Evaluación del comportamiento sísmico de viviendas de estratos marginales con cubiertas verdes: estudio de caso del municipio de Soacha, Colombia

Seismic behavior assessment in vulnerable housing with green roofs: case study in the township of Soacha, Colombia

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Fecha de Recepción: 16/01/2014

Fecha de Aceptación: 01/03/2014

PAG 98-114

Resumen

El grupo de investigación *Ciencia e Ingeniería del Agua y el Ambiente* y *PROSOFI* (Programa Social de la Facultad de Ingeniería) de la Pontificia Universidad Javeriana propusieron para viviendas de población socialmente vulnerable la construcción de techos verdes que se basan en cubrir parte de la cubierta de las viviendas con vegetación potencialmente productiva. Teniendo en cuenta que la masa inercial de las cubiertas verdes puede incrementar la vulnerabilidad sísmica de las viviendas; el grupo de investigación *ESTRUCTURAS* y *CONSTRUCCIÓN* realizó un análisis estructural (con enfoque sísmico) de la vivienda que se ha usado como prueba piloto de este tipo de cubiertas verdes. Se realizó un estudio de dinámica estructural de la vivienda con acelerómetros sísmicos y con modelaciones por elementos finitos. Los resultados sugieren que la vulnerabilidad sísmica de la edificación se incrementó con la presencia del techo verde ya que la distorsión de entrepiso creció un 62% y los esfuerzos máximos se aumentaron en un 241%; no obstante estos incrementos no son peligrosos para la estabilidad y funcionalidad de la casa prefabricada.

Palabras claves: Techos verdes, análisis dinámico, comportamiento sísmico, vulnerabilidad sísmica

Abstract

The research group *Science and Engineering of Water and the Environment* and *Social Program of the Faculty of Engineering (PROSOFI)* of the Pontificia Universidad Javeriana proposed, for socially vulnerable population, green roofs based on covering the rooftop of houses with potentially productive vegetation. Taking into account that the inertial mass of the green roof could increase the seismic vulnerability of the house, the research group *STRUCTURES* and *CONSTRUCTION* performed a seismic structural analysis on the house used as a pilot test for this type of green roofs. A structural dynamic analysis of the building was performed with seismic accelerometers and finite element modeling. Results suggest that the seismic vulnerability of the building was increased by the presence of the green roof as the seismic interstory drift grew 62% and maximum stresses increased by 241%; nevertheless, these increases do not endanger the stability and functionality of the house.

Keywords: Green roofs, dynamic analysis, seismic behavior, seismic vulnerability

1. Introduction and justification

In Colombia, forced relocation as a consequence of environmental disasters, armed conflicts and other economic, social and political factors have resulted in a total of 5,445,406 affected people between 1985 and 2012 (CODHES, 2012). Being Bogota D.C. the country's capital city and the economic and political center, it attracts most of this vulnerable population. According to (CODHES, 2012), nearly 41,246 people came to the Capital District in 2011 as a consequence of relocation, which means approximately 114 people per day. Additionally, the inadequate government policy concerning economic assistance and supply of decent and safe housing, has encouraged non-authorized urbanizations in high risk locations, which are built without complying any of the technical requirements, with materials such as non-confined masonry, prefabricated systems that are not endorsed by the Earthquake-Resistant Standard, wood and even corrugated metal roofing. In most cases, this type of buildings is seismically vulnerable.

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On the other hand, given the lack of growing land and green areas that allow a better quality of life and environmental sustainability within the cities, alternatives such as “green roofs” have been developed in buildings around the world, which have currently become a recurrent subject, up to the point that the Council of Bogota has tried to implement, promote and encourage the use of these technologies through agreements N° 338 DE 2009, N° 418 DE 2009 and through the resolution 6423 of 2011; as well as what has been stipulated in the reference (Secretaría Distrital del Medio Ambiente, 2011). One of the advantages of green roofs is that they are self-sustainable and when properly implemented they can contribute with additional economic incomes to the owners of vulnerable housing.

Therefore, the research group Science and Engineering of Water and the Environment and Social Program of the Faculty of Engineering (PROSOFI) of the Pontificia Universidad Javeriana proposed for Bogota’s socially vulnerable population (low socioeconomic classes), and nearby townships, a construction typology of green roofs based on covering the rooftop of houses with potentially productive vegetation (lettuce, radish and onions) (Forero & Devia, 2012). This vegetation is introduced in recyclable containers (soda bottles) full of substrate. This system can be classified in the category of lightweight green roofs.

In all case studies, the additional weight of green roofs do not exceed the resistance of the house due to gravity loads, although we should mention that these loads change depending on variables such as the roof’s dimension, type of introduced vegetation, substrate depth, and the water holding capacity of the vegetation and organic soil.

As we already mentioned, most of the structural systems of vulnerable housing are not built according to the guidelines of the Colombian earthquake-resistant construction standards AIS, 2010 (Normas Colombianas de Construcción Sismo Resistente); and it is evident that green rooftops provide an inertial mass that could increase the seismic vulnerability of these houses.

Therefore, the research group STRUCTURES and CONSTRUCTION of the Department of Civil Engineering of the Pontificia Universidad Javeriana performed a seismic structural analysis on the house used as a pilot test for this type of green rooftops. A structural dynamic analysis was performed in the (prefabricated) one-story house located in Soacha, inhabited by a low-income family who considers the implementation of productive green rooftops as a good option for the family economy.

The following methodology was applied:

1. Technical inspection visits to assess: constructive system, building dimensions, materials characteristics, on-site inspection of the green roofs’ weights.
2. House monitoring with seismic accelerometers to measure environmental vibrations with and without green roofs (determination of the fundamental period of vibration).

3. *Finite element modeling of the building and comparison of periods estimated with the model vs. periods measured on site.*
4. *Seismic vulnerability assessment of the building with and without green roofs through: 1. Flexibility indexes and 2. Maximum stresses induced by seismic ground motions.*

2. Implemented green roofs

A productive green roof was built (see Figure 1) according to the method proposed by Forero et al. (2012). This roof has two plant species: herbaceous (*Lactuca sativa*) and cruciferous (*Raphanus sativus*). These species were chosen due to their shallow depth roots (Casseres, 1980), high growth rates (around two months) and suitability for human consumption, which could be interesting for the target community. The implemented green roof consists in more than 100 recycled plastic bottles (each bottle with an original capacity of 2.5 liters) used as containers for three seedlings (two *Lactuca sativa* and one *Raphanus sativus*). The bottles are connected through rainwater channeling pipes which also form an efficient irrigation system. The average soil depth is 8 cm, with 60% black soil and 40% rice husk. The purpose of the irrigation system is to guarantee the minimum water content needed for the plants' growing and survival (see Figure 1). It is important to highlight that the elements of the vegetable rooftop are not anchored; the connections of the irrigation system keep them in place.

Figura 1. Imágenes de techo verde propuesto
Figure 1. Image of the proposed green roof

This type of green roof has been studied since 2011, concluding that it could impact the community not only regarding agricultural production, favoring self-management and appropriation of the land (Forero et al., 2012), but also in relation to cost reductions in the construction of urban drain infrastructure, and the mitigation of flood risks in vulnerable territories (Oviedo & Torres, 2013). Families of the Cazucá sector (victims of relocation forced by violence) have sown lettuce, radish, scallion, spinach and parsley on their roofs. These plants are not higher than 10 cm, since they are in controlled conditions of nutrients and water, which limits their growth. Each roof fulfills another function: they capture water, which in a different scenario would fall to the ground and contribute to the hillside erosion.

Nevertheless, there are no definitive results available on energy, environmental (air, water) and structural matters, which could restrain or favor the use of this type of systems in segregated territories; this paper is a first step regarding the structural evaluation of the system.

3. Characteristics of the studied house

One of several charitable foundations in Colombia was the promoter and main responsible for the construction of the studied prefabricated home. The typology implemented for this house is very similar to that which other foundations (Un Techo para mi País, Fundación Catalina Muñoz, TECHO, among others) have built throughout Colombia for socioeconomically vulnerable classes (Figure 2a). The constructive system of the prefabricated house consists in modular concrete panels fitted in profiles of thin galvanized steel sheets (see Figure 1a). These components enable the assembly of all parts of the house. The main components are:

- *Modular concrete panels, aluminum-reinforced.*
- *Profiles of galvanized steel sheet folded 22 gauge, which enable the assembly of the panels.*
- *Wooden roof support.*
- *Fiber-cement roof tiles.*

The studied house is a one-story home with 25.39m² of built area, with available space for two rooms, kitchen, living and dining room. The architectural distribution is shown in Figure 2b.

Figura 2. a) Imagen de la vivienda bajo estudio b) Plano Arquitectónico vivienda. Unidades: Centímetros (cm)
Figure 2. a) Image of the studied house b) Architectural drawing of the house. Units: centimeters (cm)

Figure 3 shows the geometrical characteristics of the galvanized steel profiles of the house and their layout.

Figura 3. a) Ubicación de los perfiles de acero galvanizado. b) Perfil esquinero (E). c) Perfil Unión Simple (U). d) Perfil Tipo 1 (1) e) Perfil Viga Techo (U). Centímetros (cm)
Figure 3. a) Position of galvanized steel profiles, b) corner profile (E), c) simple connection profile (U), d) type 1 profile (1), e) Roof beam profile (U). Centimeters (cm)

Furthermore, the foundation is made up of a poor concrete plate which provides leveling and stability to the structure. It has a gabled rooftop with a slope of approximately 18° (33%), where fiber-cement tiles are supported on wooden beams, as indicated in Figure 4.

Figura 4. Vigas de madera que soportan la cubierta a dos aguas
Figure 4. Wooden beams which support the gabled roof

Although the main materials used in the construction of the home follow a standardized manufacturing process, the constructive system leaves many open spaces for uncertainty in relation to its structural behavior, since it has a rigid diaphragm and one structural unit, because concrete panels (3.2 cm thick) are assembled without no type of connection between them.

All elements forming the green roof were weighted independently so as to be able to rely on a proper estimate of the additional mass to be imposed on the house. Weights were taken on site with electronic scales calibrated for this purpose and its total weight was estimated in 3693.9 N (pet bottles full of substrate, weight of vegetables, irrigation system, and water in the system).

4. House implementation

In order to perform the measurements, a complete high-sensitivity electronic system was designed, including the following components:

- Four Wilcoxon uniaxial seismic accelerometers, which are capable of measuring accelerations in a range from 0.000001 to 0.5g. The frequency response of these sensors is lineal in a range between 0.05 and 200 Hz.
- Amplifiers and filters for the accelerometers, allowing amplifications of 10, 100 or 1000 mV/g and filters of 450 Hz and 100 Hz.
- Data purchase system for the four channels (brand "National Instruments"), which allows data collection at a speed of 2000 data per second.

- Laptop with the registered software Labview ("National Instruments"), for data collection and control.
- Supports for installing the accelerometers on the roof.

Figure 5 shows the data purchase system and one of the seismic accelerators.

Figura 5. a) Sistema de adquisición de datos b) acelerómetro sísmico marca Wilcoxon
Figure 5. a) Data purchase system b) Wilcoxon seismic accelerator

The main objective of the measurement was to determine the fundamental period of the house (with and without green roof) through the assessment of environmental vibrations. The house was implemented both in the east-west and north-south directions, but it was evident that the structure would respond in the direction of its fundamental mode that was aligned in the east-west direction. This is mainly due to the fact that in the north-south direction the building has greater wall density and smaller number of voids (doors and windows), which make it more rigid. Therefore, it is probable that in the event of an earthquake the structure will show east-west displacements mainly.

The four seismic accelerometers were located as indicated in Figure 6.

Figura 6. Ubicación de acelerómetros a) Vista en planta b) Vista en alzado
Figure 6. Location of accelerometers: a) Top view b) Front view

The accelerometer of channel "0" was located at the foundation level, accelerometers of channels "1" and "2" were located at two opposing sides of the rooftop and the accelerometer of channel "3" was installed at the geometrical center of the house. Figure 7 shows images of the measurement process with and without green roof. During the measurement season, more than 50 records of 2 minutes were taken at different times of the day, with a sampling rate of 400 data per second for each one of the 4 channels.

Figura 7. Fotografías de la instrumentación a) sin techo verde b) con algunas plantas del techo verde
Figure 7. Photos of the implementation: a) without green roof b) with some plants of the green roof

By means of processes similar to those implemented in (Emiliani, Rincón & Ruiz, 2012), (Zabala, Gutiérrez & Ruiz, 2012), (Cifuentes & Ruiz, 2007), (Ruiz, Otálora & Rodríguez, 2007), periods were estimated through environmental vibrations. Once the environmental vibrations were recorded, the method estimated the transfer functions between the sensors located in the rooftop and the base sensor located at the foundation level (Chopra, 2001). This allows seeing the amplifications for frequencies close to those of the vibration modes of the assessed dynamic system, in this case, the house with and without green roofs. Figure 8 shows examples of environmental vibration records in the east-west direction for the accelerometers of channel "2" and channel "0".

Figura 8. Ejemplo de señales registradas con los acelerómetros
Figure 8. Example of signals recorded with the accelerometers

After the measurements, the records were processed by numerical techniques in order to create transfer functions. Figure 9 shows the transfer function for the house without green roof, for the main motion direction (east-west). The same is done in Figure 10 for the transfer functions of the measurements taken in the house with green roof.

Figura 9 Función de transferencia de vivienda SIN techo verde
Figure 9. Transfer function of the house *WITHOUT* green roof

Figura 10. Función de transferencia de vivienda CON techo verde
Figure 10. Transfer function of the house WITH green roof

When analyzing the above results, it is evident that the presence of green roof changes the dynamic properties of the house, increasing its fundamental period of vibration, since the transfer functions go from amplifications for a frequency of 12.25 Hz (period of 0.0816 s) WITHOUT green roof to amplifications for a frequency of 7.86 Hz (period of 0.127 s) for the house WITH green roof.

5. Finite element numerical modeling of the house

The numerical models of the house WITH and WITHOUT green roof were developed with the help of the SAP2000 software (CSI, 2012). In both models, the geometrical and mechanical characteristics of the materials were kept identical; however, the load and mass corresponding to the green roof, induced by PET bottles and other accessories such as the irrigation system, were applied to only one of the two models.

During the house modeling, it was necessary to create three (3) types of materials: concrete, steel and wood. The unit weight of concrete was calculated following the recommendations of the Colombian Earthquake-Resistant Standard (NSR-10), mentioned in the reference (AIS, 2010). This unit weight is 22 kN/m³. On the other hand, according to the reports of (Ruiz et al, 2013), the reference (AIS, 2010) overestimates by 40% the real modulus of elasticity of concrete for Bogota. Therefore, and based on the formulas recommended in (Ruiz et al, 2013), shown in Figure 11, a modulus of elasticity of 17872 MPa was assigned to the concrete panels, corresponding to a concrete with compressive strength of 21 MPa at 28 days.

It is important to mention that if we had used the modulus of elasticity recommended in (AIS, 2010), there would have been no proper adjustment between the experimental periods (environmental vibrations) and the periods estimated with the numerical model.

Figura 11. Estimación del módulo de elasticidad para los concretos usados en Bogotá (Tomado de (Ruiz et. al., 2013))

Figure 11. Estimate of the modulus of elasticity of concrete used in Bogota (based on (Ruiz et al, 2013))

For the steel material of the galvanized steel profiles, the following mechanical properties were used (AIS, 2010): Unit Weight of 78 kN/m^3 and Modulus of Elasticity of $200,000 \text{ MPa}$.

In relation to wood, the values chosen for the unit weight and the modulus of elasticity were 9 kN/m^3 and $49,000 \text{ MPa}$ respectively. It should be noted that wood is a heterogeneous, composite and anisotropic material, and therefore its mechanical properties vary according to factors such as humidity, sense of the fibers and its defects and imperfections; thus, predicting its structural behavior is much more complex and the margin of error is greater. However, this material has no significant influence on the structural system, because it is not relevant in the seismic-resistant system.

Steel profiles and wood beams were modeled as frame-type elements, and five types of profiles were created for the house's different types of frames. The geometrical properties required by the finite element model, such as area, torsion constant, moment of inertia, among others, were manually determined for each metal profile. Concrete panels were modeled as "shells" with an average thickness of 32 mm . The finite element numerical model calculated the weight and mass of all the elements that form the structural system. However, the loads and masses of the green roof (formed by individual bottles, water storage tank and irrigation system) as well as the fiber-cement tiles, were applied as superimposed loads (and masses). The green roof weight of 3694 N was applied to the wooden beams as evenly distributed loads and was considered as distributed mass for the dynamic analysis.

This weight corresponds to an evenly distributed load of 0.3 kN/m^2 , which is lower than the load resistance of fiber-cement tiles, which is 1.0 kN/m^2 according to the manufacturer; this allows to bear the weight of the rooftop live loads considered by the NSR-10 (0.35 to 0.5 kN/m^2). The weights established by the manufacturer were used for the fiber cement tiles and their accessories. The tiles' weight is 3524 N , which was also assigned as load and distributive mass to the wooden beams.

As for the seismic load, a modal response spectrum analysis was run considering a directional combination on the house of 100% seismic action in east-west direction, simultaneously with 30% seismic action in north-south direction and vice versa. The analysis included several acceleration response spectra used in the 2010 Seismic Microzoning of Bogota (FOPAE, 2010). These earthquakes correspond to the study of seismic threat in Colombia and Bogota. The design spectrum of the municipality in which the house is located was also used, which is very close to the capital city of Colombia. The response spectra of evaluated earthquakes are of regional and nearby origin; typically adjusted to medium and low seismic threat regions of the Republic of Colombia. All assessed response spectra and the design of the Earthquake-Resistant Standard NSR-10 (AIS-2010) are shown in Figure 12.

Figura 12. Espectro elástico de diseño para un coeficiente con respecto al crítico del 5%
Figure 12. Elastic design response spectrum for a coefficient of 5% in relation to the critical one

Regarding the analysis of the stresses induced on the structural elements, the following load combinations were used: $1.2D + E$ and $1.4D$; where D corresponds to the effects derived from the dead load and E to the effects of the seismic load. The coefficient of seismic force reduction (parameter R according to (AIS, 2010)) was established as 1.0, because precast constructions with low periods do not dissipate too much energy. This is based on (ATC, 1995), which states that in buildings with relatively short periods, lower than 0.12 seconds, the energy dissipation coefficient tends to be one.

The finite element model was based on the information of the above paragraphs. Figure 13 shows images of the fundamental modes of vibration of the house with and without green roof. The period of the house without green roof is 0.087 seconds, while that of the same house with the additional superimposed mass of the green roof has a period of 0.115 seconds.

Figura 13. Modos de vibración a) Sin techo verde (0.087 s) b) Con techo verde (0.119s)
Figure 13. Modes of vibration: a) without green roof (0.087s) b) with green roof (0.119s)

These periods are similar to those estimated with the transfer functions of the environmental vibrations' measurements which were 0.0816s WITHOUT green roof and 0.127s WITH green roof. Thus, the error of the numerical model period is 6.21% for the model WITHOUT green roof and 6.72% for the model WITH green roof. These error percentages are considered sufficiently low and allow stating that the numerical model is reliable for estimating the flexibility indexes and stress levels.

Assessments for the previously established load combinations were made, and maximum displacements were obtained in the nodes of the rooftop of the house. Afterwards, the interstory distortion was calculated (seismic drift according to (AIS, 2010) as the displacement of the roof node divided by the height of each node from the foundation level. These results are shown in Figure 14 for the building WITH and WITHOUT green roof.

Figura 14. Comparación de la distorsión de piso para la vivienda con y sin techo verde
Figure 14. Comparison of the floor distortion for the house with and without green roof

Figure 14 allows deducing that displacements increase significantly when the green roof is present (up to 62%). Nevertheless, in none of the two loading cases the drift values endanger the stability and functionality (damage in non-structural elements) of the prefabricated house, considering that the drift is not higher than 1% (interstory distortion), which is the limit value established by the NSR-10.

On the other hand, Figure 15 shows a distribution of maximum stresses for the combination of critical seismic loading for the wall of axis 6 of the studied house; for the structure both WITH and WITHOUT green roof. It is evident that the maximum stresses, which could induce cracking in the concrete panels, significantly increase with the presence of green roof.

Figura 15. Esfuerzos máximos actuantes sobre muro del eje 6 a) Sin techo verde y b) Con techo verde
Figure 15. Maximum stresses acting over wall of axis 6: a) without green roof and b) with green roof

In order to make a global analysis of these stress levels in the house, Figure 16 shows the comparison of maximum stresses induced by the seismic load combination for all finite elements of the building. This analysis is made for the house WITH and WITHOUT green roof.

Figura 16. Esfuerzos máximos actuantes sobre la vivienda bajo análisis
Figure 16. Maximum stresses acting over the analyzed house

Based on the information of Figure 16, when installing the green roof on the rooftop of the house, the maximum stresses associated to the seismic load combinations increase by up to 241% in the house WITH green roof.

According to the results of (Mogollón, 2012), the average resistance to tensile stress of the concrete used for this type of prefabricated houses is 1656 kPa, and therefore a reference dotted line is drawn in Figure 16. Based on the foregoing, it is evident that the seismic vulnerability of the house increased with the presence of the green roof; however, results are not critical nor put the stability and functionality of the prefabricated house at risk if we take into account that only 3 panels exceed the rupture stress. Furthermore, we should expect that the house has greater energy dissipation capacity, which would allow assuming a higher seismic force reduction coefficient (R up to 1.5).

6. Conclusions

- The structural period for the prefabricated house increased with the installation of the green roof. The period estimated by experimental techniques was 0.0816s WITHOUT green roof and 0.127s WITH green roof, which means a 56% increase.
- The interstory distortions (seismic drift) of the prefabricated house increased when the green roof load was put on the structure. In the light of the results, displacements due to seismic motions increased by up to 62%. It is important to highlight that these displacements did not ever exceed the limit values defined by the Colombian seismic-resistant standard (NSR-10).
- The maximum tensile stresses in the concrete panels (which are part of the structural system of the house) increased by up to 241%, as a consequence of greater seismic forces caused by the additional inertial mass of the green roof. Only 3 concrete panels of the house exceeded the maximum stress of 1656 kPa when the structure was modeled with the green roof.
- Based on the above, it is evident that the seismic vulnerability of the house increased with the presence of the green roof; however, results are not critical nor put the stability and functionality of the prefabricated house at risk.

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