

Analysis of the state of the structure of a bus stop subjected to loads exerted by a green roof, case study: Bogotá, Colombia

Análisis del estado de la estructura de un paradero de buses sometido a cargas ejercidas por un techo verde, caso de estudio: Bogotá, Colombia

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Abstract

This article presents the analysis of the structural conditions of four modified bus stops with the change of a load represented by a green roof in the city of Bogotá. The methodology has two phases for accounting the bus stop behavior; As a first step, a finite element model was the main tool to compare the critical stresses of the structure before and after the use of the green roof, and to observe the location of said stressed areas before the happening of a seismic force; and on the other hand a physical model which is subjected to different frequencies in a shaking table to compare the movement and damage of the structure before and after being modified. An increase in stresses of about 80,57% took place by the connection between the column and the central beam, however, given that this value is less than the yield limit of the material, it can be said that the structure will not suffer damage due to the green roof additional load.

Keywords: Stress, response spectrum, yield, modeling, green roof

Resumen

Este artículo presenta el análisis de las condiciones estructurales de cuatro paraderos de buses modificados con la incorporación de una carga representada por un techo verde en la ciudad de Bogotá. La metodología se compone de dos fases para la aproximación del comportamiento del paradero de buses; como primera medida se desarrolló un modelo computacional con el fin de comparar los esfuerzos críticos de la estructura antes y después de la instalación del techo verde, y observar la ubicación de los mismos ante la acción de una fuerza sísmica. Posteriormente se realizó un modelo físico el cual fue sometido a diferentes frecuencias en una mesa vibratoria con el fin de comparar el movimiento y los daños de la estructura antes y después de ser modificada. Se encuentra un aumento de aproximadamente un 80,57 % en el esfuerzo que siente la conexión entre la columna y la viga central, sin embargo, dado que dicho valor es menor que el límite de fluencia del material, se puede decir que la estructura se encuentra en el rango elástico pese a la implementación del techo verde.

Palabras clave: Esfuerzo, espectro de respuesta, fluencia, modelación, techo verde

1. Introduction

Currently, the safety that structures inspire among the citizens is the starting point for communities to entrust civil engineering with the construction of their homes, study and workplaces, communication routes, among others.

Through its professionals, the civil engineering field is called to take care of the surrounding infrastructure. The analysis of the constructions within a community plays a relevant role, given the need to understand, for example, the behavior of the structures following a seismic event.

The state of knowledge in structural engineering progresses gradually and it is a tool that allows improving the integrity of old structures, structures whose use has been altered, with unplanned loads, or structures built before the publishing of the last earthquake resistance building code (El-Betar, 2016). Structural design and construction engineering aim at achieving a ductility level in their elements that allows them to deform enough to indicate an anomaly before collapsing in the event of an earthquake (El-Betar, 2015).

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With the purpose of studying the condition of a city in relation to its preparedness to face an earthquake, management methodologies are proposed to assess the hazard represented by the action of such event. For example, the “Radius” methodology regarding the planning and seismic risk reduction includes a prevention plan, an emergency plan, and reconstruction and recovery measures (Boukri et al. 2018). For the Colombian case, the National Agency for Disaster Risk Management (Unidad Nacional para la Gestión del Riesgo de Desastres. UNGRD, in Spanish) describes a risk management methodology composed of three phases: hazard knowledge, risk reduction, and disaster management (Unidad Nacional para la Gestión del Riesgo de Desastres. UNGRD, 2015). The present research aims at improving the hazard knowledge by studying the current structural conditions of bus stops that were modified with the implementation of green roofs, in the city of Bogotá.

Given the global climate change, communities are subjected to new environmental conditions, which have become research topics in the context of complex environmental issues for the coming generations. Technologies such as solar panels to counteract the energy consumption in a building; green roofs or walls (associated to a structure covered with vegetation) installed on structures, with the aim of mitigating the pollution, reducing the temperature levels or introducing rainwater management, among others (Shafique et al., 2018), represent sustainable mechanisms for preserving the environment. With these problems in mind, the city of Bogotá installed green roofs on top of certain public transport bus stops, as part of the initiative of the Administrative Department for the Public Space Defense (Departamento Administrativo de la Defensoría del Espacio Público. DADEP, in Spanish), which seeks to measure the retention of heavy metals, particulate matter, carbon dioxide, among others (Pérez Díaz, 2014).

The present paper presents a study, in the Colombian capital city, concerning the structural condition of bus stops exposed to green roof loading, in case an earthquake occurs. The following section addresses the methodology used in the project execution, the characterization of modified bus stops, and the modeling carried out to represent the behavior of the structure.

2. Methodology

Since the objective of this work is focused on analyzing the structural condition of bus stops under static and dynamic green roof loading, numerical and physical simulations were used as a means to observe their behavior in different scenarios.

First, information was looked up in the literature and companies that developed the idea of green bus stops (bus stops whose roofs are covered with vegetation), with regard to dimensions, materials, foundation soil and exposed loads of the studied bus stop structure. Likewise, information was gathered in relation to the composition and weight of the green roof. The ANSYS software was used for simulating the static and dynamic conditions, which allowed obtaining the approximate behavior of the system under a saturated condition of the green roof, considering the seismological characteristics of the foundation soils. Furthermore, the construction of a physical model based on a scale system allowed observing its behavior by means of a shaking table test, and its deformation was statically measured with a digital deformeter.

3. Characterization of the Green Bus Stop

Currently, the city of Bogotá has eight green bus stops, distributed in the localities of Chapinero, Kennedy, Engativa, Fontibon and Santa Fe, as shown in (Figure 1). The red dots show how the green bus stops are distributed and each dot indicates two green bus stops, one after the other.

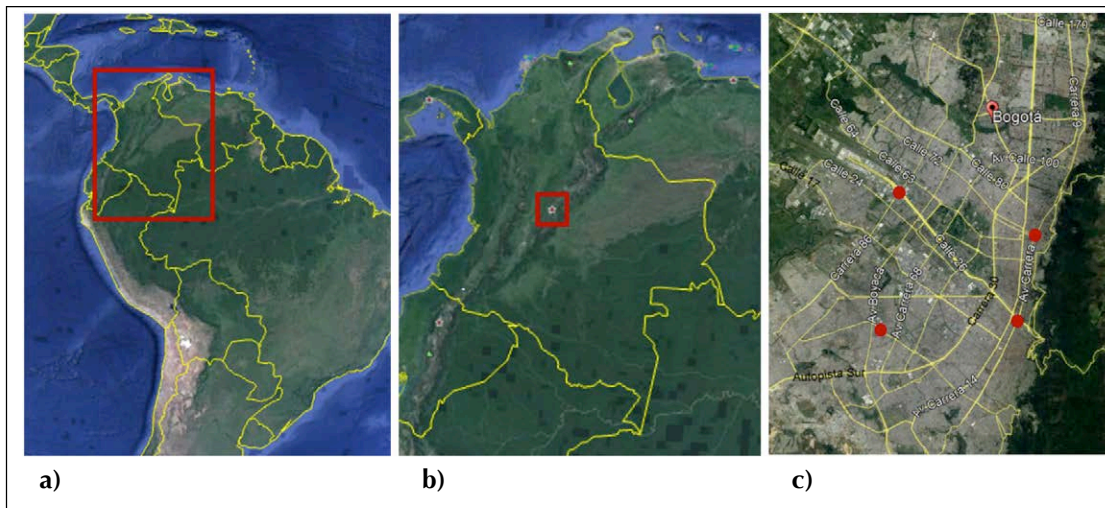


Figure 1. Location of green bus stops. a) Colombia, b) Bogotá, c) Location of green bus stops in the city of Bogotá

The green bus stops are built with three columns and three beams representing the system's strength; in turn, the green roof is considered the differentiating element with regard to the loads. See (Figure 2).

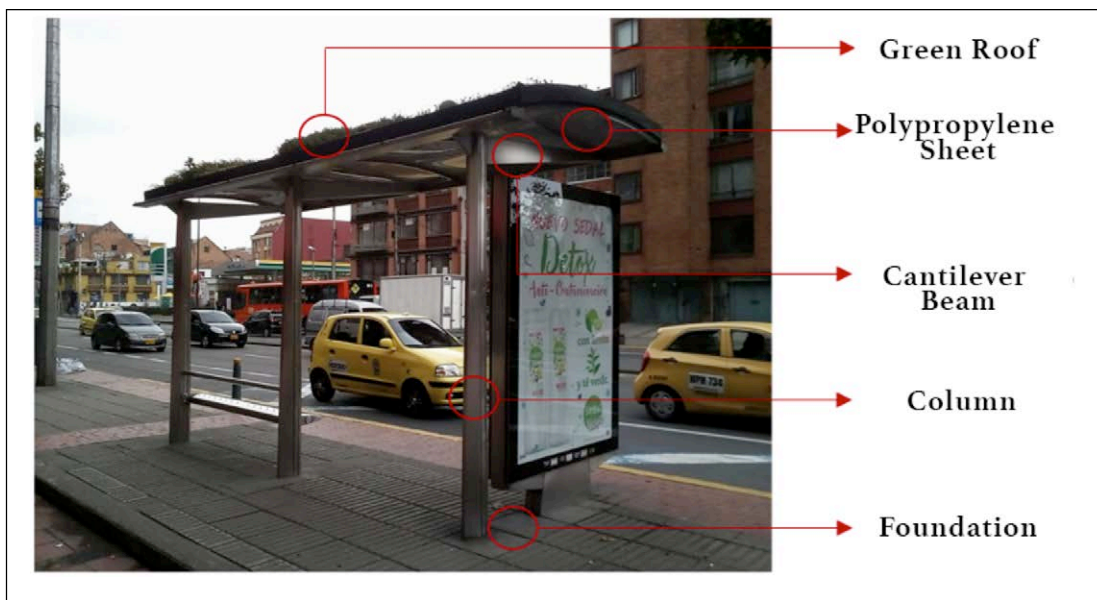


Figure 2. Green bus stop

The bus stop is also formed by a bench, a steel frame for advertisement posters and, separated from the main structure, two gutters connecting the cantilever beams with each other, six curbs joining these beams to the original roof and, finally, the green roof installed on top of the original roof. The green roof is made of an ultra-light substratum layer (vegetation growing medium) (Alcaldía Mayor de Bogotá 2014) and a vegetation layer, which includes plants from the Sedum species, given their resistance to sudden temperature changes, which usually occur in the city of Bogotá. Below, (Table 1) summarizes the results obtained from the green roof loading analysis. This data are the base for building the computer model.



Table 1. Green roof loading analysis

Element	Material	Linear Load (kN/m)
Initial Roof	Polypropylene of 3 mm	0.081
Transverse Curb	Stainless Steel of 1.5 mm	0.0035
Front Gutter	Stainless Steel of 1.2 mm	0.0395
Back Gutter	Stainless Steel of 1.2 mm	0.0474
Green Roof	Ultra-light substratum and plants of the Sedum species	1.14

3.1 Numerical Model of the Structure

The green bus stop is designed as a geometrically symmetric system in relation to its strength elements. The loads are distributed in terms of each beam's shaded area. Since the central elements are exposed to greater loading due to their area of influence, the column and the beam that are located in the center of the system were modeled with the ANSYS software, and the resulting model was analyzed with the finite element method. This model was built based on the resulting geometry, its mechanical properties and the definition of boundary conditions regarding the movement restrictions and application of external forces.

3.2 Geometry

The Inventor design software was used for creating the detailed geometry of the model. (Figure 3) shows the cross-section of the two main elements in relation to the system's geometry. The column has an irregular geometry, whose area decreases according to its height. On the other hand, the beam considers a rectangular cross-section, which, as in the column, decreases in relation to the distance to the center of the bus stop.

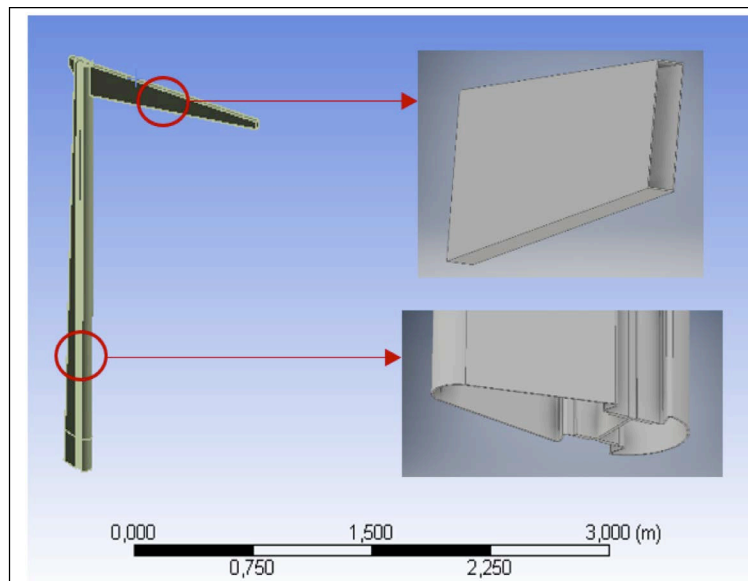


Figure 3. Computer model of the green bus stop

This system is made of stainless steel AISI 304, which has a yield strength of 241 MPa, an ultimate tensile strength of 586 MPa, a Charpy V-notch impact strength equal or higher than 325 J, and an elongation to failure of 60% (ASM International, 2000).

3.3 Boundary Conditions

The movement restriction of the model is given according to the foundation of the system. The bus stop has two layers of concrete foundation of 20.68 MPa, which allow fixing the columns with four bolts, thereby restricting the displacement of the lower area of the column. The loads' transmission expressed in (Table 1) was analyzed, with the aim of obtaining a pressure line at the end of the beam. (Table 2) shows the factored linear load corresponding to the beams' width. Since the load is greater in the center beam, because it has a wider shaded area than the end beams, the computer model analyzed the column and beam located in the center of the structure.

Table 2. Model loads

Element	Dead Load (kN/m)
Center Beam	19.20
End Beam	11.34

The seismic force for the bus stop's dynamic analysis was modeled using the response spectra of the seismic microzonification of Bogotá (Ingeominas and Univesidad de los Andes, 1997) for each type of soil in which the green bus stop foundations are laid. (Figure 4) shows the relationship between the ground acceleration and the structural period, and it allows observing that, for a piedmont soil, the ground accelerations can affect the movements of the structure with short periods. Thus, maximum stresses are expected in the piedmont soil given the low height of the analyzed structure.

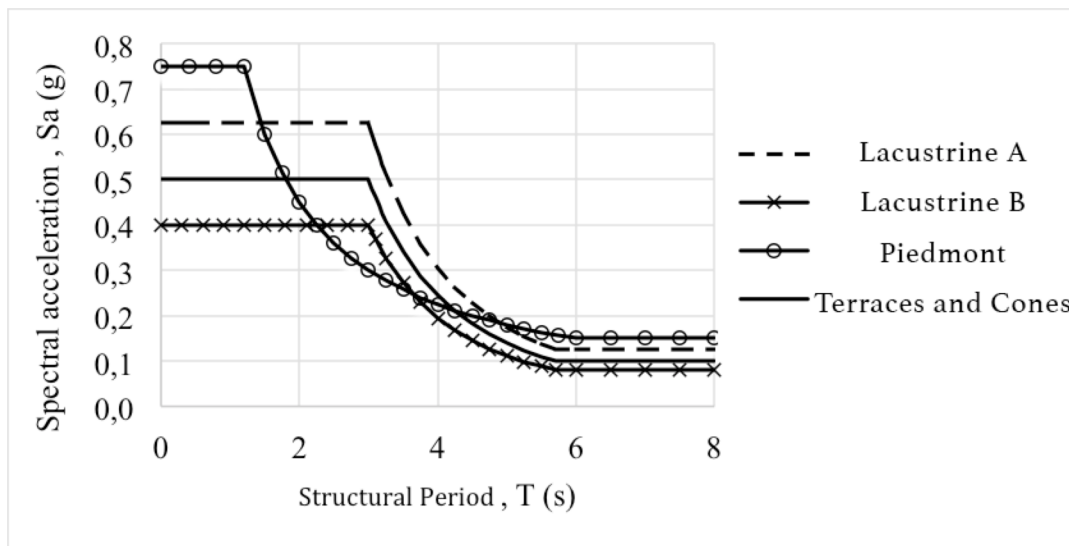


Figure 4. Response spectra of the foundation soils of green bus stops

The objective of the computer simulation is to be able to compare the behavior of the structural system in terms of stresses under normal conditions (without considering the green roof weight) and under modified conditions (considering the weight of the green roof).

4. Physical Modeling

With the aim of observing the behavior of the structure to scale, a physical model of the green bus stop was built. In the construction of the physical model, a CNC machine was used to cut sections on Taskboard sheets, which were bonded with liquid silicone. This physical modeling has proven to be a valuable conceptual tool, given this material's capacity to accurately simulate elastic and inelastic phenomena, compared with tests made with steel elements at real scale (González Rincón et al., 2016). (Figure 5) shows this model. For the embedment modeling (foundation), epoxy filler was used in the joint between the lower area of the column and the rectangular wooden element that simulates the soil where the foundation is laid; this section has circular holes to fix the system to a shaking table where its dynamic behavior is analyzed. Furthermore, the load is represented by metal fragments, which are subsequently used for analyzing the static behavior of the system.

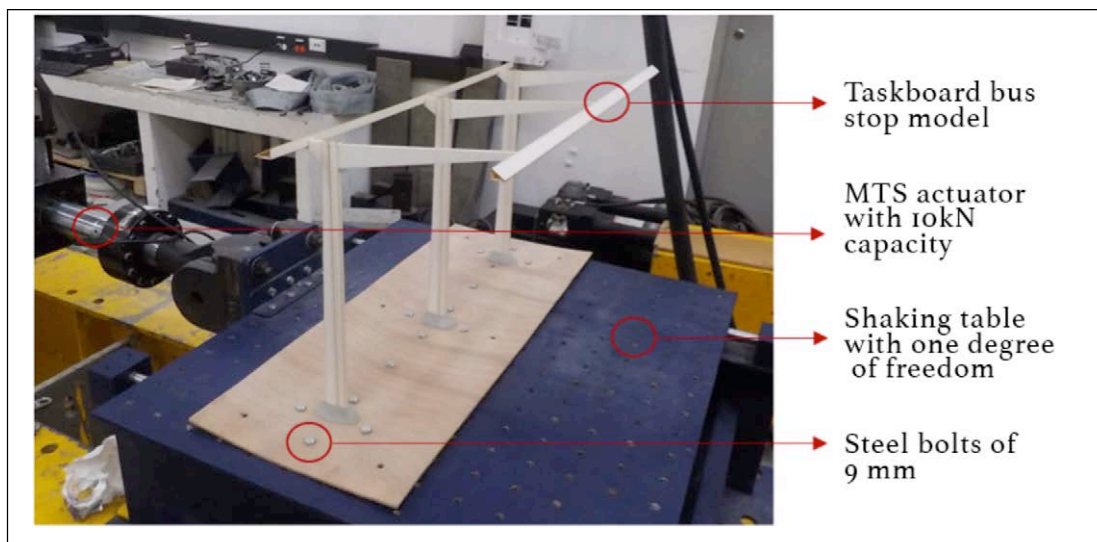


Figure 5. Physical model of the green bus stop

Since the weight of the structure and the green roof are known, they were directly related to the weight of the physical model, whose objective was to find the green roof's representative load in the scale model.

4.1 Loading Protocol

Initially, the original bus stop model was subjected to frequencies from 1 Hz, which were gradually increased to 10 Hz, with an amplitude of 1 cm on the shaking table. Then, the second model, including the green roof loading simulated by metal elements placed in the longitudinal direction of the cantilever beam, was subjected to the same frequency and amplitude conditions.

5. Results and discussion

The following section presents the results obtained by the static analysis and the response spectrum analysis, considering the seismic characteristics of the soil. It also reports the damages observed in the physical model, the system's maximum displacements, and the bus stop stress increases in its initial condition, when a green roof was installed on top of the original roof.

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(Figure 6) shows the maximum stress area of the structure through a response spectrum analysis under green roof loading. The connection between the column and the beam, and the lower area of the column, are stress-sensitive areas and, therefore, a bending moment in the opposite direction of the load is produced around these areas. The maximum simulated stress is 50.59 MPa, compared to the material's yield strength, which is 241 MPa.

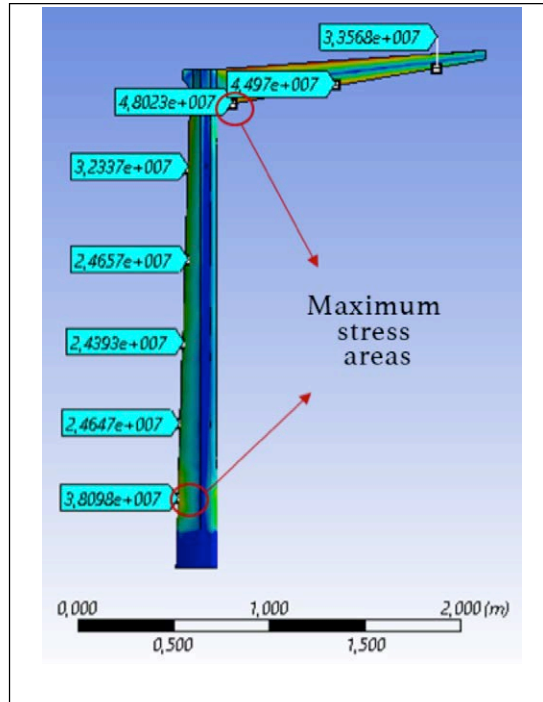


Figure 6. Location of maximum stress in the response spectrum analysis

The green bus stops are distributed in different types of soil in the city of Bogotá. (Figure 7) allows observing how the soil affects the behavior of the structure in relation to the generated stresses. The piedmont soil evidences the maximum stresses, and it is considered the stiffest among the four types of soil compared.

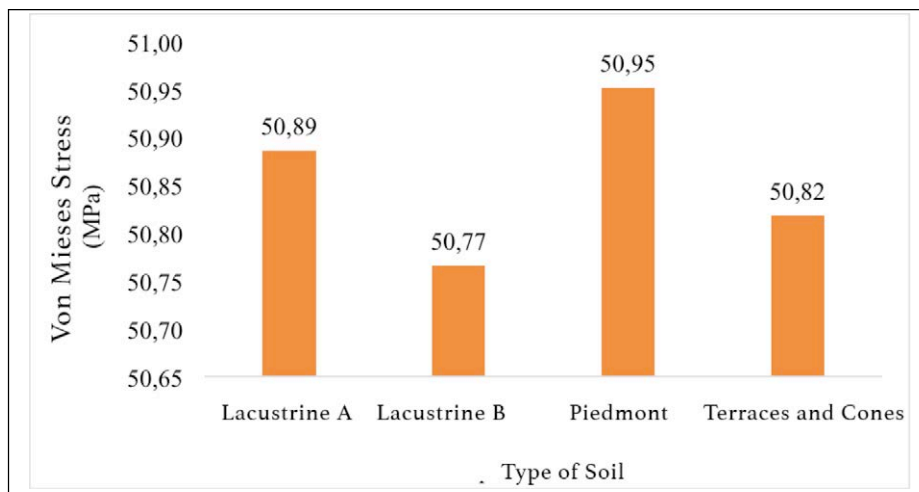


Figure 7. Maximum stresses based on the foundation soil

The physical model was fixed to a shaking table, where it showed an increase of the beam's movement amplitude when the model incorporated the load simulating the weight of the green roof. On the other hand, (Figure 8) allows observing an anomaly at the base of the column after applying the loading protocol, where there is a stress-sensitive area.

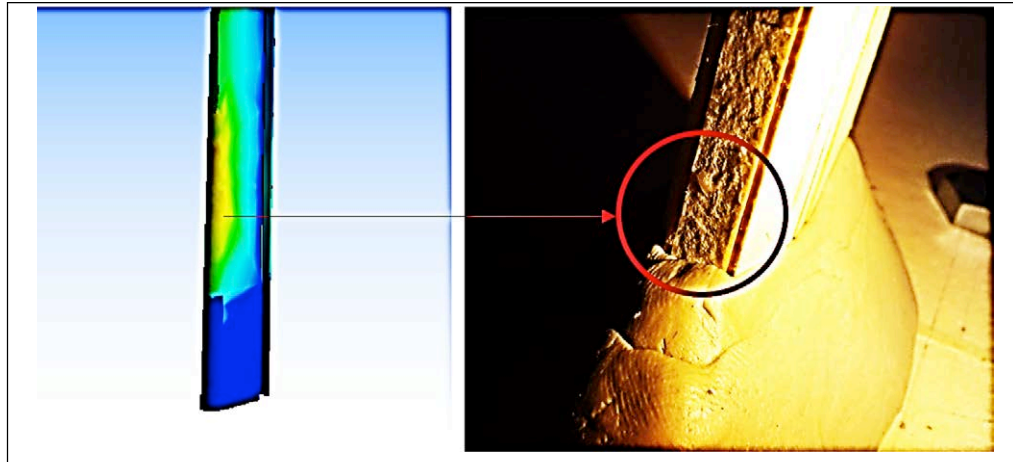


Figure 8. Damages in the physical model in terms of local bending in the flange

Tests with regard to the structure deformation were also carried out. As expected, the computer model indicated that the biggest displacements occurred at the end of the cantilever beam. Deformation measurements of that point were taken and, since the digital deformeter used generates an extra displacement in the physical model, measurements were recorded five seconds after applying the green roof loading. Thirty (30) measurements were recorded, whose median was 2.14 mm, with a standard deviation of 0.061 mm and a coefficient of variation of 2.86. This statistical analysis allows suggesting that data are reliable.

In the computer modeling, the maximum deformations should occur at the end of the beam, since it has a cantilever geometrical configuration. For the maximum deformation point at the center beam, the modeling shows a magnitude of 6.72 mm, under a saturated green roof condition. The system's maximum displacement increase is 81.69% in relation to the original characteristics of the bus stop. See (Figure 9).

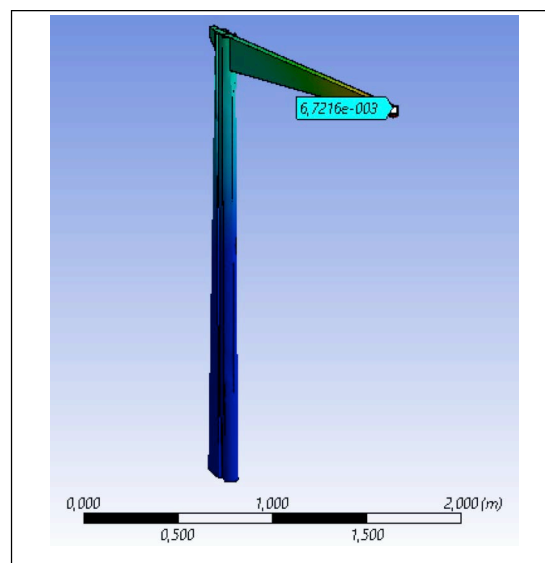


Figure 9. Location of the maximum displacement in the static analysis

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(Figure 10) shows a diagram reflecting, from a static perspective, the effect of the green roof on the structure. It should be noted that, once the green roof load is applied, the connection between the column and the cantilever beam also experiments stress increases. (Figure 11) indicates the stress values obtained by the computer model.

The von Mises yield criterion is used to calculate the stresses; this criterion indicates if the material under the simulated loading condition is close to the yield point. When putting a green roof on top of the bus stop structure, the mass of the system increases by 211.41%, considering a saturated condition of the green roof substratum. Likewise, the maximum stress to which the bus stop structural elements are subjected to increases by 80.57%.



Figure 10. Representation of the green roof loading effect on the bus stop structure

Both for the dynamic analysis and the static analysis, the stress magnitudes produced in the previously mentioned connection increase considerably. However, the yield point of the structure's material is still higher than these values; therefore, it can be assumed that the structure of the bus stop will not collapse due to these stress increases.



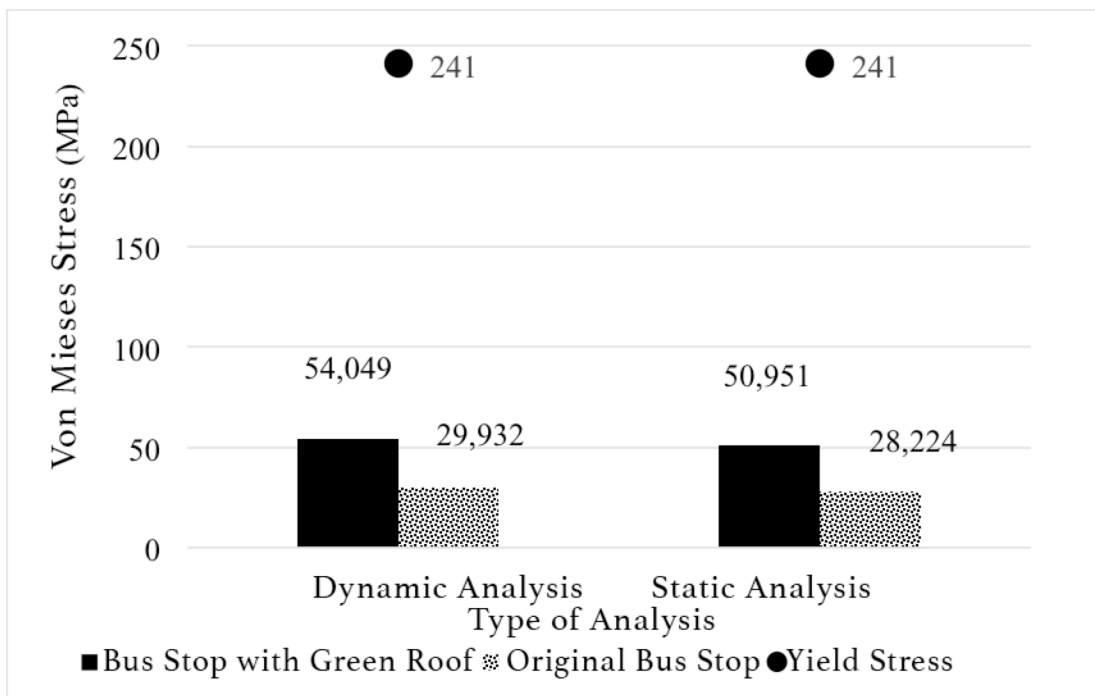


Figure 11. Comparison of stresses before and after installing the green roof

The implementation of green roofs on top of bus stops could generate uncertainty regarding its structural behavior. In the first place, the overload on the bus stop roof increases the stress of the structural elements supporting the roof of the bus stop itself. On the other hand, the type of soil in which the structure is founded affects the vibration frequency of a seismic wave, which propagates due to stiffness changes (Ingeominas and Universidad de los Andes, 1997).

Given the variability of the soil in which green bus stops are founded, they can show different behaviors in case a seismic wave is produced. Thus, the seismic demand is produced not only in terms of the mass (which was modified for the case study with regard to the original design), but also of the peak acceleration of the foundation soil.

6. Conclusions

The execution of computer models allows observing approximations of the behavior of a structure subjected to seismic loads, and other loads that were not initially considered in the design. The green bus stops subjected to seismic forces were modeled based on the soil on which they are founded; bus stops located on soils classified as piedmont were found to be most affected. This behavior is explained by the fact that the bus stop will probably have short structural periods in the event of high ground accelerations. Likewise, it was possible to evidence that maximum deformations occur at the point that is most distant from the cantilever beam.

Furthermore, the physical model was fitted to the computer model as damages were found in the material of the physical model, in the higher stress areas indicated by the software. These failures occurred because the external fibers were subjected to tensile stresses when the seismic movement, simulated by the shaking table, caused a structure displacement.

The von Mises yield criterion allowed knowing the condition of the structure once the bus stop load was increased due to the green roof loading. An approximate stress increase of 80.57% is observed in the beam-column connection; however, this value is below the materials' yield point, which indicates that, even if it bears an additional load, the structure withstands the green roof satisfactorily.

Finally, the test carried out on the shaking table evidenced that the failure mechanism simulated in the physical model corresponds to the local bending of the sheet, given the type of damages observed after applying the loading protocol.

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