SEISMIC RESISTANT ARCHITECTURE: A THEORY FOR THE ARCHITECTURAL DESIGN OF BUILDINGS IN SEISMIC ZONES

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SUMMARY

The interaction between the architectural and the structural design produces situations that reduce the seismic resistant capacity of buildings. Though several studies and recommendations have been carried out to avoid such situations, the author proposes a general theory to be developed in the Earthquake Engineering research Institute "Ing. Aldo Bruschi", National University of San Juan. Such theory allows architects to develop a systematic study and a methodology to be applied to the architectural design of buildings in seismic zones. This theory is called "Earthquake Resistant Architecture".

The partial advances were presented in Meetings all over the world: Tokyo, 1988; Madrid, 1992; Acapulco, 1996.

This paper compiles the last advances and presents the theory. That is, purposes, principles, definition, contents, methodology, architectural responses in morphological terms and guidelines to make the architectural and the structural designs compatible.

This theory considers the building as a set of components interacting during the earthquake. The situations affecting negatively the building earthquake resistant behaviour are avoided.

On the other hand, such negative situations causes the stepping of the building seismic resistant capacity. This allows the formulation of the theory's principle: "The earthquake resistant structure should be capable of offering all its seismic resistant capacity simultaneously during the ground shake. Otherwise, the stepping occurs causing the building be on the point of collapsing."

Therefore, the aims of the Earthquake Resistant Architecture are: First, to avoid the building earthquake resistant stepping and, Second, the interaction of all the elements interacting during the quake should be positive; thus the optimisation of the building earthquake resistant capacity is achieved.

The final conclusion is that the Earthquake Resistant Architecture constitutes a general theory that enables architects to properly design buildings in seismic zones not only avoiding the negative situations but also making their earthquake resistant capacity optimum.

ARCHITECTURE IN SEISMIC ZONE

Architecture in Seismic Zone (ASZ) refers –in its broadest sense – to the responsibilities architects should take in order to help solve the seismic problem of human settlements in highly hazardous seismic zones.
Broadly speaking, it covers six study lines:

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I- *Urban Planning*

- Seismic hazard.
- Urban design.

II- *Emergency*

- Prevention (seismic resistant standards)
- Emergency provisions (seismic protection scheme)

Natural Disasters Prevention and Provisions Law.

III- *Seismoresistant Building Architecture (or design).*

- Matching of architectural and structural designs.

IV- *Esthetical and Morphological Characteristics of the S. R. A.*

V- *Preservation and Restoration of the Patrimony of Historical Buildings.*

VI- *Training and Professional Performance of Architects of Seismic Zones.*

The reason for the importance of the ASZ results from the fact that it is present throughout the architecture body.

The name adopted in III is justified by the fact that its overall objective is to prevent that the interaction of the seismoresistant structure with the building architectural design during seismic shaking would create maladjustments which would decrease the seismoresistant capacity of the building. In addition, the study pursues the optimization of such capacity.

SEISMORESISTANT ARCHITECTURE

Introduction

The neglectfulness of the interaction between the resistant structure and other non-structural elements in the building modifies the resistance-stiffness relationship of structural elements. In such a situation, it is possible that the structure does not show all the resistant capacity simultaneously as required during the seismic action. This stepping of the building's seismoresistant capacity results in its partial damage or a total collapse.

This is one reason for the pure structural analysis becoming insufficient to assert the seismic invulnerability of a building.

Therefore, an additional approach becomes necessary, which may regard the seismoresistant system as a whole, where all the structural, non-structural and space-forming elements conforming a building are considered to be interacting with each other and hold responsible for the seismoresistant capacity.

According to this approach, such responsibility is shared by both the structural analysis and design.

As a matter of fact, it is not pursued here to obtain from the computing engineer a quantitative evaluation of positive and negative effects of all the interacting elements of a building, but rather to match them with the structural design.

For instance, if a sismoresistant structure or rigid frame is made up of a given number of columns, they should all show the seismoresistant capacity simultaneously during the seismic stage. Otherwise, if owing to any reason, not regarded in the *Structural Design and Analysis*, just part of them act at the beginning of the shake, this will be insufficient and eventually will break down. The remaining ones will fail in turn, bringing about the collapse of the building.

This stepping does not refer to such plastic deformations which may be adjusted by means of an adequate redistribution of solicitations and stresses. It refers to severe steppings where such plastic deformations are remarkably overwhelmed.

Definition

From our viewpoint, the SRA deals with the interaction of each subsystem of the building during seismic shaking, in order that the architectural project does not originate structural maladjustments which would decrease the seismoresistant capacity of the building.

General Objectives

- To prevent seismoresistance stepping.
- To optimize the seismoresistance.

S. R. A. THEORY

The development of our SRA was done on four study lines.

a- To schematize and improve the Seismoresistant Structural Design under the constraints of the Architectural Design.

b- To define the general principles of the Seismoresistant Building Architecture.

c- To schematize and improve the interrelations and compatibilization between the Structural Design and the Seismoresistant Architectural Design.

d- To develop a SRA based upon the congruent interrelations between every and each interacting structural subsystem (or component).

Basic Principle

The theory, methodology and research which will help develop that approach should unavoidably meet the following requirements of this basic principle: "*The seismoresistant structural elements should produce the stiffness, strength ductility and synchronization as anticipated in the structural design and analysis when subjected to seismic action*".

That is, they should be able to show their seismoresistant capacity almost simultaneously. Otherwise, the resistant capacity may step up, and this eventually may cause the structure's failure.

From the structural analysis point of view, and for the cases of stiff slabs or floors, this is achieved by distributing the seismic shear proportionally to each resistant element's stiffness and torque proportional to stiffness, and distance to the center of torsion.

As a whole, and as a primary factor, the structural and architectural designs should achieve the necessary compatibility among all the structural elements of the building, in order to satisfy this basic principle.

Basic Criteria

The following four basic criteria for Seismoresistant Structural Design are valid in the SRA as well, not only to prevent the seismoresistance stepping, but also to optimize the design.

1- The seismic coefficient for the various stories of a buiding increases according to the building height. Consequently, during the architectural design, it is very important to place archives, swimming pools, or rooms containing heavy equipment in lower levels, in order to minimize seismic effects.

2- The resistant elements may be placed with a certain degree of independence from the vertical load.
This feature remarkably facilitates both the structural and the architectural designs. In fact, it allows us to place the main resistant elements in the most suitable fashion to minimize the torsional effects and to attend to architectural project requirements.

3- Seismic forces are proportional to the building weight.
With seismic forces proportional to the building weight, it is advisable to reduce the latter. In practice, this goal can be attained in the following items:
   - Partition walls Floor slabs Floors Wall plastering and/or covering Resistant structure Building Typology

This principle, simple as it may seem, is nevertheless neglected in many building projects, even nowadays.

EFFECTIVENESS AND OPTIMIZATION OF THE SEISMORESISTANT RESPONSE IN BUILDINGS

Essentially this objective may be achieved either decreasing the seismic forces or increasing the efficiency of the seismic capacity of buildings.

Reduction of values of seismic forces may be achieved in various ways, i.e.:

1- By using lightweight materials or avoiding unnecessary fillings and finishings.

2- By relocating heavier weights, that is, trying to place those rooms that will bear heavier weights (e.g. archives, swimming-pools, meeting rooms, etc.) in lower levels. Seismic bending moments and shearing acting on the structure are thus reduced and consequently, the size of the resistant elements. These are very important facts for the Architectural Design.

3- By avoiding the pseudo-resonance. This means to prevent the fundamental period of the building from coinciding with the main one of the foundation soil.
The optimization of the seismoresistant capacity of the building must be done by using spatial shapes that may lead to a building with a clear and simple structure, having its torsion stress center coincident with its mass center.

This combined purpose of effectiveness and optimization is a clear challenge for the Architecture, since it involves to study specific methodologies which enable the architectural design to make significant contributions for the best solution to the seismic problem.

REASONS WHICH CAUSE THE STEPPING OF THE SEISMORESISTANT CAPACITY OF A BUILDING

Reasons for which the maximun earthquake- resistant capacity of a building is not equal to the sum of the capacities of each element.

1- Inherent causes to the structural design: The process for matching both the resistance and the stiffness of structural elements undergoes trials with difficult solutions in the earthquake structural design practice, which introduces an uncertainty factor that may give rise to a decrease in earthquake resistant capacity characteristics, and a later collapse of the structure.

2- Earthquake torsion: The fact that the seismic shear in a column caused by a torsion moment is proportional to the distance to the center of torsion or stiffness (CT) results in, for columns which are dimensionally equal, but placed at different distances from CT, their seismic stresses are different.
This may be the fundamental cause for the decrease in resistant capacity, especially if the torsional effects have not been provided for.
This may be the cause of the stepping up of the seismic resistance, especially if the torsional effect has not been adequately provided for. There are some other cases where the development of a moment is due to an unpredicted strain of floors.
Finally, even when torsion is taken into account into the structural analysis, it is still difficult to keep the stiffness- resistance ratio for columns.

3- Flexible floor: A flexible floor greatly decreases the seismic shear on the remaining stiffer floors, but, at the same time, the shear increases on the flexible floor itself. Here, again, we have a stepping up of seismic resistance. Taking this fact into account during the structural analysis calls for ductility and resistance characteristics which are very difficult to achieve in the practice. It would be better to assign the necessary stiffness-resistance ratio to such a floor instead of using it to improve the seismoresistant performance of the whole building.

4- Short beams: With rigidly framed structures, when one of the beams on a certain floor or level is of a notably lesser length than the remaining ones, the so-called short beam case occurs. Here the problem arises because angular stiffness is inversely proportional to its length. Like in the previous cases, the difficulty here is to achieve the required resistance-stiffness relationship. The concentration of bending moments may break the beam, facilitating the decrease of the seismoresistant capacity of the structure.

5- Non-structural elements: It is known that non-structural elements such as walls, partition walls, installations, etc. interfere with the expected behaviour of the resistant structure. This interference may be either of a positive or a negative sense. This has also been a frequent reason for decreasing the building total seismic capacity.

6- Constructive defects: A localized constructive defect on the resistant structure, besides decreasing the seismoresistant capacity, may originate stepping. In fact, it may give rise to an unexpected torsion moment.

7- Like constructive defects, this may be the cause of a decrease in the seismoresistance capacity and its unexpected stepping.

METHODOLOGICAL PROPOSAL

The methodological proposal requires to elucidate:

- The referential variables of seismoresistant seismology and engineering which should necessarily be analyzed during SRA's development, study and research, such as:

a) The dynamic nature of seismic activity. b)Seismic intensity. c) Epicentral distance (near and far epicenter).
d) Three-dimensional resistant systems (spatial behaviour) e) Short columns. f) Flexible floors. g) Seismic torsion. h) Ductility.

Structural Design Requirements

a)To avoid short columns. b)To exclude any unnecessary weight, and to use lightweight materials.c) To use rigidly framed structures of high hyperstaticity in order to attain ductility. d) To prevent seismic torsion. e) To promote symmetric plans. f) To prevent building collision. g) To avoid flexible floors. h) To avoid liquefiable soils. i) To consider epicentral distance. j) To design either flexible or stiff buildings according to the predominant period of the foundation soil. k) To prevent pseudo-resonance

Each of the above constraints interacts with the following subsystems or building components:
a) Constructive system.b) Structural system c) Spatial configuration. d) Installations. e) Economical f)Esthetical.

STANDARDS OF COMPATIBILIZATION OF ARCHITECTURAL AND STRUCTURAL DESIGNS

The referential variables which are to be morphologically compatibilized are considered at the very beginning.

- Flexible floor
- Building Collision
- Seismic Torsion
- Pseudo-resonance
- Sudden stiffness changes in plan and elevation
- Stiffness-Flexibility
- Concentrated weight
- Short columns
- Tall buildings
- L- U- and T-shaped buildings

Now, the morphological answers for each variable. The following table is a first attempt which would admit an immediate application of the suggested solution.

Flexible Floors.

This situation arises when, at a certain floor, the stiffness of a tall building is considerably reduced in relation to the contiguous floors.
This situation causes a strong concentration of seismic forces on the site, giving rise to a dangerous stepping mechanism of the building resistance.
The morphological answer is to avoid this feature in the architectural design. Whenever a floor with large separations between columns is required, it should be the last one or it should be placed outside the tower site, preferably designed as a single level.

Building Collision

This phenomenon takes place when there are no joints between contiguous buildings and the collision is produced when the oscillations are not synchronized. This is a completely abnormal situation which must be definitively avoided. The morphological answer is building separation, as current rules specify. It is recommended to take into consideration into the design the various functions of the completely separated bodies for the case of the same building, in order to prevent building collision, to provide a uniform structure and also to avoid sudden stiffness changes in plan and elevation.

Seismic Torsion

This effect is produced whenever the Stiffness Center (SC) and the Torsion Center (TC) do not coincide, thus causing additional constraints especially in those elements which are far removed from the SC, which might lead to the stepping of the seismoresistant capacity of the building.
Although this problem is considered in the structural analysis, it is completely undesirable since it generates large additional and disbalanced seismic forces in the set of columns, giving rise to the stepping of the seismoresistant capacity of the building.
The morphological solution is met by designing buildings with a symmetrical plan and elevation. In addition, the structural and non-structural interacting elements symmetry is required, as well as the functional symmetry of the architectural site.

P**seudo-Resonance**

This phenomenon arises whenever the period of the building matches the predominant period of the foundation soil. This condition remarkably increases the seismic effects. On the other hand, if the fundamental vibration period of the building depends on its dimensions and structure stiffness, then, the morphological solution is to manipulate these parameters.

Sudden Stiffness Changes in Plan and Elevation

This situation can be prevented by using compact, homogeneous spatial shapes in the architectural design.
Stiffness-Flexibility

Whenever a rigid or a flexible building is required, i.e. one that can be strained to a certain low or high degree respectively, the common practice is to use for the first case rigid structures such as partition walls made up of reinforced concrete and/or high density and high resistance masonry walls, 0.20m. thick, and for the second case, the selection is for materials which are adequate for flexible buildings.
Both cases will influence the spatial morphology of such buildings.

Concentrated Weight

In most of the current seismoresistant standards, the seismic coefficient increases almost proportionally to the floor level with respect to the ground level. Consequently, in Architectural Design, this principle must be borne in mind, not only to avoid using heavy materials, subfloors, partition walls, coverings,etc., at higher levels, but also to place the sites designed for archives, swimming-pools, or heavy equipment at lower levels. In so doing, two purposes are achieved: firstly, a reduction of the seismic forces, since the seismic coefficient increases at higher levels and secondly, a logical reduction of the seismic shear and moments.
The following example clearly illustrates the importance of this later concept.

It presents a six-level construction for comparing the seismic effect caused by a certain P weight, which is firstly placed at the fifth level and then at the first level of the same construction. (Figure 2)

The results are conclusive. In the case of P placed at the fifth level, the overturning moment becomes 25 times greater than that for P placed at the first level. Besides, the seismic shear affects to levels 1 up to 5, whereas, in the second case, only the first level is affected but to a lesser extent (5 times less).

Short Columns:

Another aspect related to the resistance-stiffness problem is the so-called “Short Column”. In this case, the seismic shear increases inversely proportional to the cube of its height for columns of equal cross-sectional area. In addition, this situation worsens for short columns because concrete is unsuitable for resisting strong tangential stresses, thus notably decreasing its ductility.
These instances are originated by a particular feature of masonry which reduces the columns height and consequently, their stiffness becomes greatly increased. This causes the seismic shear to concentrate on the column, which logically cannot resist. The rupture of the resistant elements could make the rest of the elements yield as well, which could in turn bring about the total collapse.
This situation can be easily avoided by appropriately designing the shape and location of spaces and openings. On the other hand, when this problem results from differences in elevation between medium-height mezzanines, its elimination is practically impossible. Therefore, these elevation differences must be removed from the seismoresistant architectural design.

TEACHING OF THE SRA TO ARCHITECTS

The teaching of SRA to architects is focused neither on the seismoresistant structural calculus and optimized design nor on the structural optimization process. It is focused on the responses of the building’s morphological and spatial configurations during the architectural design.
In fact, the SRA should not be mistaken for the optimized seismoresistant structural design. It rather deals with the solutions from the architecture to seismic constraints.
The SRA has established not only its aims, principles and methodology, but also the standards and recommendations for each seismic constraint, in terms of plane, spatial and morphological configurations.
The approach presented is a SRA which has facilitated its comprehension and teaching, as well as the training of architects. It does not require thorough understanding of seismoresistant engineering; it does not modify the overall goal of teaching “STRUCTURES” to architects, i.e. the basic Design and Predimensioning of buildings.
Figure 1 shows the traditional building design pattern. Figure 2 shows our proposed pattern for building design in seismic zones.

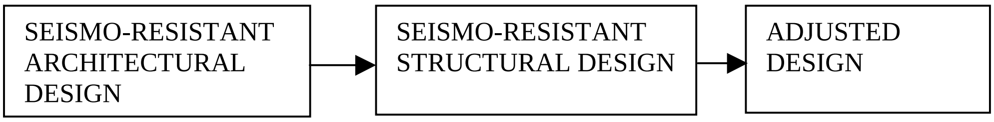

fig.1

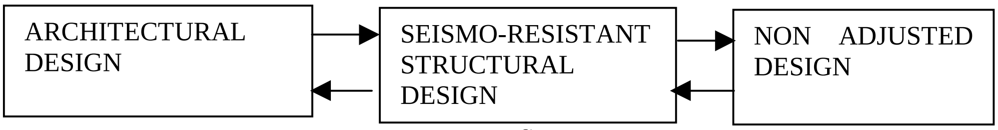

fig.2

OBJECTIVES

General Objectives

- To attain ability to put forward building architectural designs which ensure that during seismic shaking all the building component parts (structures, non-structural elements, installations, formal space, etc.) will interact positively with each other, thus promoting its seismoresistance.
- To prevent maladjustments which may bring about the stepping which would endanger the seismic safety of the building. This is referred to as *Compatibilization of Architectural and Structural Designs.*

Particular Objectives

Seismoresistant Building Architecture

- To understand the reasons why an inappropriate architectural building design may bring about the stepping of the building seismoresistant capacity, and consequently its partial and even total collapse.
- To interpret the objectives, basic principles and methodology of compatibilization of architectural and structural building designs.
- To interpret the concepts of the compatibilization patterns.
- To interpret the concept of optimized and compatibilized design as the ultimate objective of Seismoresistant Building Architecture.

Contents

Seismoresistant Building Architecture

- Objectives. Basic Principles. Methodology of Structural and Architectural Designs Compatibilization.
- Causes which may result in the stepping of the building seismoresistant capacity: short columns, flexible floors, torsion asymmetry of building plan and height, sudden changes of stiffness, pseudo-resonance, rattling, etc.
- Compatibilization patterns.

CONCLUSIONS

This new approach is the result of the building being considered as a whole in which every component interacts with each other during seismic activity. This interaction may be either positive or negative. Consequently, the analysis of such interrelations and their compatibilization from the architectural design viewpoint is required to prevent a decrease of the building seismoresistant capacity.

From this global approach to the problem, we have developed a general Theory of Seismoresistant Architecture. Such a theory has got a definition, objectives, basic principles, general methodology and overall criteria of architectural and structural designs compatibilization.

This theory pursues that architecture should make its own synthesis facing the seismoresistant demands, and naturally give its answers from morphology.

Our General Theory of Seismoresistant Architecture allows architects to assume their responsibility in the seismic problem from the architecture itself (morphology) rather than from the seismoresistant design of

structures inherent to seismoresistant engineering. In order to face this approach somewhat alien to the architect, it was necessary to change each and every seismic constraint into morphological constraints of the architectural project.
On the other hand, the knowledge needed to understand and apply such Seismoresistant Theory is the knowledge which stems from the basic design of seismoresistant structures, a typical aim of teachings of the “Structures” courses in seismic zones.
The approach does not require to perform structural analysis or complex analytical methods or formulas. It requires, instead, of an adequate selection of contents and their systematic comprehension through concepts.

REFERENCES

1- Giuliani, H., Aladro, S., Benavidez, E. "Objectives and fundamental principles of a Seism-Resistant Architecture" (1998) 9 WCEE.
2- Giuliani,H. "A new approach for the Integral Solution of Building Design".(1992) 10 WCEE.
3- Giuliani, H., Rodriguez Acosta, V., Yacante, M.J.,Campora,A.M., Giuliani, H. L. "Seismic Resisting Architecture on Building scale"(A Morphological Anwer) 1996-11 WCEE.