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REGULAR AND IRREGULAR PLAN SHAPE BUILDINGS IN SEISMIC REGIONS ; APPROACHING TO AN INTEGRAL EVALUATION

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ABSTRACT

Literature in the Earthquake-Resistant Engineering emphasize the inconvenience of using irregular plans, recommending instead the use of simple shapes. On the other hand, we find that the so-called irregular plans provide in most cases a lot of environmental, functional, aesthetic and urbanistic advantages. Once considered the contrasting viewpoint of engineers and architects in relation to the use of irregular plan shapes, it is necessary to make an integral evaluation and quantify its advantages and disadvantages, so as to go beyond subjective cualifications that are so common in specialized literature. This is the main goal of this paper. To fulfill this objective, the architectural and engineering advantages and disadvantages associated with the floor plan shape of a building were identified, analyzed and quantified in terms of costs and benefits. To illustrate this integral evaluation, quantification parameters were applied to two specific cases, one regular and one irregular building.

KEYWORDS

Earthquake architectural; irregular buildings; irregular floor plan shapes; integral approach.

INTRODUCTION

In architectural design it is usual to chose irregularly shaped plans as an answer to the various factors, such as functional, spatial, environmental, conceptual, formal, etc., which are part of the conception of a building. However in engineering the use of such plans is criticized due to their inappropriate seismic behavior (Arnold *et al.*, 1982; Dorwick, 1984). Global or integral analysis of the advantages and disadvantages related to the use of irregular plans for buildings has been little studied and, in general, partial and isolated observations are found. All this, together with the lack of studies that quantify both architectural benefits as well as seismic disadvantages, accounts for the difficulty in harmonizing the opposite positions that architects and engineers have on this topic. This paper is aimed at identifying and analyzing the advantages and disadvantages resulting from regular or irregular plans, from the architectural point of view, but without putting aside the engineering standpoint, and at quantifying most of them in terms of their monetary benefits and costs. Preliminary results have been presented by Raven *et al.*, (1994).

ANALYSIS OF THE ADVANTAGES AND DISADVANTAGES RELATED TO THE SHAPE OF THE PLAN AND DEFINITION OF QUANTIFICATION PARAMETERS

Buildings are complex systems and multiple items have to be considered at the moment of designing them.

Most of these items are associated to the desires and needs of the users, and to the interaction and integration of both the building itself and its users with the environment. Since the seismic item is only one of those to be considered, it is convenient to analyze it together with all the others to have a more integral view of the influence of a determined plan shape on the global behavior of the building. To this end the main aspects to be solved by architects and engineers in building design were determined. For every item, the advantages and disadvantages of regular and irregular shapes were analyzed, defining as well as possible, quantification parameters in terms of benefits and costs in order to establish a direct comparison at the moment of applying them for the evaluation of a real case.

Seismic items

Seismic behavior of irregular shaped plans differs from regular shapes because the first can be subjected to torsion due to their asymmetry and/or can present local deformations due to the presence of re-entrant corners or excessive openings. Both effects give origin to undesired stress concentrations in some resisting members of the building. On the contrary, the ideal rectangular or square plan, structurally symmetric, with enough in-plane stiffness in its diaphragm, presents an ideal behavior, characterized because has the same displacement in every point in the slab. To quantify the seismic behavior of different plan shapes, the following two parameters are defined (López *et al.*, 1994): 1) Coefficient of variation **(CVE)** of column square displacement distribution in every story, and 2) maximum value of quadratic displacements divided by the mean value **(MCE)** for every story. The quadratic displacement is related to the potential energy per stiffness unit absorbed by each column. For the rectangular plan with a rigid diaphragm, adopted as the ideal case, **CVE** and **MCE** are 0 and 1, respectively. For irregular plans, these parameters increase with the size of the irregularity.

To quantify seismic costs of the irregular shaped plan, it was adjusted through modifications in the structural elements until **CVE** and **MCE** were near the ideal values, 1 and 0, so as to approximate the behavior of the regular shape plan, and define as cost the result of this adjustment, that is, the cost of the project of structural adjustment and constructive cost associated with the additional material volume and with the structural changes.

Architectural items

Environmental items. They are all those resulting from the relation between what happens inside the building and the environment that surrounds it, whether natural or urban. For this study we will base upon our tropical climate.

a) Ventilation: Ventilation experts agree upon the advantages of achieving spatial comfort through natural ventilation instead of the mechanical or forced one (Puppo *et al.*, 1972 ; Ingersol *et al.*, 1977), and in general they consider it healthier both psychologically and physically. In Figure 1, which presents two possible

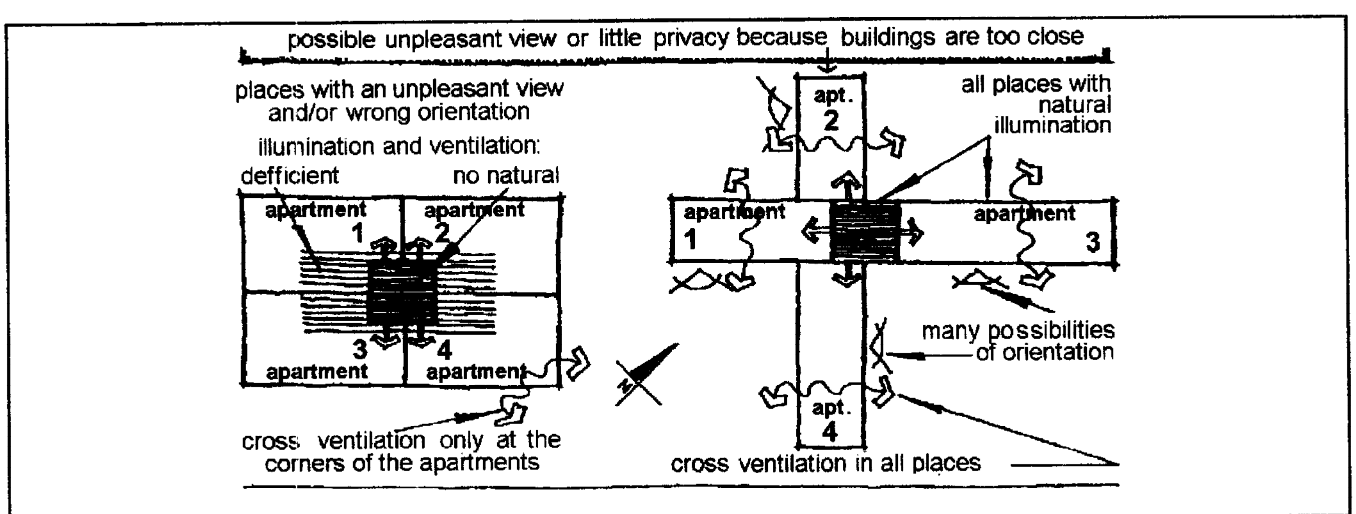


Fig. 1 Illumination, ventilation, views, etc. in both regular and irregular building.

apartment buildings, we can see how a regular shaped plan can generate bad ventilated spaces, or even worse, spaces without natural ventilation at all, both in the apartment as well as in the circulation corridors, situation not found in the irregular building. In the case of non ventilated environments, costs were quantified through: i) costs of the mechanical ventilation project required by the local regulations referred to building ventilation; ii) costs of installing the proposed ventilation system; iii) costs of the system and equipment reposition during the useful life of the building (50 years); iv) cost of energy for the use of mechanical ventilation during this useful life. In the case of environments without crossed ventilation, it is proposed to quantify the costs related to the mechanical ventilation that would be necessary to match the ventilation level (number of changes/hour) in the environment with crossed ventilation. Psychological and physical benefits of natural ventilation itself belong to those which are not quantified within this study.

b) Illumination: Natural illumination is healthier, more efficient and comfortable than artificial illumination. This latter is blamed for sight disturbances, sight tiredness, and even negative psychological effects, particularly when it is permanent because the environment is completely closed. Moreover, closed circulation areas propitiate personal insecurity, because they hide potential robberies and assaults from persons outside the building. Figure 1 shows how the regular shape can also have areas with little or no natural illumination; in fact, since the perimeter of the facade is lower, the inside of the building has less contact with the outside environment, as compared to the irregular building. For the cost quantification the following measurements are proposed: i) energy costs related to daily artificial illumination, necessary to replace the lack of natural illumination, to meet legal requirements; ii) lamp reposition cost according to their useful life because they have to be additionally used during the day. Psychological and physical benefits related to natural illumination are considered as non quantified.

c) Views and orientation: the decision to adopt irregular plan shapes is frequently associated with the possibility of having better views from the habitable environments, and of avoiding unfavorable orientations that would contribute to increase heat in such environments (e.g. oriented towards west). Figure 1 shows how a regular shaped building can force the location of certain environments in places with a wrong orientation, unpleasant views or without privacy, because they are near other buildings. We determined by means of surveys, how much an individual would pay for enjoying a better view, orientation or privacy. This parameter, multiplied by the number of individuals that would enjoy this advantage, represents a monetary benefit that makes a difference from one building to another.

d) Adjustment to the ground conditions: ground shape, which is usually irregular, its topography and the natural or built elements within it (trees, rocks, hills, utilities, etc.), greatly limit the plan shape of the building to be located on it. In many cases, adopting a regular plan may bring about land movements, felling and replanting of trees, or the use of explosives for excavations or demolition. Such situations could be overcome if an irregular shape is selected.

Constructive items. Different building plan shapes give rise to different constructions and starting-up costs. In this study, these costs basically refer to fencing and finishing, because constructions costs related to structure, ventilation and illumination were already taken into account. Since the evaluation is strictly comparative, for the estimations in the cases under study only those items with different amount for both buildings will be considered and the costs will be those at the market for January, 1993.

Miscellaneous. There are other architectural items to be taken into account in the conceptual, formal, creative, aesthetic, symbolic and urban aspects of a building, that are beyond the scope of this work.

APPLICATION TO TWO BUILDINGS, A REGULAR AND AN IRREGULAR ONE

Building description

Figure 2 shows the architectural ground plan of the selected buildings, both hotels, with four 3m-high-stories, and a surface area of 571.5 m^2 per story. As regular plan a symmetrical rectangular shape **(R)** was selected, and as irregular plan, an asymmetric L-shape **(L)**. Both buildings have 18 rooms per story, each with a bathroom, identical for both buildings.

The buildings are made of reinforced concrete, with 24 columns/floor. The dimensions or their elements ere

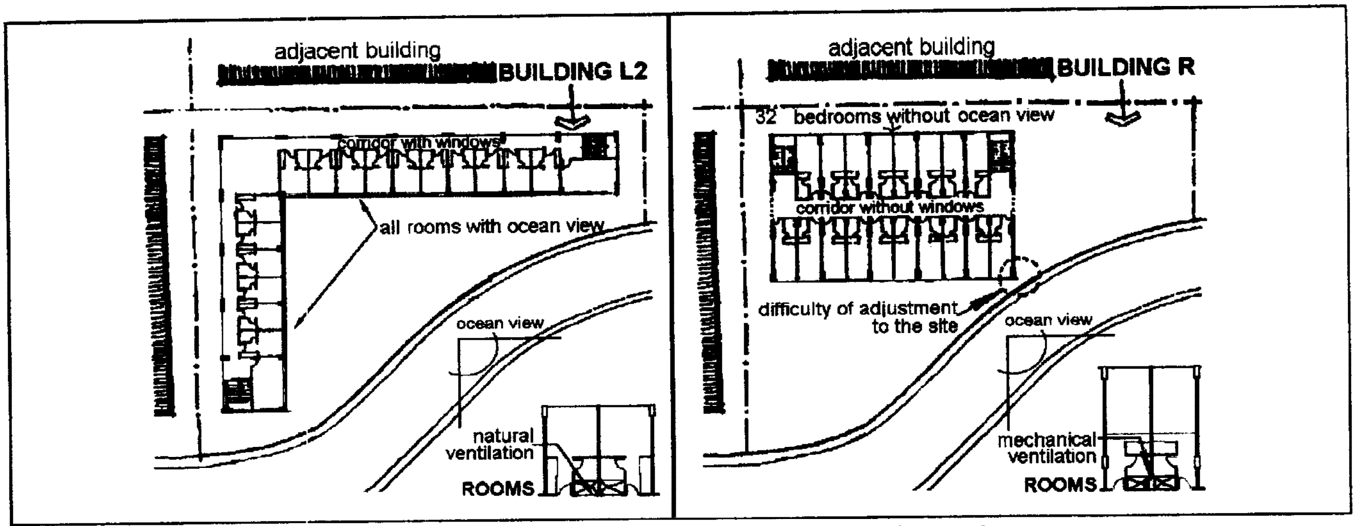


Fig. 2 Plan of the buildings selected for the study.

defined by averaging the values obtained from two designer engineers, even though little differences were found among them. The column orientation was determined by architectural demands with the short dimension being limited to 40 cm. Figure 3 shows a structural scheme of each plan. Rectangular plan has a solid 15 cm-slab, 6 m-spans, 30 x 60 cm^2 inside beams, 30 x 50 cm^2 perimetrical beams, and 40 x 70 cm^2 outside and 40 x 80 cm^2 inside columns in the first two stories, with a 10 cm-reduction in the long side of every column for the last two stories. L-shaped plan has a solid 20 cm-slab, 6.87 m spans, 40 x 70 cm^2 inside beams, 40 x 60 cm^2 perimetrical beams and 40 x 80 cm^2 columns for the first two stories, except in the 60 x 60 cm^2 inside and 50 x 50 cm^2 outside corners, also with a 10 cm reduction in the last two stories.

Since it is impossible to have natural ventilation in the bathrooms, **R** building required a mechanical ventilation system composed by 8 vertical masonry ducts each providing ventilation for 2 bathrooms per floor (totaling 8), with their respective 1/10 hp-ceiling fans (direct centrifugal mushroom ventilators). Illumination in both buildings (**R** and **L**) was designed under the same criteria of illumination requirements using fluorescent light for the corridors and incandescent light for the rest of the environments. Location of both building was assumed in a plot of land adjacent in the front to a beachside road and in the sides and back to buildings with the same height and use, as seen in Figure 2.

Seismic evaluation

Each building was spatially modeled by means of finite elements techniques, incorporating the flexibility of the diaphragm, and dynamically analyzed for simultaneous seismic motion according to two horizontal directions, defined by spectra given by Venezuelan Seismic Standard.

Differences in seismic behavior between **R**, **L** and **L2** buildings are shown in Figure 4, where quadratic displacement (or energy) has been plotted per column and for each story. Variability of quadratic displacement distribution per story was measured through the parameters **CVE** and **MCE** defined previously which are shown in Table 1.

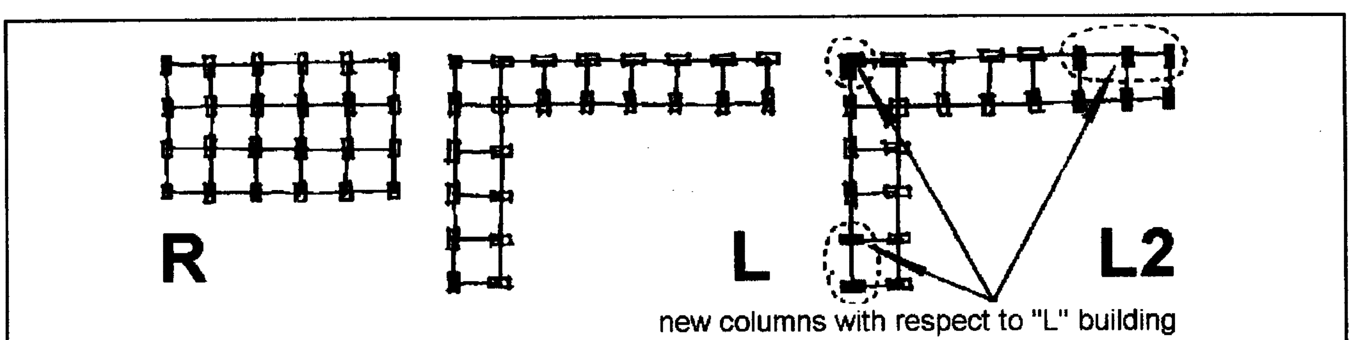


Fig. 3 R, L y L2 structures (L2 is L modified).

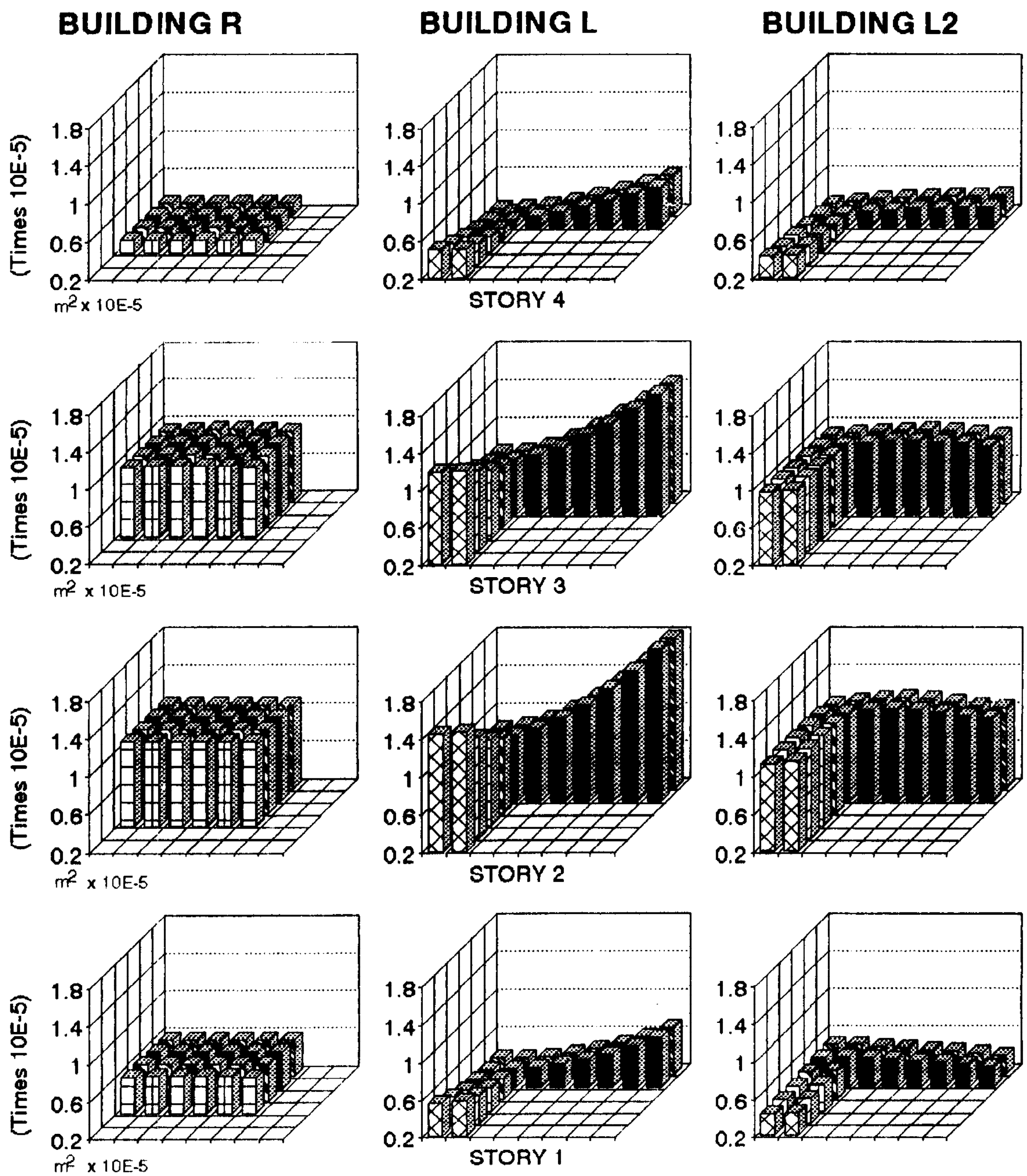


Fig. 4 Quadratic displacements in each column. R, L and L2 buildings

Table 1. Response parameters (CVE, MCE) and module of the eccentricity vector (e) at each story for buildings R, L, L1 and L2.

	CVE				MCE				e(m)			
STORY	**R**	**L**	**L1**	**L2**	**R**	**L**	**L1**	**L2**	**R**	**L**	**L1**	**L2**
1	0.00	0.24	0.07	0.05	1.00	1.49	1.12	1.08	0.00	2.22	0.54	0.23
2	0.01	0.21	0.02	0.03	1.01	1.44	1.03	1.04	0.00	2.23	0.39	0.21
3	0.00	0.21	0.03	0.03	1.00	1.45	1.04	1.04	0.00	2.34	0.24	0.36
4	0.00	0.16	0.07	0.05	1.00	1.38	1.09	1.07	0.00	1.93	0.78	0.38

It can be noted that the unfavorable behavior of the **L** building is greatly due to the high value of the eccentricity vector (distance between mass and rigidity centers) which is shown in the same Table 1. The criterion followed to adjust the **L** building was to modify its structure so as to reduce **CVE** and **MCE** down to values similar to those of R plan. Modifications introduced, buildings **L1** and **L2** (Figure 3), basically consisted of rotating the columns and increasing some sizes by means of a trial and error procedure. The best results, although not necessarily the optimal ones, after approximately 20 trials are shown in Table 1. It has to be considered that there is a wide range of alternatives to achieve the adjustment of the **L** building. Examples **L1** and **L2** are only an illustration of the methodology described in the previous sections.

Evaluation of costs and benefits

Costs and benefits were estimated (at prices of January 1993) for both buildings, **L2** and **R**, applying the parameters described previously. Cost differences per item between both buildings, **R** and **L2**, were estimated. Then cost variation percentages per item for **L2** and **R** were calculated by means of the formula: $V = ((R - L2) / R) \times 100$, where positive results represent benefits and the negative ones the costs of building L2 in relation to **R**.

Seismic items. A cost was assigned to the engineering consulting work need for seismic adjustment, and to the difference of structural construction cost between the **R** building and the **L2** building.

Ventilation items. The cost related to the need of forced ventilation in the bathrooms in **R** building was calculated. For the estimation of project, installation, and maintenance, the market prices for January 1993 were used. For the estimation of the cost of the electric power (kwh) consumed by ventilators with a real power of 75 Watts each, hotel occupancy percentages were established (according to surveys) at 90% and 60% for high and low season respectively. Accordingly, since the extractors work independently, it was estimated that one equipment could be out of service during the high season and 3 during the low one. The consumption in kwh/day was estimated and the electric service fare taken was that provided by the Venezuelan electricity service company (0.03 $ / kwh). The results do not include the high cost of energy subsidy by the State. Even though rooms in **L2** building can have crossed ventilation, thanks to its open corridors, the benefit of this situation was not estimated due to the lack of data.

Illumination items. Rooms and bathrooms were illuminated with the same resources for both buildings, therefore the cost calculated were lamps and electrical system installation for circulation areas in each building, on the one hand, and electricity and bulbs consumption for the illumination over the useful life of the building, on the other. The calculation was based on the following data: in **L2** building, with open corridor, lights remain on half a day, whereas in **R** building, closed corridor, lights are on 24 hours a day, due to the permanent darkness of this area. Moreover, a useful life of 2000 hours was considered for fluorescent lamps (data provided by the manufacturer). Additional consumption of daily artificial light generated by the bathrooms in **R** building, since they are completely closed, and psychological comfort given by open corridors in **L2** building, were not calculated.

Views and orientation items. The result of the surveys on how much more would be a hotel customer willing to pay for having a ocean view in his room resulted in a minimum value of 10% over the normal cost of a room without a view. Based on surveys, in low season **L2** building has one room per day more, with this advantage, than **R** building, and 6 rooms more in high season, resulting in a total of 5,620 rooms/year. At a very conservative cost per room of $20/day, a total amount of $12,400/year would be obtained for the additional advantage offered by **L2** building.

For the extension of the work it is proposed to match the values obtained from the surveys with the information about what people is really paying for this benefit, which, according to our research, gives a higher value than the one used here. Privacy in rooms in **L2** building with respect to adjacent buildings, due to its orientation towards the ocean, as well as the disadvantage in R building view towards these buildings, were taken as non quantified items.

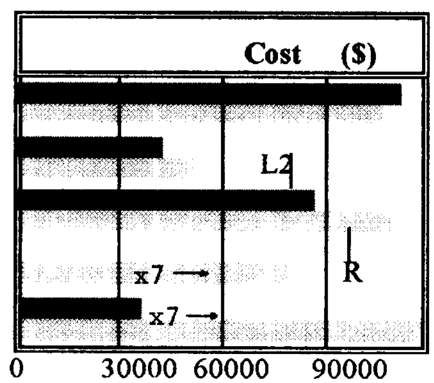
Construction items. The difference in construction costs between both buildings, was calculated. Those items were: Finished inside walls, finished outside walls, rooms windows, bathrooms windows, inside painting (6 times in 50 years). and outside (6 times in 50 years) and windows (11 times in 50 years) painting. **L2** building has a larger amount of outside wall and windows, whereas R building has a larger amount of inside walls, with the corresponding effect on maintenance.

Summary of costs and benefits

As a result of applying measurement parameters, the percent costs (negative values) and benefits (positive values) were obtained for **L2** building versus **R** building, calculated at the current value and for the whole period of useful life in both buildings (50 years) and for the following items: initial investment, maintenance, electric power consumption, enjoyment of ocean view and the total over 50 years (Table 2). From Table 2 we can observe that for this particular case, initial investment in project and construction is higher in the irregular building, however, this investment is easily recoverable over the first year, if we take into account the potential benefits, not only due to the additional income obtained from the ocean view, but for the savings in maintenance and electric power in **L2** building, thanks to its natural ventilation and illumination, with respect to **R** building.

Table 2. Percentages of cost variation (V = ((R - L2) / R) x 100) and total costs (R and L2)

DESCRIPTION OF ITEMS	V(%)
INITIAL INVESTMENT	-5
MAINTENANCE	18
ELECTRIC POWER CONSUMPTION	19
ENJOYMENT OF OCEAN VIEW	100
TOTAL COSTS OVER 50 YEARS	72



CONCLUSIONS AND RECOMMENDATIONS

Advantages and disadvantages related to the shape of a building plan were identified and analyzed in this work, and some of them were quantified in terms of monetary benefits and costs. This methodology represents an integral evaluation of the effect of the plan shape on buildings, that goes beyond of the mere seismic evaluation found in the literature.

Assuming that the rectangular building with structural symmetry represents the desired ideal seismic behavior, the parameters defined by the variation coefficient of the plan quadratic displacements **(CVE)** and the maximum value of quadratic displacements divided by the mean value **(MCE)** allow us to evaluate the effect of structural modification that can be introduced in an irregular building during the process of its adjustment.

For the specific case presented in this work, a 4-story asymmetric L-shaped building, **CVE** and **MCE** coefficients were considerably reduced through moderate structural changes, achieving a seismic behavior similar to that of the ideal 4-story rectangular building.

By applying this work methodology to the aforementioned buildings, it was detected that, in relation to the rectangular building, the L-shaped building, after a seismic adjustment, offers long term benefits due to savings in maintenance and electric power, as well as additional income during its useful life, which considerably exceed initial investment in project and construction.

The application of this work is limited to the presented examples. Its current extension is oriented towards the analysis and quantification of a greater number of items, the application to a wider range of buildings and the incorporation of other factors which influence the irregular structural behavior of buildings.

REFERENCES

Arnold C. and R. Reitherman (1982). *Building configuration and seismic design*. John Wiley & Sons, New York.

Dowrick D. (1984). *Diseño de estructuras resistentes a sismos*. Limusa, España

Ingersol K. and M. Szokolay (1977). *Viviendas y edificios en zonas calidas y tropicales*. Paraninfo, España.

López O. A., E. Raven and W. Annicchiarico (1994). The effect of floor plan shape on the seismic response of buildings. Fifth U.S. National Conference on Earthquake Engineering, Chicago, USA.

Puppo E. and G. Puppo (1972). *Acondicionamiento natural y arquitectura*. Marcombo Boixerau Editores, España.

Raven E. and O.A. López (1994). Evaluación integral de edificaciones de planta irregular, beneficios vs. costos. 9 th Internacional Seminar on Earthquake Prognostics. San José, Costa Rica.