THE JANUARY 25, 1999, EARTHQUAKE IN THE COFFEE GROWING REGION OF COLOMBIA: ACCELEROGRAPHIC RECORDS, STRUCTURAL RESPONSE AND DAMAGE, AND CODE COMPLIANCE AND ENFORCEMENT

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SUMMARY

In order to understand the full impact of the damage to buildings that occurred due to the January 25, 1999, earthquake that affected the Central-Western region of Colombia, it is necessary to describe the evolution of the building practice in the country. The impact of the mandatory use of the first earthquake resistant regulations, enacted in 1984, is very important when interpreting the observed damage. The construction types prevalent in Colombia are discussed. The behavior of buildings during previous earthquakes is presented. A brief description of the Colombian earthquake resistant regulations is given, for both the 1984 Code and the 1998 update. The accelerographic records obtained during the January 25 1999 earthquake are presented. The building damage in the coffee-growing region is discussed, along with the statistics of building type, height and usage. The Code compliance and enforcement is discussed.

TYPE OF CONSTRUCTION IN COLOMBIA

The construction industry in Colombia is one of the main contributors to the gross national product and is the source of employment of a significant percentage of the labor force, especially for moderately and low trained workers. From less than 4 million inhabitants at the turn of the present century the population of the country has grown close to 40 millions today. Although the annual rate of growth declined in the last decade to 2%, the demand for housing is high and it explains why residential construction makes 75% of the production of the construction industry.

The main structural construction materials in Colombia are reinforced concrete and masonry. Although structural steel is used in large span roofs and in bridges, its use in the framing of buildings is limited. For reinforced concrete buildings, the moment resisting frame has been the traditional system and recently structural walls have appeared as an alternative in low-rise and high-rise buildings. Masonry is used for single family dwellings, and low-rise and high-rise apartment buildings. Adobe construction is used in some rural areas but its use in Colombia is decreasing everyday.

Reinforced concrete was introduced in Colombia in the 1920's. The structures built in that time just followed what was common practice in North America and Europe. By the 1940's, a local evolution in the construction of slabs had occurred and left in place wood fillers made with "guadua" -- a local type of bamboo -- became popular and are still used in some regions of the country. During the 1950's, a development of slab-column frames occurred, and a special type of waffle slabs named "reticular celulado" became popular, its employment extending to other Latin-American countries. The use of reinforced concrete structural walls was a result of the requirements of the 1984 building code [MOPT, 1984], and the timid usage encountered in the late 1980's has increased steadily since then. Notwithstanding, moment-resistant building frames still make the majority of the reinforced concrete structural system of buildings.

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Both non-engineered and engineered masonry is used in Colombia, with the former mainly in single dwelling low-cost construction, where the owner is the builder. Single family dwellings are built of masonry as a rule. Unreinforced masonry was forbidden by the building code in 1984 [MOPT, 1984], but a large amount of unreinforced masonry buildings still exists. The rest of masonry construction is engineered, with the following types being popular: (a) Reinforced masonry -- This term locally means engineered masonry built using masonry units with vertical cells. It is used from one story homes to medium-rise buildings. It is mainly used in low-income housing projects that need less parking space. It was introduced to the country in the decade of 1970's; (b) Confined masonry -- Consists of masonry walls surrounded by a light reinforced concrete frame. The use of confined masonry in Colombia dates from the 1930's and it is probably the most widely used structural masonry system. It is used from single story dwellings to apartment buildings up to five stories. It is engineered in most cases although the code includes a complete chapter on empirical design of this type of masonry.

With respect to non-structural elements, building partitions in apartment, and even office, buildings traditionally have been built using clay tile. The same is true for façades in apartment buildings where plastered clay tile and un-plastered solid clay brick are used. The seismic implications of this practice are discussed ahead.

BEHAVIOR OF BUILDINGS IN PREVIOUS EARTHQUAKES

Three earthquakes occurring in the late 1970’s and early 1980’s were crucial in defining the scope of the first Colombian building Code enacted in 1984 [García, 1984, and MOPT, 1984]. These earthquakes were: (a) November 23 of 1979 ($\mathbf{M_s}$ = 6.4) affecting the coffee-growing region; (b) December 12, 1979 ($\mathbf{M_s}$ = 7.8) in the subduction zone in the Pacific Ocean coast; and (c) the March 31 of 1983 ($\mathbf{m_b}$ = 5.5) affecting the city of Popayán.

The main features of the observed behavior were:

- Collapses and significant damage concentrated in low-rise buildings with less than five stories. A local prejudice that low-raise buildings did not require earthquake resistant design was the main culprit of this.
- Excessive flexibility under lateral loads of most buildings. Absence of seismic design or non-compliance of the drift requirements was the common reason for this behavior.
- A disproportionate large amount of column failures, mainly because of lack of appropriate lateral reinforcement combined with small element section area.
- Significant damage and even collapse of reinforced structural masonry buildings. Lack of appropriate building and supervision practice was the common factor. Absence of horizontal shear reinforcement was the culprit in some cases.
- In the Popayán earthquake, a large amount of damage to unreinforced masonry. The depth and large epicentral distance of the other two earthquakes probably prevented damage to unreinforced masonry.
- Non-structural damage in masonry partitions and façades. The importance of this fact was probably obscured by the more spectacular structural damage.

During the years between the enactment of the Code in 1984 and the occurrence of the January 25, 1999, earthquake several earthquakes occurred in Colombia. Four earthquakes with large to moderate magnitudes: October 18 of 1992 ($\mathbf{M_s}$ = 7.2), June 6 of 1994 ($\mathbf{M_s}$ = 6.4), January 19 of 1995 ($\mathbf{M_s}$ = 6.5), and February 8 of 1995 ($\mathbf{M_s}$ = 6.4); were felt, with appreciable intensity, respectively in the Colombian cities of Medellín, Cali, Bogotá, and Pereira. Although the hipocentral distance to all of them, in each case, was more than 100 km, and no structural damage of importance was reported on buildings designed under the 1984 Code; they caused appreciable amounts of nonstructural element damage, specially in Medellín during the 1992 earthquake. These events increased the concern that the then current story drift requirements were insufficient and stricter limits were needed, as a response to the continuing use of brittle unreinforced masonry façades and partitions.

COLOMBIAN EARTHQUAKE RESISTANT REGULATIONS

The need in Colombia of a modern mandatory building code was made evident by the March 31, 1983, Popayán Earthquake. The Colombian seismic code was enacted in June of 1984 [MOPT, 1984]. The Code tried to take care of the problems brought out by earthquakes described previously. These earthquakes emphasized the deficiencies in the Colombian earthquake resistant building practice described. 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 in the structural perspective: a recent survey among practicing structural engineers, assigned story drift as the controlling design parameter, as opposed to base shear; when determining dimensions for a building structure [Meigs, Eberhard, and García, 1993.]. Unfortunately, a corresponding evolution in nonstructural element building practice did not occur.

Since the 1984 Code was the first such a document to be made mandatory in Colombia, the Committee in charge of its drafting decided to include what was deemed critical at the moment – mainly life threatening aspects --, and postpone several important, but not critical issues, for future Code updates. Among the themes that were postponed were:

- A change in the structural systems permitted – The use of the Code as a vehicle for sponsoring a greater use of structural walls as opposed to moment-resistant frames was studied. The restrictions imposed on the allowable story drift were a result of these discussions.
- Limitations of building irregularities – Timid recommendations were given, but a full set of requirements for limiting irregularities was postponed.
- Non-structural elements – The draft of the 1984 Code had a chapter dealing with non-structural elements. It was suppressed, unfortunately, in the final version. The main reasons behind this were the lack of realistic alternatives for dealing with these elements, and the overwhelming pressure from the building and material industries on the high costs involved.
- Other structural materials – The 1984 Code had requirements for reinforced concrete, reinforced masonry and structural steel. The experience in the country with other structural materials such as wood or aluminum was minor; neither was there evidence of their wide spread use.

Work on the update of the code was initiated by the Colombian Association for Earthquake Engineering in the early 1990's. The 1984 Code had been enacted by Decree of the President of Colombia, under special powers given by Congress, for a one-time issue only. In order to obtain new, and permanent, authorizations, special legislature was proposed in Congress. In August of 1997, Law 400 of 1997 was enacted by Congress, creating a Permanent Code Committee empowered to recommend to the President of Colombia updates of the Code when deemed necessary. The update of the Code was enacted in January 1998, using these authorizations from Congress [AIS, 1998] and its official denomination is "Reglamento NSR-98".

The seismic events that occurred from 1984 to 1997 increased the concern that the story drift requirements were insufficient and stricter requirements were needed, as a response to the continuing use of brittle unreinforced masonry façades and partitions. The update of the Code contains story drift requirements that are more conservative than those contained in the 1984 version, plus several other schemes, to limit nonstructural element damage. The possible additional construction cost brought out by these new requirements motivated a formal evaluation of the type of structural systems used [García and Bonacci, 1994], of the drift design procedures [Sozen and García, 1992], and of their economic impact [Serna, 1994], [García, Pérez, and Bonacci, 1996], [García, 1996]. The ultimate goal, was to bring into a practical designers perspective the issues involved; the rationale beyond selecting different member section dimensions; and, last but not least, the economic implications on the structural alternatives for the client to chose from, given a performance limit established by the story drift limit.

Table 1 – 1998 Colombian Code Update Content

Title	Content	Remarks
A	General Earthquake Resistant Design Requirements	Updated
B	Loads	Updated
C	Structural Concrete	Updated
D	Structural Masonry	Updated
E	One and two-story dwellings	Updated
F	Metal Structures	Updated
G	Wood Structures	New
H	Geotechnical Requirements	New
I	Supervision	New
J	Fire Requirements	New
K	Other General Requirements	New

The three main features of the Code update, among others, are worth mentioning: (a) with respect to non-structural elements, a new Chapter was included for the design of these elements; special responsibilities were given to the architect, the builder, the supervisor, and the owner with respect to non-structural elements; (b) more strict drift limits are required, in order to incentive the use of more structural walls and restrict non-structural damage; and (c) all the critical facilities of the country are required to make seismic vulnerability assessments of their buildings and corresponding upgrades in no more than six years from the enactment of the new Code. The contents of the new Code are described in Table 1.

ACCELEROGRAPHIC RECORDS FROM THE JANUARY 25, 1999, EARTHQUAKE

Records from approximately 40 strong motion accelerographs were obtained for the main event of January 25, 1999, and a corresponding number for the main aftershock that occurred in the evening the same day. The stronger records were obtained at the Universidad del Quindío, in Armenia on soft soil, just 14 km north from the epicenter (see Figures 1 to 3). Peak ground accelerations recorded in this station were 0.53**g** EW, 0.46**g** vertical, and 0.59**g** NS. The soil profile at this site consists of approximately 30 m of volcanic ash fill.

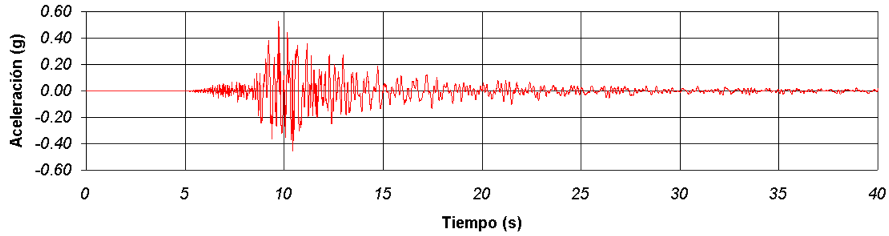

Figure 1 – EW record at Universidad del Quindío in Armenia (a_{max} = 0.53g)

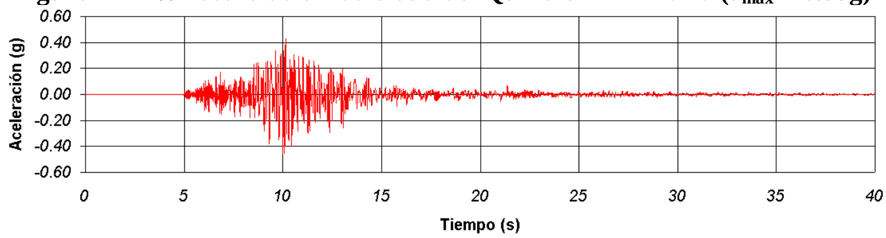

Figure 2 – Vertical record at Universidad del Quindío in Armenia (a_{max} = 0.46g)

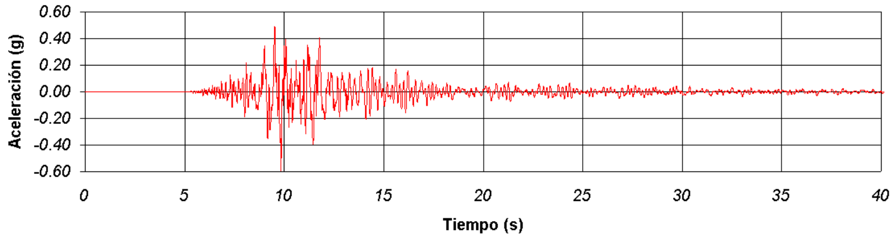

Figure 3 – NS record at Universidad del Quindío in Armenia (a_{max} = 0.59g)

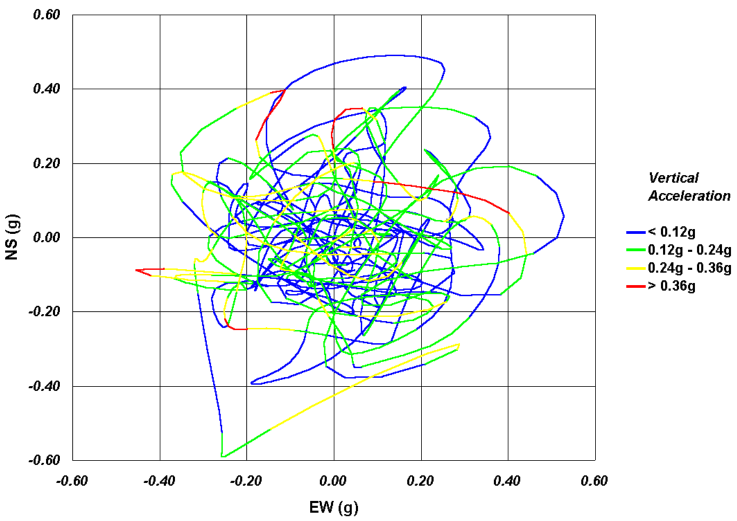

Figure 4 – Universidad del Quindío (Armenia) site accelerograph shown in plan view

The two horizontal components of the Universidad del Quindío accelerographic record are plotted together in Figure 4, with the corresponding vertical acceleration is described using a color code. It is possible to observe that in some instances the two horizontal peaks occur simultaneously, and are accompanied by a very strong vertical acceleration. The acceleration response spectrum is shown in Figure 5. A high content of short period components can be observed. The EW component peaks at a vibration period of 0.25 seconds and the NS component at 0.56 seconds. The displacement response spectrum, shown in Figure 6, flattens at a period of approximately 1 second. The energy spectrum, Figure 7, shows characteristics periods of the order of 0.5 - 0.6 seconds for the horizontal components, and of 0.25 seconds for the vertical component. The Fourier spectrum, Figure 8, just confirms these observations.

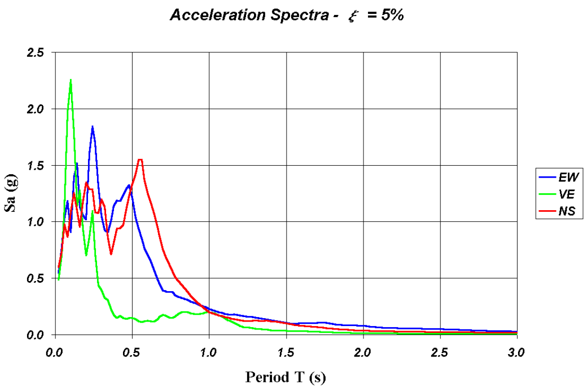

Figure 5 - Acceleration spectrum at the Universidad del Quindío site in Armenia

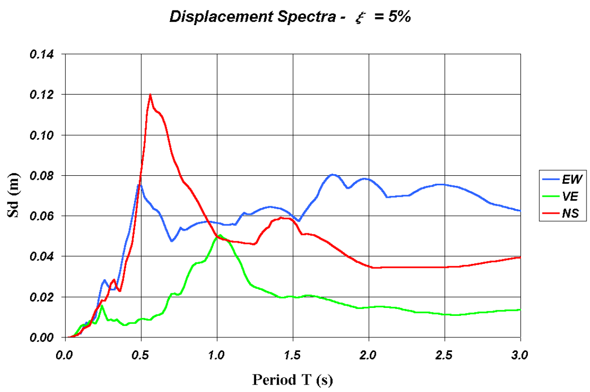

Figure 6 - Displacement spectrum at the Universidad del Quindío site in Armenia

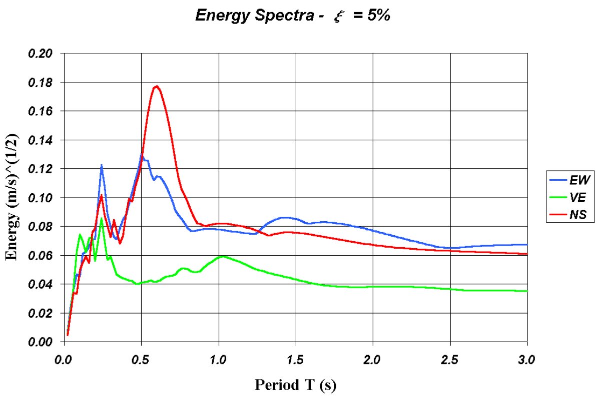

Figure 7 - Energy spectrum at the Universidad del Quindío site in Armenia

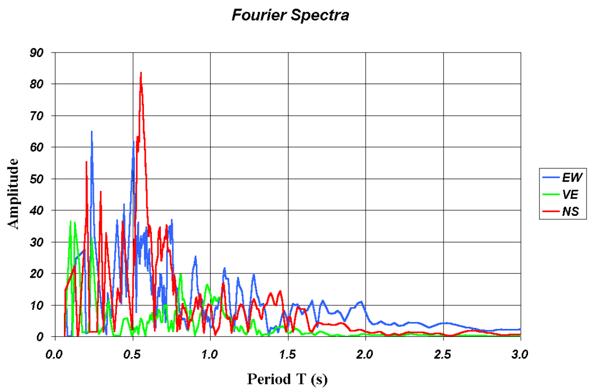

Figure 8 - Fourier spectrum at the Universidad del Quindío site in Armenia

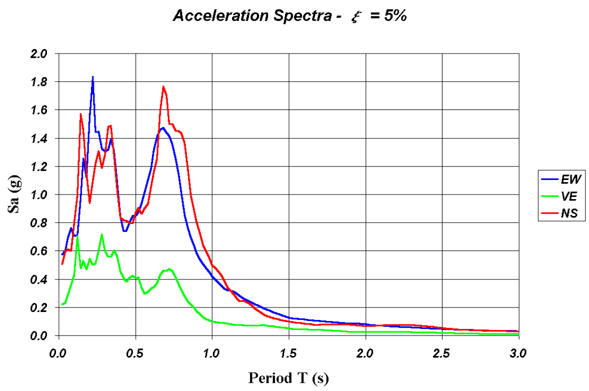

Figure 9 - Acceleration response spectrum at the Filandia site

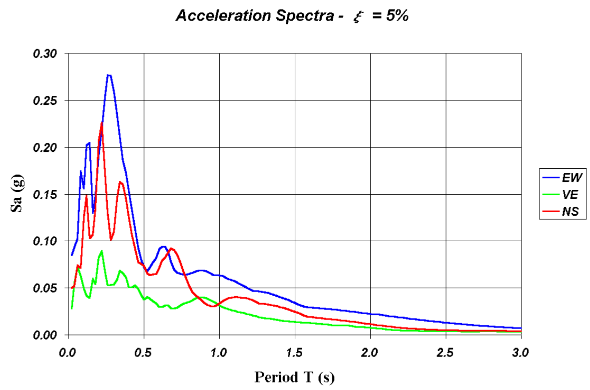

Figure 10 - Acceleration response spectrum at the Bocatoma (Pereira) site

In Filandia, a town located north of Armenia, 33 km from the epicenter, the peak ground accelerations recorded were 0.57**g** EW, 0.19**g** vertical, and 0.49**g** NS. The soil profile consists of approximately 20 m of volcanic ash fill. Figure 9 shows the acceleration response spectrum for this site. The Bocatoma site located 10 km east of Pereira at the city waterworks sluice distant 48 km from the epicenter. It is sited on rock, and the record obtained there corresponds to the rock register obtained closer to the epicenter. The peak ground accelerations recorded here were 0.084**g** EW, 0.028**g** vertical, and 0.050**g** NS. Figure 10 shows the acceleration response spectrum for this site.

Several records were obtained within the city of Pereira, located approximately 48 km from the epicenter. The Mazpereira station is located in a site with a 15 m deep man-made fill, in an area where the intensity of damage has been high in previous earthquakes and during this one. Peak ground accelerations recorded in this station were 0.25**g** EW, 0.10**g** vertical, and 0.30**g** NS. Figure 11 shows the acceleration response spectrum for this site. The Castañares station is located in a similar site with a 6 m deep man-made fill. Peak ground accelerations recorded in this station were 0.21**g** EW, 0.10**g** vertical, and 0.14**g** NS. Figure 12 shows the acceleration response spectrum for this site.

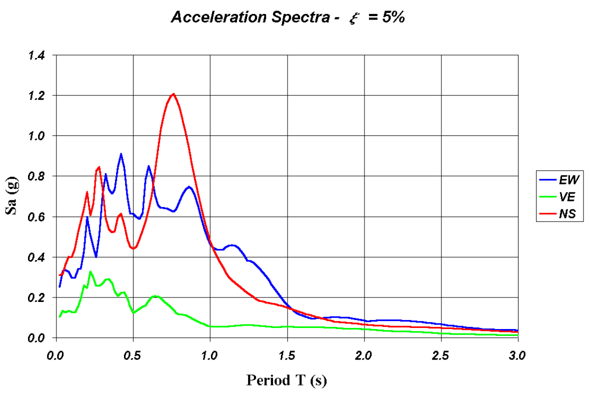

Figure 11 - Acceleration response spectrum at the MazPereira (Pereira) site

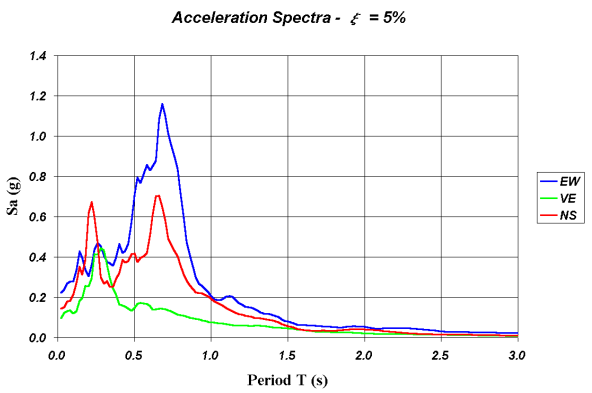

Figure 12 - Acceleration response spectrum at the Castañares (Pereira) site

In Dosquebradas, a town that is part of metropolitan Pereira, 53 km from the epicenter, at the La Rosa site the peak ground accelerations recorded were: 0.18**g** EW, 0.07**g** vertical, and 0.19**g** NS. The soil profile consists of approximately 70 m of alluvial deposits of clay, silt and silty clay alternated with sand and gravel lenses. Figure 13 shows the acceleration response spectrum for this site. At the hospital of Santa Rosa de Cabal, a town located further north approximately 53 km from the epicenter the peak ground accelerations recorded were: 0.18**g** EW, 0.06**g** vertical, and 0.26**g** NS. The site has deep deposits of volcanic ash alternated with alluvial material.

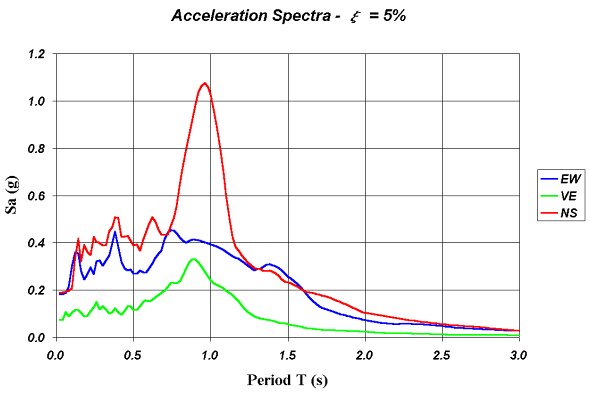

Figure 13 - Acceleration spectrum at the La Rosa (Dosquebradas) site

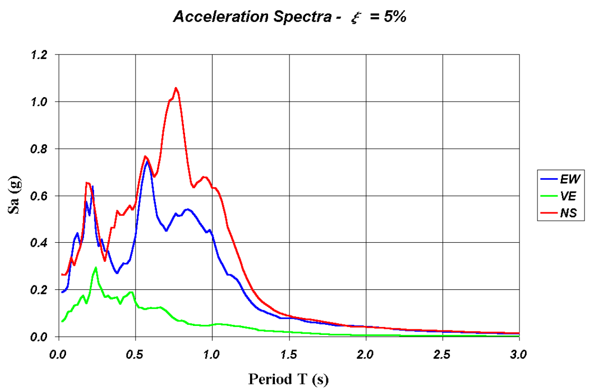

Figure 14 - Acceleration spectrum at the Hospital of Santa Rosa de Cabal

OBSERVED BUILDINGS BEHAVIOR DURING THE JANUARY 25, 1999, EARTHQUAKE

In total 27 municipalities were affected by the January 25, 1999, earthquake. The official number of fatalities was 1185, plus 98 disappeared, 8523 people injured (83% of them in the department of Quindío and 17% in the department of Risaralda). The official figure for number of buildings affected is 79,446. Of these buildings 43,474 had minor to moderate damage, and 35, 972 were severely damaged. The last figure is divided, in turn, in 17,551 buildings with partial or total collapse, and 18,421 condemned. Around 74% of the educational buildings of the region were damaged, affecting approximately 100,000 students. The official number of person left homeless is 160,397. Of these 67,539 were living in temporary shelters after the earthquake. Unemployment in the coffee-growing region increased by 22%. Table 1 presents general data for Armenia and Pereira, the two largest cities affected.

Table 2 – January 25, 1999, earthquake – General characteristics for Armenia and Pereira

	Armenia	Pereira
Distance from epicenter	14 km	48 km
Population	320,000	460,000
No. of victims	700	40
No. of buildings	66,000	108,000
No. of heavily damaged buildings	9,430	9,870

Figures 15, 16, and 17 show the distribution by type of construction, building use, and age of construction, for a 12,454 buildings sample in the center part of the city of Pereira. It is important to note that 56.4% of the buildings correspond to unreinforced masonry construction, and that 91.7% were dwellings. Only 11% of the buildings were built after the 1984 code was enacted.

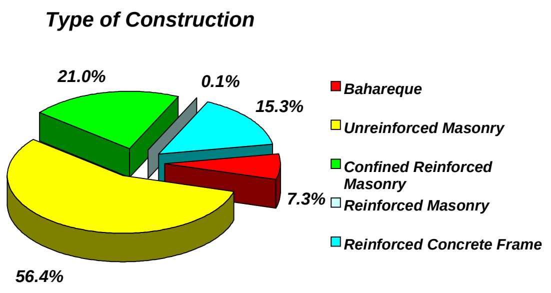

Figure 15 – Type of construction for a 12,454 buildings sample in Pereira

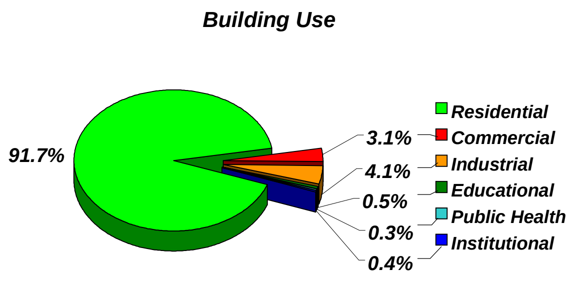

Figure 16 – Building use for a 12,454 buildings sample in Pereira

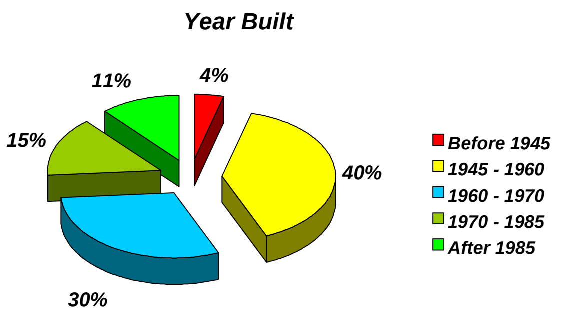

Figure 17 – Age of construction for a 12,454 buildings sample in Pereira

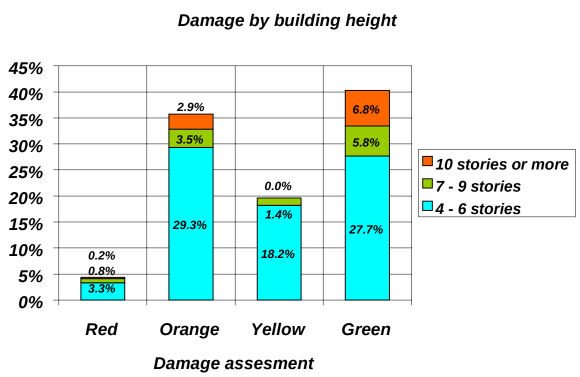

Figure 18 – Tagging of the 12,454 buildings by height for buildings 4 stories and taller

The results of the assessment of the buildings after the earthquake was performed using red tags for buildings either collapsed of with severe structural damage, orange tags for buildings with reparable structural damage or severe non-structural damage that required building evacuation while repair were performed, yellow tags for buildings with easily reparable damage that could be performed with the building occupied, and green tags for minor damage. Figure 18 shows the tagging results for the same building sample in Pereira.

The observed damage is consistent with age of construction, structural systems employed, and type of strong ground motion. The type of strong motion as depicted in Figure 4, with very strong accelerations in all three components, preclude any chance for unreinforced masonry to survive the earthquake. The short period waves containing the majority of the energy, accompanied by large vertical accelerations, is the worst combination for unreinforced masonry and low-height poorly constructed buildings. With 73% of the red tagged buildings being one and two-story buildings and 89.5% percent of the red and orange-tagged structures consisting of residential buildings: the unreinforced masonry is the culprit of most of the victims and observed damage. The sample of buildings 4 or more stories of height confirms that better quality construction was employed: 40% of the sample was green tagged, less than 5% of the sample was red tagged, and red tagged buildings higher than 6 stories comprise only 1% of the sample. Having 55% of the buildings 4 stories and taller tagged orange and yellow just points toward the problems of employing brittle unreinforced masonry partitions and façades.

CODE COMPLIANCE AND ENFORCEMENT

The observed behavior was not very different from that observed during the earthquakes that inspired the enactment of the first code in 1984, as described previously in this document. The age on the inventory of buildings in the affected zone points toward the same patterns of damage observed previously for buildings constructed before 1984. The favorable impact of the first Colombian seismic code was made evident through the entire region affected by the earthquake. The amount of non-structural element damage points toward the need of changing the Colombian practice of building partitions and façades employing unreinforced masonry. Most of the damage observed in post-code buildings could have been avoided employing enhanced supervision and inspections practices. The Code update enacted in 1998, which tends to reduce most of the observed deficiencies in non-structural element usage and supervision and inspection, did not have a chance to be effective because few buildings had been built employing its requirements.

The sad confirmation that unreinforced masonry should not be used in seismic zones should encourage Colombia to implement a program for reducing the large inventory of existing unreinforced masonry buildings. Earthquake strong motion amplification in sites with profiles of soils of volcanic origin and containing man-made fills correlate with the patterns of damage. City planning for the reconstruction is being influenced by their presence.

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