Paper No. 648. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

COST IMPLICATIONS OF DRIFT CONTROLLED DESIGN OF REINFORCED CONCRETE BUILDINGS

L. E. GARCIA, A. PEREZ, and J. BONACCI
Universidad de los Andes, Apartado Aéreo 4976, Bogotá, Colombia
Proyectos y Diseños Ltda., Carrera 8 N° 69-32, Bogotá, Colombia
University of Toronto, CE Dept., 35 Saint George St., Toronto, Ontario, Canada

ABSTRACT

An evaluation of the cost implications of different story drift requirements was performed as part of the calibration of the update of the Colombian Seismic Code. The increase of the cost of the structure, for reinforced concrete buildings; under several story drift limits was determined. The study was performed for moment resisting frames, and structural walls combined with the same frames. The merits of increasing beam or column dimensions to obtain a stiffer structure was also evaluated. The relative cost of meeting different story drift requirements was determined.

KEYWORDS

Story drift; reinforced concrete; wall structures; frame structures; cost of structures

STORY DRIFT REQUIREMENTS IN THE COLOMBIAN CODE

The Colombian seismic code was enacted in June of 1984 (Ministerio de Obras Públicas, 1984; García, 1984). The Code tried to take care of the problems brought out by earthquakes that occurred in November 23 of 1979 ($\mathbf{M_s}$ = 6.4), December 12 of 1979 ($\mathbf{M_s}$ = 7.8) and March 31 of 1983 ($\mathbf{m_b}$ = 5.5). These earthquakes emphasized a series of deficiencies in the Colombian building practice, of which one of the most important was excessive flexibility of the structural systems used (García, 1984). The reinforced concrete moment resisting frame was, and still is, one the most widely used structural systems. The absence of code, and the lack of awareness of the problems associated with the excessive flexibility of frames responding to lateral loads, was the culprit of much of the bad behavior encountered. Because of these reasons the 1984 Colombian code made strict story drift control one of its main objectives. The results were outstanding, a recent survey among practicing structural engineers (Meigs, *et al.*, 1993), assigned story drift as the controlling design parameter, as opposed to base shear, when determining dimensions for a building structure. The 1984 Code was based on ATC-3 (Applied Technology Council, 1979), therefore follows the ATC-3 procedure for story drift evaluation: the structure is analyzed using lateral forces divided by a response modification factor, **R**, and the structure lateral displacements from the analysis are amplified by a displacement amplification factor, $\mathbf{C_d}$, to obtain the values that are used to verify the story drift. The current Colombian story drift limit is 1.5% of the story height.

Several recent earthquakes, among them a 7.9 $\mathbf{M_s}$ magnitude event in October 1992, a 6.4 $\mathbf{M_s}$ magnitude event in June 1994, a 6.5 $\mathbf{M_s}$ magnitude event in January 1995, and , a 6.4 $\mathbf{M_s}$ magnitude event in February

1995; have affected different regions in the country, although they were either too deep or with epicenters located more than 100 km away from large cities, they all produced great amounts of non-structural element damage. This increased the concern that the 1984 Code story drift requirements could be insufficient and that stricter requirements were needed. The update of the Code, currently in the process of being enacted by the Colombian Congress, contains story drift requirements that are more conservative; reducing the allowable story drift to 1% of the story height.

COST IMPLICATION OF DIFFERENT STORY DRIFT REQUIREMENTS

An evaluation, in cost terms, of different story drift requirements for the same building was performed as part of the calibration of the new requirements contained in the code update draft (García, 1993). The calibration was performed for buildings located in different regions of the country. Only the results obtained for high seismic risk regions are presented in this paper.

Methodology employed

In order for a cost impact study of any new requirements in a Building Code to be representative, it must address current practice, but at the same time highlight the parameters under study. The usual solution consist in redesigning an existing building under the new requirements, and compare results with those obtained before. The main drawback of this methodology rests with the unavoidable influence of the dimensioning techniques used by the engineer in the design the original structure. With this in mind, a completely different tack was adopted: produce a group of reasonable solutions, study their compliance with the former and new requirements, evaluate the cost of all solutions; and then, study the relationship between cost variations and the relevant parameters.

Cases studied

An eighth story apartment building with a plan layout as shown in Fig. 1 was used. Earthquake base motions were characterized using a design spectra defined by parameters $\mathbf{A_a} = 0.25$ y $\mathbf{A_v} = 0.25$, which correspond to a high seismic risk zone as defined by the Colombian Code (Equivalent to a Zone 3 of UBC). A soil profile S_1 (rock) was used. Live and dead loads employed were customary loads, for typical buildings in the country.

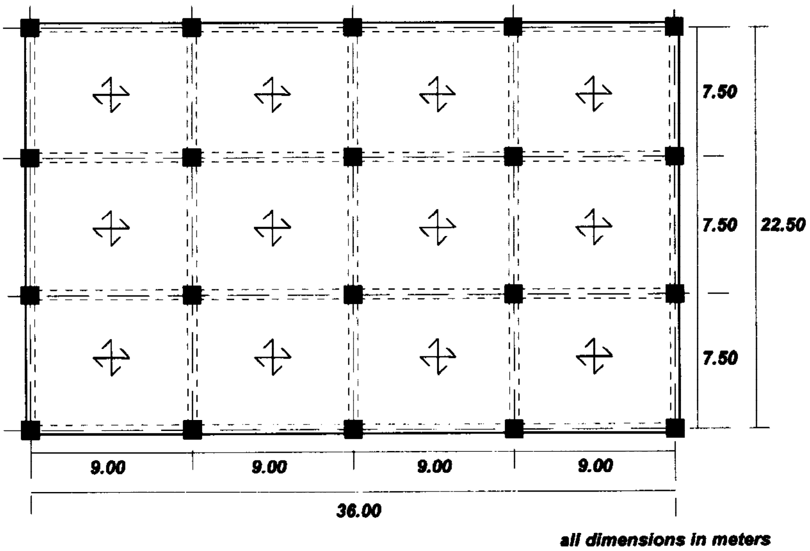

Fig. 1. Plan structural layout of the eight story building studied

Square columns sections were used for all columns, and the same dimensions were used throughout the height of the building. The cases studied have all possible combinations of square column sections with 0.40, 0.60, 0.80 y 1.00 m side dimension and 0.40 m wide and 0.40, 0.50, 0.60, 0.70 y 0.80 m deep girders. In total 20 different alternatives of the 8 story moment-resisting frame structure were processed and studied. Maximum story drift and associated cost of girders and columns were obtained. All other structural elements, such as slabs, and foundation remained constant, therefore only girder and column cost variations were calculated. The economic evaluation was performed using typical material and labor costs. The least cost was used as a base for comparison, assigning a cost ratio of 1.0 to it. Cost ratio variations are expressed in function of this least cost, and it reflects only the cost of girder and columns.

Material and story drift variations

Fig. 2 shows the total amount of reinforcement for beams and columns, in kg of steel per structure square meter. Steel usage varies from a low of approximately 15 kg/m^2, to a high of 25 kg/m^2. The minimum corresponds to the buildings with 60 x 60 cm columns. Figure 3 shows the amount of concrete, in cubic meters of concrete per square meter of structure area, required for the beams and columns of all the buildings studied. Values vary from a low of 0.06 m^3/m^2, to a high of approximately 0.16 m^3/m^2.

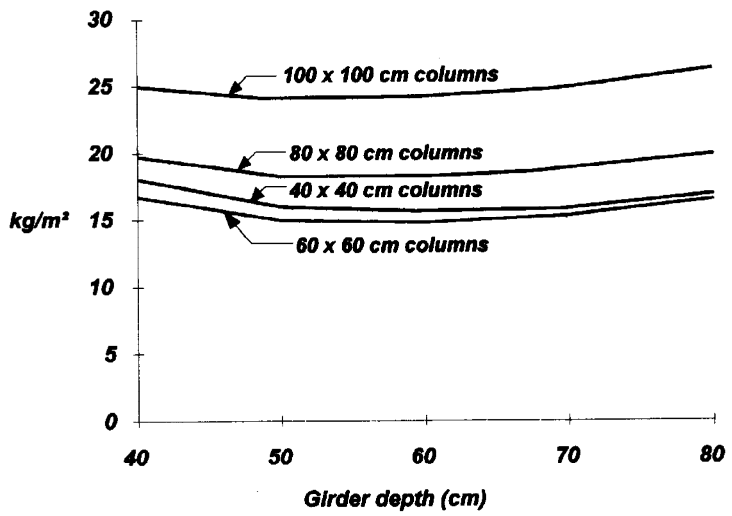

Fig. 2 Total beam and column reinforcement

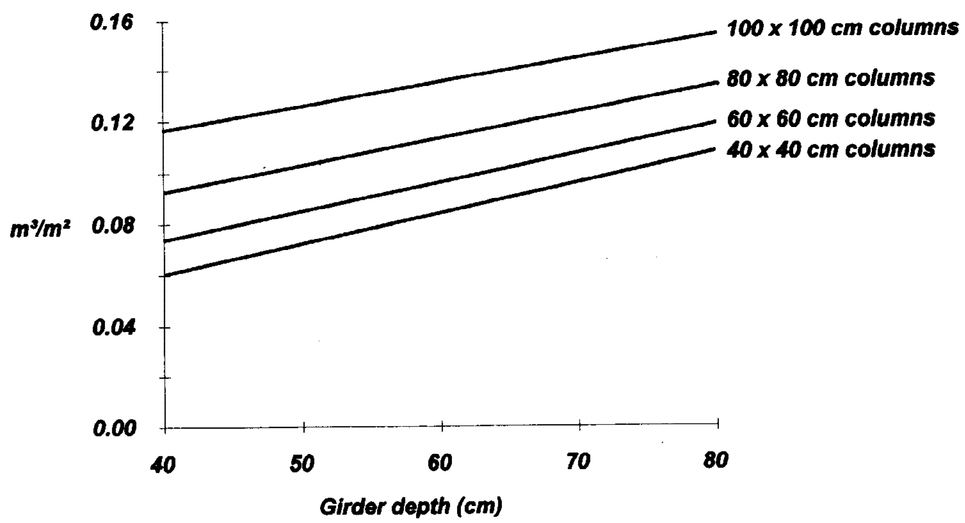

Fig. 3 Girder and column concrete

All the solutions comply with the reinforced concrete requirements of the Code, which are based on ACI 318. Therefore, in those elements whose dimensions are larger than required for strength, the amount of reinforcing steel is controlled by minimum Code requirements.

Fig. 4 presents the maximum story drift obtained for each of the buildings studied. Maximum story drift varies from a low of approximately 0.05% --one third of the current Code requirement -- for the building with the larger beams and columns, to a high value of approximately 4.5% -- three times the current Code requirement--, for the building with the smaller beam and column dimensions.

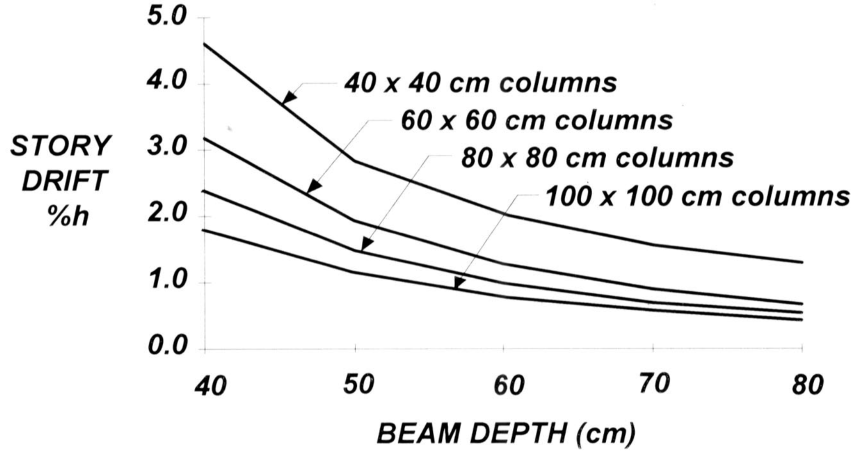

Fig. 4 Maximum story drifts obtained

The cost ratios, for all the buildings, using the one with the minimum cost (40 x 40 cm columns and beams) as a base of 1.0, are shown in Fig. 5. The maximum cost is of the order of 1.75 times the minimum one, but at the same time the maximum drift obtained is on the order 9 times the one obtained for the least expensive alternative.

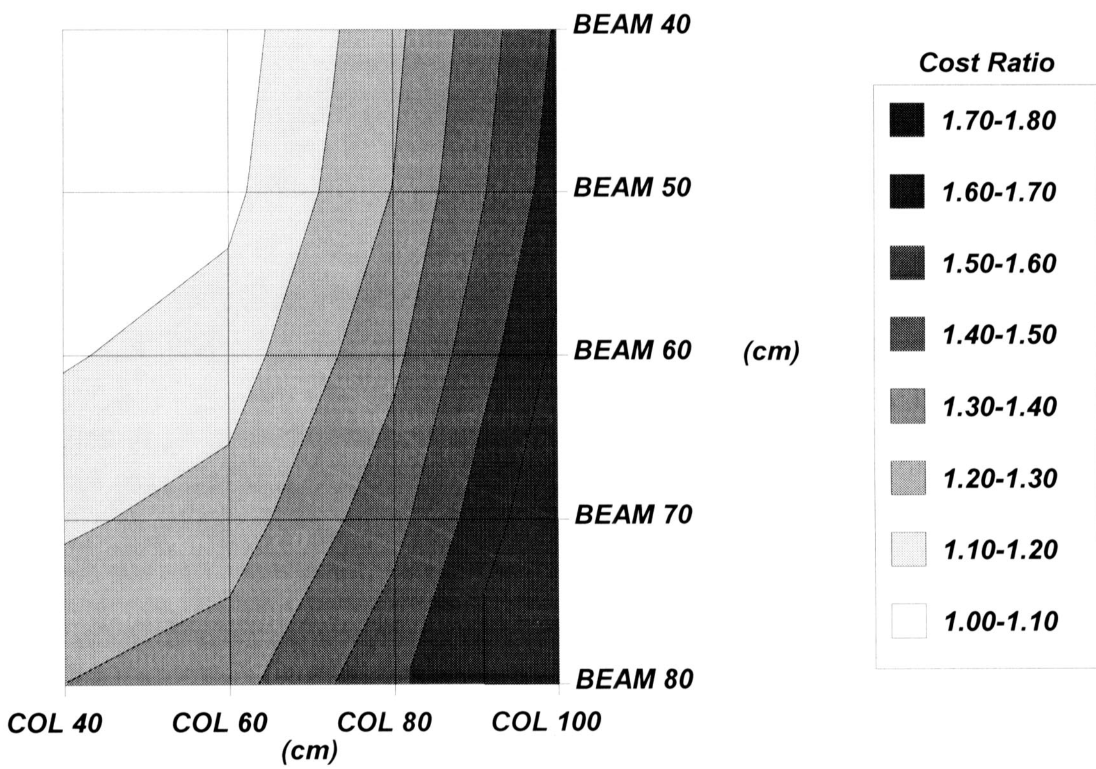

Fig. 5 Cost ratio for the frame buildings

<u>**Conclusions for Frames**</u>

Superposing the maximum story drift obtained to the cost ratio, produces the graph shown in Fig. 6. The alternative that leads the least cost, is the one with the smallest dimensions (40 x 40 cm columns, and 40 x 40 beams), but at the same time is the one that has the maximum story drift reported (4.56% of the story height).

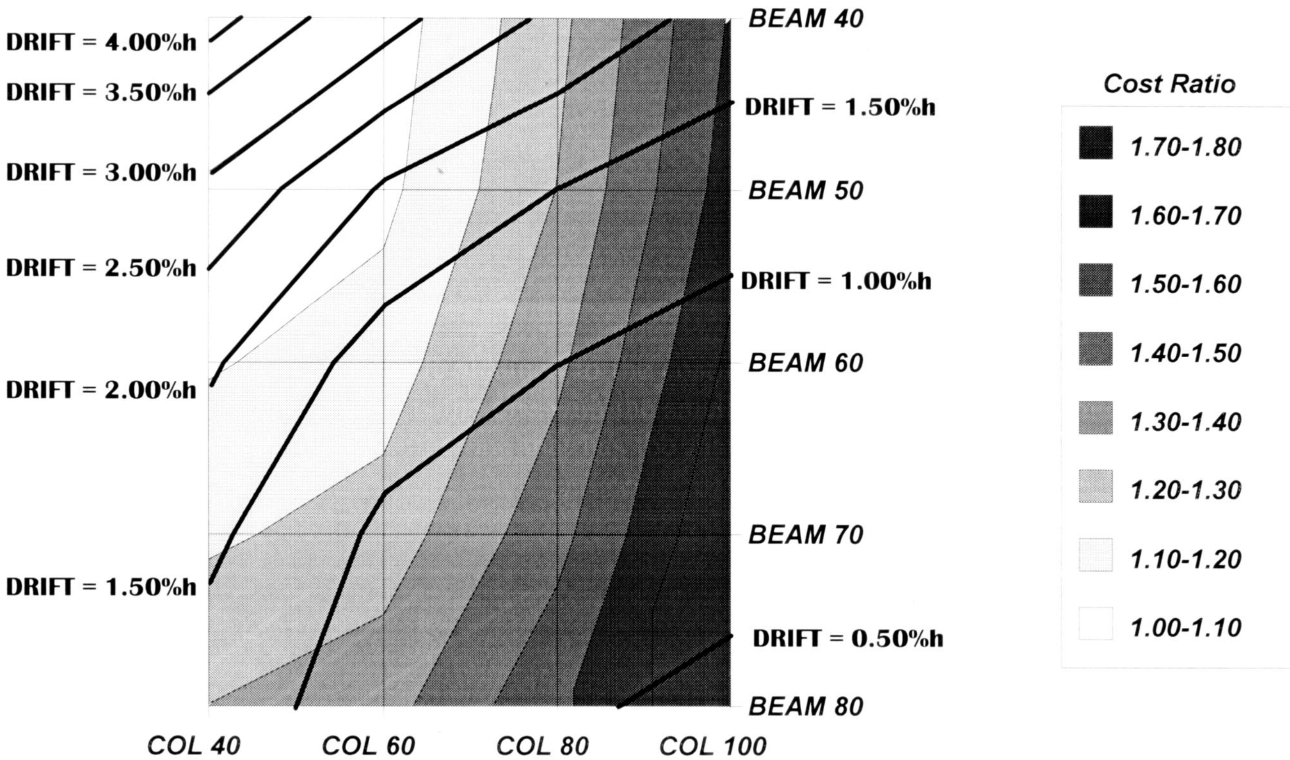

Fig. 6 Cost Ratio Superimposed to Story Drift

The following conclusions can be drawn from the results shown in Fig. 6:

- The best strategy to stiffen the structure is to increase both column and beam sections at the same time. There is not a preference to obtain a drift reduction by increasing only the beam sections, or the column sections, independently. In order to obtain a stiffer structure, the engineer must vary the dimensions as moving, in Fig. 6, from the upper left corner to the lower right corner.

- The studied variations of the column and beam section dimensions can increase the cost of these elements up to 80% with respect to the building that uses the minimum dimensions. The marginal cost of increasing, or decreasing, the story drift, can be obtained superimposing the cost ratios to the story drifts reported. As an example, the reduction of the story drift form the non realistic value of 4.5%h, to a value of 1.00%h, can be achieved with an additional cost for the beams and columns of the order of 25%., which in turn will correspond to less than 10% of the total cost of the structure.

- Total cost of beams and columns is less sensitive to variations of the beam dimensions as compared with variations of the column dimensions. The uniform cost lines have a vertical tendency in most cases. This means that the primary responsibility of the designer is to select an appropriate column dimension rather than the beam depth. Beam depth can be accommodated latter without the risk of increasing the cost of the structure.

Garcia, pg 6.

THE EFFECT OF THE USE OF STRUCTURAL WALLS

In order to evaluate the influence of the use of structural walls in the same building, two schemes of walls layout were studied, as presented in Fig. 7 and 8. The dimensions of the beams and columns of the frame were maintained constant (40 x 40 cm beams and 60 x 60 cm columns). Wall thickness of 15, 30 and 45 cm were evaluated.

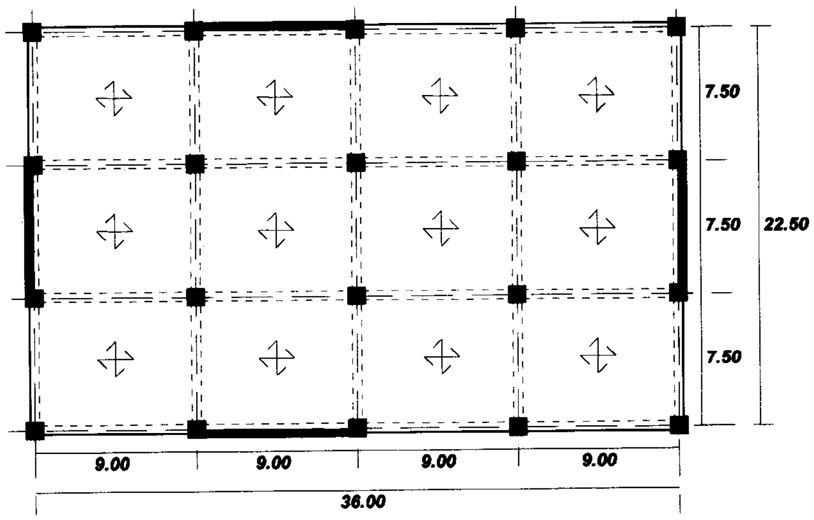

Fig. 7 Wall scheme N° 1

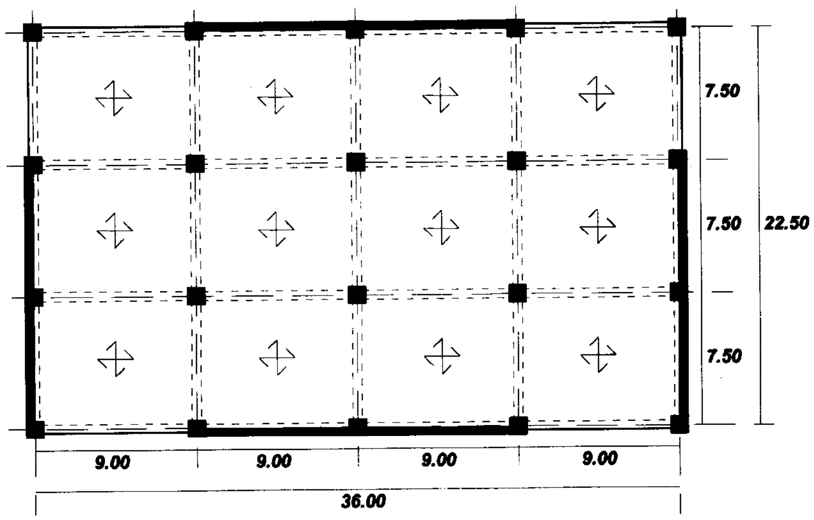

Fig. 8 Wall scheme N° 2

The corresponding cost ratios, using the frame without walls as reference, are presented in Figure 9. Different slenderness ratios (**H/L**) are obtained. The graph shows that the cost is more sensitive to an increase of the thickness of the walls as compared with a reduction of the slenderness of the wall.

The superposition of the cost ratio and the story drift produces the results shown in Figure 10. An important reduction in the story drifts is obtained, with maximum values of the order of 0.25%h. A good strategy to reduce drift, without increasing the cost is to reduce both slenderness and thickness at the same time, which corresponds to traveling in Fig. 10 from the upper left corner to the right lower corner. Moving in this direction decreases the drift, without increasing the cost. A more drastic drift reduction consists in using less slender walls, but the cost increases (this corresponds to moving horizontally in the graph).

CONCLUSIONS

The following conclusions can be drawn form the preceding presentation:

- With an appropriate selection of beam, column and wall dimensions it is possible to reduce the story drift with a small cost increase.
- It is more efficient, in cost terms, to reduce story drift through the use of walls than to increase member dimension in a frame.
- The reduction of the story drift requirements of the code to half of the actual requirements, will produce cost increases of the order of 5% to 10% of the total cost of the structure.

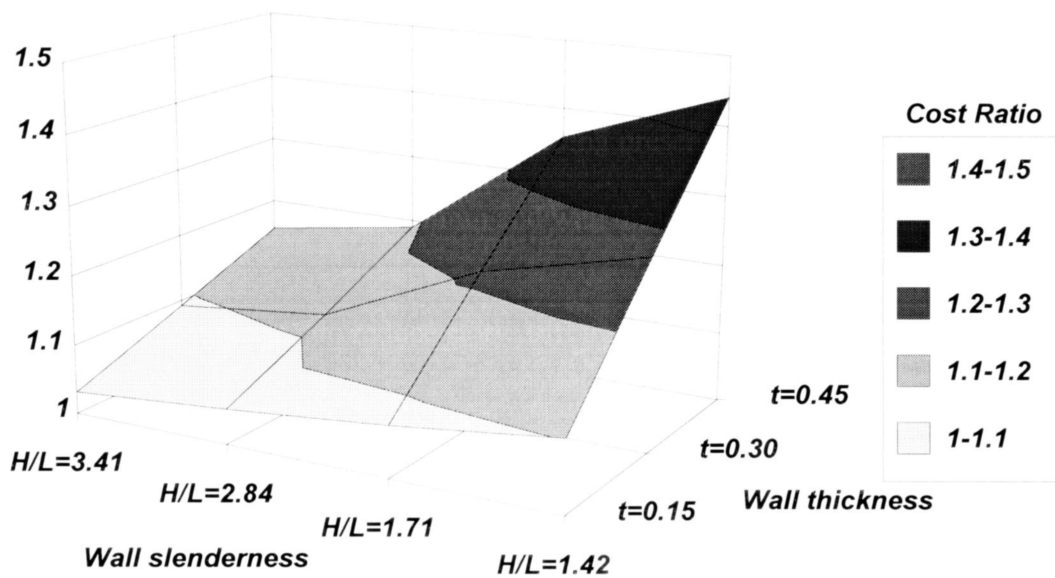

Fig. 9 Cost ratio for structures with walls

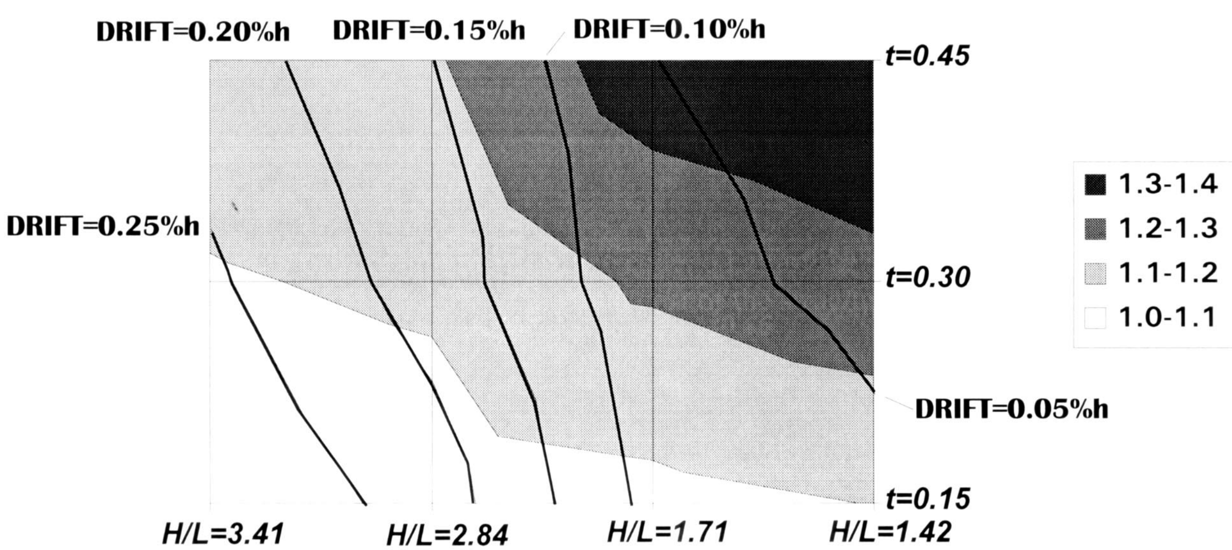

Fig. 10 Superposition of cost ratio and story drift for structures with walls

Garcia, pg 8.

REFERENCES

Applied Technology Council (1978), Tentative Provisions For The Development Of Seismic Regulations For Buildings ATC-3-06, Palo Alto, CA, USA.

García, L. E., (1984), Development Of The Colombian Seismic Code, *Proceedings of the Eight World Conference on Earthquake Engineering*, Earthquake Engineering Research Institute, San Francisco, CA, USA.

García, L. E. (1993), Apreciaciones Sobre el Diseño Sismo Resistente en Colombia y sus Implicaciones Económicas, 6° Seminario Internacional de Ingeniería Sísmica, Universidad de los Andes, Bogotá, Colombia.

Meigs, B. E., Eberhard, M. O., and García, L. E., (1993), Earthquake-Resistant Systems for Reinforced Concrete Buildings: A Survey of Current Practice, Department of Civil Engineering, University of Washington, Seattle, WA, USA, 50 p.

Ministerio de Obras Públicas y Transporte (1984), Código Colombiano De Construcciones Sismo Resistentes - Decreto 1400 De Junio 7 De 1984, Asociación Colombiana de Ingeniería Sísmica, Bogotá, Colombia,

Sozen, M. A. (1989), The Chilean Formula For Earthquake Resistant Design Of Medium-Rise Reinforced Concrete Structures, 5th Chilean Conference on Earthquake Engineering, Santiago, Chile.