FOR CURTAIN WALL SYSTEMS IN SEISMIC REGIONS

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ABSTRACT :

Despite the fact that they are not part of the structural systems of buildings, glass and aluminum curtain wall systems are far from being secondary in importance. The response of a curtain wall to seismic action depends on the response of the structural system to which it is connected. Thus, it depends not only on the characteristics of the ground motion that excites the structural base of the building, but also on the dynamic characteristics of the buildings. Until 1990, buildings with curtain walls were practically absent in Romania. Today, glass and aluminum curtain walls are found in city centers, in many new buildings, being quite popular as cladding and exterior walls for all types of commercial, industrial, institutional and residential buildings. The need for modern buildings led to the situation in which the private investors, together with certain autonomous administrations, finance buildings with claddings made of different curtain wall systems. Almost everybody has unfortunately ignored one single aspect: the peculiar characteristics of the Vrancea source seismic ground motion in Romania. The author of this paper was involved in the design of a high-rise building with a curtain wall system in a high seismic region, while being confronted with a critical problem: the lack of technical regulations for curtain wall systems. He was also in charge with the drafting of a code for the Romanian "Ministry of Development, Public Works and Housing" concerning the design of curtain wall systems in seismic regions. The paper presents a summary of this code, focusing on its specific earthquake provisions to cope with Romanian intermediate depth earthquakes.

KEYWORDS: curtain wall, seismic design, glazing, code

1. INTRODUCTION

The curtain wall fulfills one of the most demanding roles in building construction. Not only does it provide the primary image for the building, but it also performs the multiple functions required of an exterior skin – that is to form a protective enclosure, to keep out the outside environment and to maintain the inside environment – in an efficient, economical manner. Before 1990, the use of architectural glass in storefront wall systems was practically absent in Romania. Today the situation has changed; the use of curtain walls is common and widespread. Glass and aluminum curtain walls are found almost everywhere in new buildings, being quite popular as cladding and exterior walls for all types of commercial, industrial, institutional and residential buildings. The need for modern buildings led to the situation in which the private investors, together with certain autonomous administrations, finance buildings with claddings that are carried out with different curtain wall systems. Almost everybody has unfortunately ignored one single aspect: the peculiar characteristics of the Vrancea source seismic ground motion in Romania. Taking into account the need of enhanced safety it appears necessary to provide some information on the main features of the strong earthquakes that have occurred in this European country.

2. MAIN FEATURES OF STRONG EARTHQUAKES IN ROMANIA

During the last 68 years, Romania was struck by two destructive intermediate-depth earthquakes which occurred in the Vrancea region on November 10, 1940 ($M_{G\text{-}R}$ =7.4) and March 4, 1977 ($M_{G\text{-}R}$ =7.2). These two were followed by other three strong earthquakes, with the foci in the same region, on August 30, 1986 ($M_{G\text{-}R}$ =7.0), May 30, 1990 ($M_{G\text{-}R}$ =6.7) and May 31, 1990 ($M_{G\text{-}R}$ =6.1).

The seismic areas cover over 65% of the territory of Romania, generating almost 70-80% of the national economic output. The most important seismogenic zone is the Vrancea area, which is the source of more than 95% of the energy released in Romania. The Vrancea intermediate depths earthquakes (depth between 80 and 160 km) affect with high intensities extensive parts of the territory of Romania (Figure 1). During the last century three events with magnitudes $M_{G\text{-}R} \geq 7.0$, as well as two events with $M_{G\text{-}R} \geq 7.2$ have occurred. Other crustal seismogenic zones, in the Fagaras Mountains, in Banat, along the northwestern border, in the Tarnave region, in the South of Dobrogea (the Shabla-Caliacra zone), and are characterized by less intense activity, though they can generate locally very high intensities (e.g. $M_{G\text{-}R}$ =7.2, $I_0 = X$ MSK for the 1901 Shabla-Caliacra earthquake and M_S=6.5, I_0 = VIII for the 1916 Fagaras earthquake).

The capital city Bucharest is affected mainly by earthquakes originating in the Vrancea zone, which generated frequently high intensities with return periods of some 20 years for $I = VII$, of 50 years for $I = VIII$, and of 200 years for $I = IX$, where I represents MSK intensities (Georgescu, 1999).

Figure 1. The seismic hazard (zoning) map of Romania (MSK intensities).

2.1 March 4, 1977 Vrancea earthquake *(Vlad and Vlad, 2008)*

The first strong motion recorded in Romania was the triaxial accelerogram obtained on a 1967 SMAC-B type strong motion accelerograph during the March 4, 1977 Vrancea event, in the specific soil conditions of Bucharest. The peak ground acceleration values in the N-S, E-W and vertical directions were 0.20g (PGA=194.9 cm/s^2), 0.16g and 0.10g, respectively. A glance at the record shows that the long period components were predominant, aspect that surprised the engineering community of Romania, although engineers were acquainted with the code proposal written by engs. Emilian Titaru and Alexandru Cismigiu at the 2WCEE (Japan). So, one can consider as birth date of the instrumental earthquake engineering in Romania the date of March 4, 1977.It is very important to note that the shape of the spectrum was very different of that generally assumed in the code in force at that time. It must be mentioned that the elastic spectra shape had been imported from the Soviet code SN-8-57, characterized by a maximum dynamic amplification factor β_0 =3.0 and a corner period of response spectra T_C=0.3s, which, at its turn, roughly corresponded only to the main peak of the 1940 El Centro earthquake spectra. *The highest spectral values occurred in the range of periods 0.9...1.5 s for the N-S component, and of periods 0.7...1.2 s for the E-W component*. Taking into account the above-mentioned values of the dominant periods, it was to be expected that the damage should occur especially for the flexible buildings, having fundamental eigenperiods of vibration of more than 1.0s. With this information in mind, one can make a pertinent characterization of the behavior of residential buildings and dwellings during earthquakes in Romania.

2.2 August 30/31, 1986 Vrancea earthquake (Vlad and Vlad, 2008)

During the night of 30 to 31 August 1986, Romania was shaken by another earthquake originating in the Vrancea seismogenic zone. This earthquake affected with high intensities extensive areas. The maximum acceleration recorded during this seismic event was close to 0.3g (in fact, the highest *PGA* value was recorded in Focsani, a town located in the nearest neighborhood of the instrumental epicenter). The *PGA* values in Bucharest ranged between 0.06 g and 0.16 g (for the N-S component) and between 0.04g and 0.11g (for the E-W component), with important peaks between 0.7 and 1.3 seconds. There were considerable differences in the spectral contents of the motion at different sites. The magnitude of this earthquake was $M_W = 7.3$ ($M_S \cong 6.8$, $M_{G\text{-}R} = 6.9$, $m_b = 6.5$ to 6.6). The 1986 INCERC record at the same location as in 1977 had *PGA* values of 0.10g (E-W component) and 0.09g (N-S component), with predominant period of 1.1 s. This supports the idea that intermediate depth earthquakes tend to produce longer predominant periods when their magnitude increases.

2.3 May 30 and 31, 1990 Vrancea earthquakes (Vlad and Vlad, 2008)

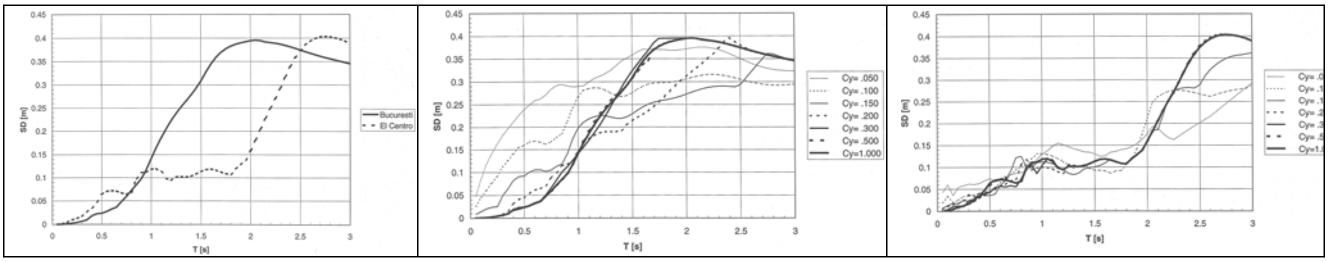
During the May 1990 earthquakes at least 29 seismic instruments were triggered in various towns, especially in the East and South of the Carpathians, and 9 seismic instruments recorded the motion in different locations in Bucharest. Firstly, it must be mentioned that 5 stations recorded *PGA* values larger than 0.20g in a wide area (maximum value in Campina equal to 0.26g). A variety of *PGA* values between 0.07g and 0.14g were reported during the main shock in Bucharest. Several new lessons seemed to emerge with the first information obtained from the 1990 accelerograms in Bucharest. Many records of the main shock on the E-W direction were stronger than on the N-S components (opposite to the previous two seismic events). The second important remark was that the predominant periods were, this time, much shorter. The characteristics of the strong motions recorded in *Bucharest* during the 1977, 1986 and 1990 Vrancea earthquakes are summarized as follows (Pomonis, 1990):

- *PGA* (cm/s^2): 215 (1977); 60 to 160 (1986); 70 to 140 (1990);
- range of predominant periods (s): 0.9 and 1.5 s (1977); 0.7 to 1.3 s (1986); 0.25 s to 0.8 s (1990).

3. SEISMIC EFFECTS ON A CURTAIN WALL SYSTEM

A seismic event causes the building frame to undergo various (absolute and relative) displacements, producing relative inter-floor deflection (vertical component of seismic motion) and inter-floor story drift (horizontal component of seismic motion). Since the masses of the building frames and floor slabs are extremely large as compared to the masses of curtain wall systems, it is impractical to design the curtain wall system to resist the inertia forces inherent in the relative inter-floor deflection or inter-floor story drift. Therefore, the curtain wall system must be designed to tolerate the seismic-induced building frame displacements, which are function not only of the seismic zone rating, but also of the building frame stiffness. In case of seismic induced story drift, the curtain wall supporting vertical elements are forced to tilt to one side, which in turn will create the tendency to force the curtain wall panel to change shape.

The values of displacements given by the response spectra of relative displacements for the 1977 Vrancea record are much higher values in comparison with those of the 1940, El Centro earthquake for the critical spectral interval of about 1.2 s to 2.2 s. Worst is the fact that these displacements are greater just in zones with buildings having eigenperiods up to 1.5 s. In Figure 2,a the elastic displacement spectra of both Vrancea and El Centro earthquakes are given. In Figure 2,b (Vrancea, 1977) and 2,c (El Centro, 1940) relative displacements response spectra for different base shear force coefficients (c_Y), corresponding to the maximum strength capacity offered by the structural system considering the associated inelastic mechanism, are presented. The drift requirements are a consequence of the displacement spectra requirements. For this reason, the above comparison between the Vrancea and the El Centro earthquakes is carried out in terms of *displacement spectra*. At a simple glance, one can understand why the displacements demands for Vrancea earthquakes are more severe in comparison with those of El Centro type earthquake (Titaru, 2008).



(a) (b) (c)

Figure 2. Comparison between displacement spectra of the 1977, Vrancea and the 1940, El Centro earthquakes.

In the period 2000-2002, the author of this paper was involved in the re-design of a modern multi-story office building in the town Ploiesti, a town that is close to the Vrancea region. Since the initial technical project phase didn't receive the legal acceptance, the re-design process became necessary. The owner asked a curtain wall system for his building.

A deep void existed at that time in the design practice to seismic action of architectural curtain wall systems. This fact didn't prevent the design companies to accomplish buildings with glazing systems. It must be mentioned that the seismic code in force didn't contain direct provisions for the seismic design of architectural glass elements, nor did standard laboratory test methods exist for evaluating the seismic performance of the different imported curtain wall systems. As a result, it is expected that most of the existing curtain wall systems built without seismic legislation will undergo severe damage during the occurrence of a strong earthquake. This gap in the seismic design of architectural curtain wall systems must be assigned on one hand to the fact that curtain wall systems (and the architectural glazing elements within them) were not used before 1990 and on the other hand to the fact that they were considered by the designers as "non-load bearing" subsystems. Such a notion is erroneous because curtain wall systems receive structural loadings due to earthquakes, wind, weather, showers of hail, blast and even to human impact.

Practically, when the author of this paper was put in the situation of designing the curtain wall system for the above mentioned building and taking into account the peculiarities of the seismic action in Romania, the problem appeared very difficult to be solved. When contacting a company that was supplying curtain wall systems and after verifying the behavior of the proposed system to wind action (according to the code in force), it turned out that the system was not able to fit the requirements. The same results were obtained considering some other systems. At that moment, it appeared clear enough that all curtain wall systems were inappropriate for use in the high seismicity zones of Romania, making it necessary to pay a special attention and a sound engineering judgment. In this situation, a proposal for the development of a code for the design and mounting of curtain wall systems in seismic regions was submitted to the Romanian Ministry of Public Works. The proposal was approved and the code was completed according to the requirements of the "Law of Construction Quality" in force in Romania.

4. THE ROMANIAN CODE FOR CURTAIN WALL SYSTEMS

The complete title of the code is "Code for the design and mounting of curtain wall systems according to the quality requirements stipulated in the Law 10/1995 (Law of Construction Quality)". The main topics included in the code are briefly presented as follows.

Chapter 1. General. This chapter presents the object of the code and its field of application, the connection with the existing technical legislation, together with its harmonization with the new European ones (Eurocodes).

Chapter 2. Categories of curtain wall systems. A series of classifications are presented in this chapter, considering their own structural systems, their position towards the structural system of the building, their outdoor image, their manufacturing and their installation.

Chapter 3. Overall layout and materials used for curtain wall systems. A curtain wall system consists of vertical members (mullions) and horizontal members (rails), panels, thermo insulating glazing and several fastening parts. The curtain wall system must be adapted for different types of buildings and different environment conditions. In this chapter, the elements and the invariable and variable characteristics for each curtain wall system are specified. Further on, requirements for all the component elements of a curtain wall system are given. As an example, the code specifies the types of glass that are recommended to be used: monolithic glass, wire glass, tempered monolithic glass, tempered glass, heat strengthened glass, float glass and laminated glass.

Chapter 4. Specific requirements and performance criteria. At the beginning of this chapter, two types of specific requirements are presented.

The *functional requirements* are: *preserving the quality and the functioning capacity* of the curtain wall system during the lifetime that has been established in the design process and *assuring a favorable behavior* during its use, so that people, existing material values and equipment should not be affected. The *structural requirements* refer to the *resistance and the structural stability* of the curtain wall system, and to the *capacity of not to undergo damage* due to static and dynamic loading.

The code also contains the essential requirements regarding the behavior of a curtain wall system under normal loads on their plane, the possible cases when damages may occur and how these can be avoided, requirements and specific performance criteria. The curtain wall systems, together with their fastening on the structural system of the buildings, will be designed and mounted so that during the term of execution and during their lifetime none of the following events happens:

- the partial/local or total collapse of the curtain wall system;
- the destruction of the glass panels;
- the damage of the fastening and tightening systems as a result of excessive deformation of the structural system of the buildings, or of the curtain walls;
- limitation or total blocking of the opening and closing possibilities of windows and doors;
- vibrations with unacceptable levels of intensity for normal operation of the curtain wall systems.

The fulfillment of the above general demands depends on the general conception and the detailing of the curtain wall system, of its components, of the connections between these components, and of the links with the structural system of the building; it also depends on the properties, performances, and the use of the construction materials, and finally on the execution quality together with the necessary maintenance works. In the case of curtain wall systems, the occurrence of failure of *progressive collapse type* may be limited, or avoided, by adequate measures as adopting a structural configuration without sensitivity to earthquakes (redundant structural configuration) and assuring sufficient ductility for its own elements and for the connections with the structural system of the building.

The specific requirements for the investors and users in what concerns the behavior of the curtain wall system under the effect of dynamic actions of earthquakes are the following ones:

- *life safety demand*: mitigation of the risk of the downfall of glasses of the curtain wall systems; this requirement imposes measures for preventing the falling of glass pieces in case of breaking;
- *damage limitation requirement* in order to diminish the cost of repairing the curtain wall damaged by earthquakes, and the losses caused by the interruption of the activities due to the damage of the building façade.

The code specifies that the "*life safety demand*" is imposed by the existing technical legislation, while the "*damage limitation requirement*" pertains, as a rule, to the investors.

Chapter 5. Specific design requirements according to the Law of Construction Quality. According to this law, the achievement and maintenance of the following demands, during the lifetime of a curtain wall system, are mandatory: *strength and stability*; *safety during lifetime*; *fire safety*; *sanitation, people health, protection of the environment*; *thermal insulation, waterproofing and energy saving*; *acoustic insulation.*

In this chapter, the code presents the design requirements for each of the above "demands". Taking into account the subject of this paper, only the aspects related to the "strength and stability" demands will be presented, more exactly those requirements regarding the loading of the curtain wall systems by a seismic action. The code also contains provisions on the existing relation between the curtain wall system and the structural system of the building.

The checking of the behavior of the curtain wall systems to seismic action (analytically and experimentally) will establish their use policy according to the dynamic eigencharacteristics of the buildings and to the site conditions, in order to assure the prevention of: *damage to the glass panels* and of the fastening devices, and *damage to joints* that can affect the leakage for water penetration, the air tightness and the thermal and phonic insulations. The code states that an earthquake may simultaneously generate *two categories of effects* on a curtain wall system: the effect of seismic action as a result of inertia forces acting normal on its plane, together with the effect of seismic action as a result of deformations imposed to the curtain wall by the relative lateral displacements of the fastening points in respect with the structural system of the building.

The *effect of the inertia forces acting in the plane of the curtain wall system* may be estimated having in mind the following aspects:

- for the design/checking process, the *peak value of the acceleration* will be considered (the seismic acceleration for the structural analysis corresponding to the site of the building);
- the *floor accelerations* will be established for each panel/subsystem of the curtain wall, having in mind that there should be made certain adjustments to the coefficient corresponding to overstrength reserves of the structural system of the building;
- the *relative floor displacements* will be established taking into account the fact that these might impose in- plane deformations to the panels of the curtain walls, considering the drifts associated to the post-elastic stage of behavior.

In what concerns the *effect of the seismic action as a result of the imposed deformations of the curtain wall system* (relative displacements which act in the plane of the panels of a curtain wall), the relative floor displacements will be determined at each panel level of the curtain wall system.

For the buildings that make the object of this code, Eurocode 8 states that the effects of the seismic actions on a panel of the curtain wall system may be determined by applying a horizontal force "F_a", which is defined as follows (Eqn.4.1):

$$F_a = \left(S_a \cdot W_a \cdot \gamma_a\right) / q_a = \frac{1}{2} \cdot S_a \cdot W_a \qquad (4.1)$$

where:

F_a = horizontal seismic force, acting at the center of mass of the panel, in the most unfavorable direction;
W_a = weight of the panel;
γ_a = importance factor of the panel (usually $\gamma_a = 1$);
q_a = behavior factor of the panel ($q_a = 2$)
S_a = seismic coefficient pertinent to the panel, given by the Eqn.4.2:

$$S_a = \alpha \cdot S \cdot \left[3\left(1 + z/H\right) / \left(1 + \left(1 - T_a/T_1\right)^2\right) - 0.5\right] \qquad (4.2)$$

where:

α = ratio of the design ground acceleration to the acceleration of gravity;
S = soil factor (generally $S = 1.2$);
T_a = fundamental period of vibration of the panel;
T_1 = fundamental period of vibration of the building in the most flexible direction;
z = height of the panel above the level of application of the seismic action ;
H = building height from the foundation level, or from the top of the basement "rigid box".

The code also establishes the following aspects:

- the determination of size of the fastening elements between the curtain wall structural system and the structural system of the building will be realized considering the efforts resulted from the application (in the center of mass of the curtain wall panel) of a conventional seismic force $F_{fastening}=3F_a$;

- all the components of a curtain wall system should resist to seismic forces in any horizontal direction, considering a dynamic and geometrical amplification equivalent to "$3k_s$" and an additional assuring equal to 33%, corresponding to a change of the return periods;
- in the façade plane, the curtain wall system has to undergo, without affecting the constructive and the structural integrity, values of drifts that will be established for each building apart; the resulted values will be amplified by a factor equal to 1.5 for reinforced concrete structural systems, and 1.25 for steel structural systems;
- the curtain wall systems will be designed in order to be able to undergo all the lateral displacements of the structural system of the building that are generated by the seismic action (the drifts and the effects of the overall torsion of the building), and certain specific deformations.

In the regulatory basis in force in advanced countries, it is quite often mentioned that the values established for the design parameters correspond to a minimum protection level allowed. The owners of works of various categories are free to adopt a higher protection level, in case they feel that this is necessary. In cases when the need to modify the protection level in comparison with the specifications of the code P.100 appears (given the fact that, for zones affected primarily by Vrancea earthquakes, the return periods of design values are around 50 years for data specified according to the version P.100-92 and around 70 years for data specified according to the version P.100-2006), the values corresponding to a return period T_{ret} can be obtained, in the case of absence of special studies on local conditions, by means of applying a correction factor α_{ret} (P.100-92) given by the expression:

$$\log_{10}\alpha_{rev} = 1{,}45 - 4{,}2/\left(\log_{10}T_{rev} + 1{,}2\right) \tag{4.3}$$

The empirical relation (4.3) relies on the outcome of parametric probabilistic studies on seismic hazard, based on data on magnitude recurrence for Vrancea earthquakes and on data concerning the attenuation phenomenon. The (favorable) probability $P^{(+)}$ (T_{ret}, T_{exp}), of non-exceedance of a value q_{Tet} corresponding to a return period T_{ret}, during an exposure time interval T_{exp}, is given by the expression:

$$P^{(+)}\left(T_{tev}, T_{exp}\right) = e^{\left(-T_{exp}/T_{rev}\right)}, \tag{4.4}$$

while the (unfavorable) probability of exceedance, at least once, $P^{(-)}$ (T_{ret}, T_{exp}), is given by the expression:

$$P^{(-)}\left(T_{tev}, T_{exp}\right) = 1 - e^{\left(-T_{exp}/T_{rev}\right)} \tag{4.5}$$

The relations (4.4) and (4.5) correspond to the mathematical model of Poissonian stochastic process and are valid for the cases of seismic action and of wind action, both (Sandi, 2008).

Chapter 6. Loads. Load combinations. Capacity design method. This design method aims to establish a favorable succession of the development of post-elastic deformations in the case of overloading which implies the exceeding of the elastic stage of behavior.

Chapter 7. Experimental methods for testing curtain wall systems. The experimental testing of curtain wall systems for obtaining the technical agreements in Romania, do not make the object of the code. European standards were adopted for application. However, when specifying the technical characteristics of a curtain wall system special mentions about its behavior to seismic actions should be made. Two distinct situations are presented in the code:

- if in the case of a selected curtain wall system tests carried out in authorized laboratories exist, the reports of these experiments will be presented with reference to the spectral pattern considered;
- in the case of a selected curtain wall system that was not tested in authorized laboratories, *the mandatory condition for the assignment of the works* is that the winning company will have to accomplish these tests, corresponding to Vrancea earthquake demands.

Chapter 8. The mounting of curtain wall systems. The code contains all the necessary steps that a specialized company has to take, before and during, the assembling of the curtain wall system.

Chapter 9. Obligations and specific responsibilities according to the Romanian "Law of Construction Quality". Once more, the code clarifies the obligations and the specific responsibilities of all factors involved in the design, construction and operation of curtain wall systems: investors, general designers, specialty designers, project checkers, manufacturers and suppliers, building contractors, involved technical responsible teams, owners and technical agreement commissions for buildings.

5. INSTEAD OF CONCLUSIONS

Today, mall fronts, department stores, governmental buildings, office buildings and even low-rise commercial buildings, incorporate curtain wall systems in most of the populated regions. As it was already mentioned in this paper, Romania is a country with very high seismicity. Due to their deep foci, Vrancea earthquakes are of a particular nature for a large area of Romania, practically they are unique in the world. The curtain wall systems have been, and still are, imported from countries with low seismicity, where earthquakes are quite rare and of different characteristics than those in Romania. In order that a building attains the fully operational performance level, the curtain wall system must perform as reliably as the structure itself. During many past earthquakes that have been recorded worldwide, building structural systems have performed adequately, while the curtain wall systems did not. This points to a general inadequacy in current practice and approaches to the design and installation of curtain wall systems, and this often occurs because responsibility for the design and mounting of such systems is delegated to persons who are not trained in seismic engineering. This paper is intended to be an alarm signal to the Romanian authorities, as many curtain wall systems exist in populated areas that have a history of seismic activity and have not been properly designed for earthquake effects. Despite the popularity and widespread use of the curtain wall systems at present, limited information still exists in current building codes to guide for their seismic design. That's why special attention should be paid when using architectural glazing in curtain wall systems. The code tried to fill the gap, providing mandatory requirements. A special attention must be paid to the "so called" project of a curtain wall system and to the experimental investigations of panels and different components of the system (adaptation of a curtain wall system type to the seismic condition of each site, together with the checking to wind loads). On the other hand, since the endorsement of the code entitled "Code for the design and mounting of curtain wall systems according to the quality requirements stipulated in the Law 10/1995 (Law of Construction Quality)" many designers did not apply the existing provisions, benefiting from the large contribution of the officials that were in charge to avoid these situations. The author of the code and of this paper was not yet asked by the designers about any provision of the code, what means that the code is clear enough and easy to apply, but was many times asked how to try to avoid some code provisions, especially those referring to the mandatory testing. Curtain wall technology continues to evolve. As a result, curtain walls are lighter, more economical and constructed of new materials. For this reason it is important to develop experimentally verified structural models of analysis capable of predicting serviceability limit states and ultimate limit states for common types and sizes of architectural components of given curtain wall systems.

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