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Conceptual design vulnerability assessment of the housing light roofs to strong winds

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A B S T R A C T

Hurricanes are one of the most significant causes of human and material losses in the Caribbean region. These events have demonstrated their devastating impact on housing and infrastructure. The assessment of the vulnerability of buildings with light roofs, at the initial design stage, is considered to be a fundamental step in the mitigation of these damages and losses. This paper presents the introduction of an indicator-based vulnerability assessment in an effort to mitigate these damages in advance. This indicator facilitates the design team's decision to select the appropriate light roof alternative subject to strong winds at the conceptual stage of the process. The indicators that contribute to the conceptual assessment of vulnerability were identified based on a comprehensive review of the literature and numerical simulations of the risk scenarios using CFD/FEM software's. The ranking of indicator weights was determined by the Kano method according to experts' opinions. A desktop application has been developed for the assessment of the vulnerability of light roof variants for buildings at the conceptual design stage. The results reported in a case study demonstrate the viability of the desktop application based on the vulnerability indicator to assist decision making in the conceptual design stage.

1. Introduction

It is well known that the occurrence of human error during design and construction of housing can have a profound effect on the reliability of roofs and structures (Qin & Stewart, 2020; Kwan & Kopp (2021); Wang & Kopp, 2021). A large percentage of the houses in the Caribbean region have light roofs. These types of roofs, due to their lightweight and the likelihood of failure of fasteners or structures, are highly susceptible to damage from extreme wind events such as hurricanes (Stevenson, El Ansary, & Kopp, 2019).

With respect to vulnerability assessment, recent reviews have highlighted that there is no general method for analyzing, assessing, or quantifying physical vulnerability of the built environment (Papathoma-Köhle et al., 2017). Approaches include the development of matrices that relate the intensity of a process to expected damage, vulnerability curves that assess the monetary level of loss at different intensities, and vulnerability indicators that express the characteristics of housings (that make them susceptible to the impact of a natural hazard) (Papathoma-Köhle et al., 2023; Reyes Ramírez et al., 2022). However, current design practice lacks a preliminary analysis of the factors influencing the vulnerability of light roofs to strong winds.

In this article, a vulnerability assessment methodology is proposed for the design of light roofs housing exposed to strong winds, in the conceptual stage of the process. The indicators selected to characterize the sources of vulnerability in this type

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of light roofs are described. The weighting of the indicators and their aggregation into an index are then demonstrated. A desktop application based on the described methodology is presented, which can be used by the design team of project companies to apply it in the conceptual stage of development. Finally, a case study is presented to demonstrate the feasibility of the proposed methodology.

2. Material and methods

In this section, the methodology for the evaluation of the vulnerability of light roof concepts for housing under the action of strong winds in the conceptual stage of the design process is described. It also presents the theoretical concept of a desktop tool for preliminary evaluation of the vulnerability to strong winds, considering previous CFD/FEM simulation results (Reyes Ramírez et al., 2022).

Based on the characteristics of light roofs that influence their susceptibility to strong winds, a new set of indicators was identified in this study. The rank of the indicators was weighted using the Kano method. Finally, they were added to an index to evaluate the vulnerability of each solution concept.

2.1 Methodology for the vulnerability assessment of the conceptual design of light roofs subject to strong winds

Next, the methodology for evaluating the vulnerability of conceptual housing solutions with light roofs subject to strong winds is described (see Fig. 1). It is designed to be applied in project companies in the initial stages of the design process and consists of four stages.

Stage-1 Preparation: The starting point is the creation of a multidisciplinary design team. It includes all the actors involved in the process: the investor, the architect, the structural engineer, the builder, the contractor, the suppliers, etc.

The technical requirements for the design of the light roof of the house are defined on the basis of these expectations. This is done by transforming the expectations of the interested parties into a problem definition. Then, it is translated into valid technical requirements expressed as statements that the desired lightweight roofing solution has to satisfy. In addition, it is important to identify design elements that cannot be changed. This will help to identify the areas in which modifications will need to be made to possible design solutions.

In the last step of this stage, the functional requirements are evaluated and the technical task begins to be defined. The elements that technically define the design of the light roofs to be obtained are defined. A recursive and iterative process is used to define the functional requirements. Once the functional requirements have been validated and approved by the customer and interested parties, the process continues to the next stage.

Stage-2 Planning and Organization: This point in the process is the identification of the "what" the design must do at each level to enable stakeholder satisfaction. This process visualizes the functions that must be performed to meet the functional requirements of the design by analyzing and decomposing the variables or components.

The proposed methodology is based on the concept of vulnerability, which is applied to the design of the light roofs of residential buildings. Considering (Singhal & Jha, 2021) the vulnerability is decomposed into exposure and susceptibility, representing at the same time an internal variable of the studied system.

A comprehensive literature review of detailed strong winds impacts on housing with light roofs led to the selection of the indicators in Table 1.

Table 1. Indicators of vulnerability related to the impact of high winds on light roofs (Stevenson, El Ansary, & Kopp, 2019; Arrayago, Rasmussen, & Zhang, 2022; Habte et al., 2018).

Variables	Indicators
Exposure	Terrain
	Location
	Surrounding obstacles
	Coastal zone
Susceptibility	Roof shape
	Material and panel shape
	Anchorage systems
	Roof slope
	Wall material

To analyze the exposure, the first step is to characterize the elements that make up the design variant. These elements are related to the exposure of the light roof subject to strong winds. Elements like the relief, the location, the characteristics of the area, the presence of buildings around the home, transform its location (or not) into a risk scenario. In the macro and micro location, the location of each light roof design variant must be defined.

The susceptibility of the light roof is given by the behavior of its technical characteristics. At this point, the materials, shapes and dimensions, fastening elements, joint geometry, slope, support surface and other technical elements that modify the structural behavior of the light roof are defined.

Scoring individual indicators is a critical step in developing an index (Papathoma-Köhle et al., 2017). Once the indicators have been selected, it will be clear which indicators of houses with light roofs will be part of the index. The categories of these indicators and their scores are determined in this step. The indicator of the vulnerability index obtained will move in a range between 0 and 1, with 0 representing the least possible damage and 1 representing total damage. Between these values, an interval scale is established for the vulnerability values (see Table 2).

Table 2. Intervals for the assessment of the level of vulnerablity (Alarcón Borges et al., 2023; Pereira et al., 2022).

Vulnerability level	Intervals
Low	0-0.3
Average	0.3-0.7
High	0.7-1.0

Considering the review of scientific literature and the expected effect of each indicator on the vulnerability of light roof houses subject to strong winds, scores are assigned (see Tables 3 and 4). The indicators that increase the vulnerability of the light roof housing are given a higher score than the others that make the light roof housing less vulnerable. The score for each indicator varies from 0.1 to 1, where 0.1 indicates that the specific indicator reduces the overall vulnerability of the light roof housing, while a higher score increases the vulnerability of the light roof housing to strong winds.

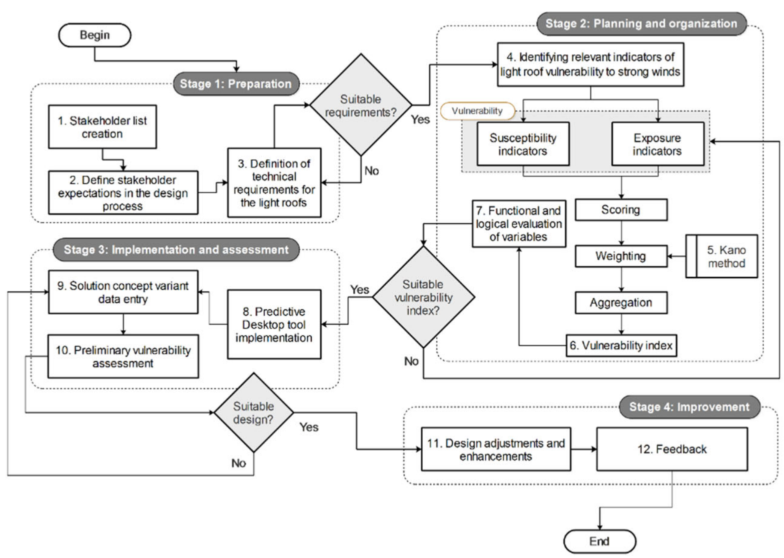

Fig. 1. Methodology for the evaluation of the vulnerability in the conceptual design of light roofs subject to strong winds

Table 3. Indicators for the exposure variable in vulnerability

Indicators	Type	Value
Terrain	Valley	0.10
	Flat	0.40
	Mountainous	0.85
Location	High urbanization	0.30
	Medium urbanization	0.55
	Low urbanization	0.75
	Rural zone	0.80
Surrounding obstacles	Trees and vegetation	0.10
	Low buildings	0.75
	Mixed buildings	0.90
	Tall buildings	0.93
Coastal zone	More than 500 m	0.10
	From 350 to 500 m	0.25
	From 150 to 350 m	0.60
	From 0 to 150 m	0.98

The preliminary evaluation of the vulnerability of the light roof solution concepts subject to strong winds is carried out by obtaining an index. To construct this index, it was first necessary to normalize the indicators (both those derived from exposure and those derived from vulnerability).

This normalization makes it possible to conjugate different indicators that have different units of measurement and different scales. In other words, they are placed on a standardized scale that allows them to be compared with each other and added to a final index. Then, since not all indicators have the same weight in the construction of the index, a weighting of these indicators was carried out.

Table 4. Indicators for the susceptibility variable in vulnerability.

Indicators	Type	Value
Roof shapes	Hip	0.25
	Gable	0.50
	Shed	0.80
Material and shape (metallic)	Corrugated	0.77
	Ribbed	0.86
	Trapezoidal	0.94
Anchorage systems	J Bolts	0.10
	Screws	0.55
	Nails	0.98
Roof slope	10-15 [Deg]	0.06
	20 [Deg]	0.05
	25 [Deg]	0.08
	30 [Deg]	0.17
	35 [Deg]	0.36
	40 [Deg]	0.68
	45 [Deg]	0.94
Wall material	Brickwork	0.17
	Wood	0.37
	Open	0.97

The Kano method was used for the weighting of the indicators for the determination of the vulnerability of light roofs subject to strong winds. This method evaluates customer satisfaction and ranks product attributes on the basis of customer appreciation. The method classifies customer requirements into three categories: attractive requirements, one-dimensional requirements, and mandatory requirements (Shin et al., 2022; Bhardwaj et al., 2021).

The Kano method was based on a questionnaire addressed to users. The questionnaire was designed for the specific case of the functional requirements involved in the characterization of risk scenarios. A total of 20 questionnaires have been carried out. The users were selected from among professionals in the construction industry, researchers, university professors and experts related to the object of the study. The weighting of the indicators according to the Kano method is shown in Table 5.

Table 5. Weighting of the indicators according to the Kano method.

Indicators	Weighting (%)
Terrain	10
Location	5
Surrounding obstacles	5
Coastal zone	10
Roof shapes	10
Material and shape	25
Anchorage systems	10
Roof slope	20
Wall material	5

The final step is to aggregate the weighted indicators into a single vulnerability index that can be evaluated in any light roof solution subject to strong winds. The indicators have to be added in an index according to the following equation, after the weights of each indicator have been defined by the Kano method (Eq. (1)):

$$V = \frac{exp(\sum(log(v_1)*P_1+log(v_2)*P_2+...log(v_n)*P_n}{\sum(P_n)} \quad (1)$$

Where v_n are the normalized values of the indicators and P_n is the weight or level of importance established for each one.

The final step of this stage is the preliminary reconciliation of the variables present in the design. The logical and functional characterization of these variables is also performed. The solution concept development process should be recursive and iterative. It should include feedback from stakeholders and external reviewers. Similarly, feedback from subsystem designers and operators should be provided whenever possible to increase the likelihood of achieving desired goals and expectations.

Stage-3 Implementation and Assessment: In the early stages of the design process, as many variations or design alternatives for the light roof are evaluated as the project team deems appropriate. This is due to the variety of variables and technical elements that need to be considered. At this stage, a desktop tool is used to preliminarily evaluate these alternatives (or solutions) of light roofs for housing subject to strong winds. For this purpose, the data corresponding to the defined variants are entered. The level of vulnerability of each variant is evaluated. Once the evaluation of the solution concepts has been completed, the design team will have the vulnerability criteria available for the definition of the solution concept which will be the winner.

By automating the calculation of the estimated range of vulnerability, it will not only be easier to predict the least vulnerable design variant or solution, but it will also be possible to modify the components of each variable in accordance with the functional requirements. This provides an immediate response to how the system will behave, thus visualizing the critical variables involved in designing the light roof subject to strong winds.

Stage-4 Improvement: After the preliminary evaluation carried out in the previous stage, the design is adjusted. It's then possible to carry out the final design of the light roof subject to strong winds. As a final step in the process, feedback is given to the previous stages. Revisions, corrections and corresponding improvements are made. This ensures the continuous improvement of the light roof design process.

There is a guarantee that the concept design of light roofs will proceed to the Executive Technical Project or detail stage, based on the preliminary assessment of their vulnerability to strong winds. And then, to the phase of execution, counting on a previous estimation of the level of their vulnerability on the basis of the defined functional requirements.

2.2 Desktop vulnerability assessment tool design

This stage begins by integrating the data obtained from the numerical simulation using CFD/FEM tools (Reyes Ramírez et al., 2022). The results provide the numerical basis for the development of a desktop computer tool that will make it possible to evaluate design alternatives for light roofs for houses, depending on the degree of vulnerability to the action of strong winds.

A unified architecture is needed to facilitate the development of a computational vulnerability assessment tool due to the heterogeneity of the data and results expressed by the virtual models of the different CFD/FEM systems. For this purpose, the ISO/IEC/IEEE 42010 standard is used as a reference. A conceptual architecture of the desktop tool is designed (see Fig. 2).

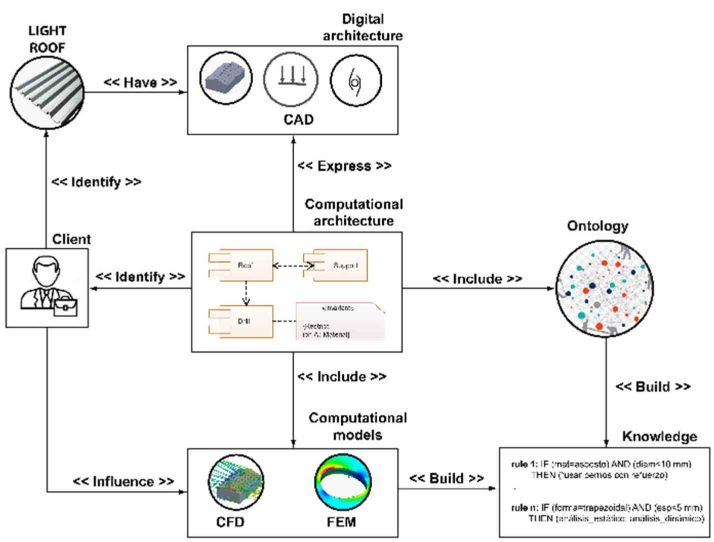

Fig. 2. Elements comprising the desktop tool for conceptual assessment of vulnerability of light roofs to strong winds (according to ISO/IEC/IEEE 42010 terminology)

The computational architecture that will support the desktop tool is the central element according to this standard. It expresses the elements that define the digital architecture of the light roof (CAD model), the loads that act on it, and the different configurations. It also identifies the requirements defined by the customer (technical task) and includes the ontology that reflects the different entities and their relationships. The customer identifies the type of light roof and influences the CFD/FEM models through the restriction and/or selection of several of its variables. Both the computational models and the ontology allow generating the necessary knowledge to facilitate managing the design in the conceptual phase of the process.

In this way, the desktop tool is conceptually defined. This allows the project team to make a preliminary assessment of the vulnerability of the design variants of light roofs subject to strong winds.

3. Results and discussion

The methodology described in the previous section is the theoretical and methodological basis both for the development of the desktop tool and for its implementation. The desktop tool can be used by working teams in engineering companies dedicated to designing residential projects with light roofs subject to strong winds. The implementation and use of the desktop tool is described and discussed in this section.

The procedure in the previous section has been the subject of a case study. It consists of the conceptual design of a single-family house with a light roof. It is located in a context where strong winds are frequent. The micro-site is located in the municipality of Gibara (1 m above sea level), in the province of Holguín, in the eastern part of Cuba.

3.1 Preparation Stage

In accordance with Decree-Law 327, the creation of the Interdisciplinary Group involved all the parties involved in the investment process in Cuba. This means the project company, the building company, the investment company, the suppliers and so on. The expectations, requirements and constraints of each party were identified. The technical requirements of the concept of the light roof to be designed were also identified. In this case, both the dimensions of the building and the area for its location were previously defined by the planning and territorial authorities. Therefore, their modification is not allowed. One of the investor's requirements was that the house's light roof must withstand maximum winds up to category 3 according to the Saffir-Simpson high intensity hurricane scale.

3.2 Planning and Organization Stage

The decomposition and characterization of the variables influencing the vulnerability of the light roof to strong winds was carried out based on the requirements defined in the previous stage:

- Exposure: the selected site is located on flat land, 410 meters away from the coast, in an area with a medium level of urbanization, surrounded by low-rise buildings, most of which are houses.

- Vulnerability: the first design variant was a gabled roof with a wooden support structure and corrugated fiber cement panels fixed with nails, with a slope of 40 degrees.

All parties interested in the project were consulted and agreed to this first variant.

3.3 Implementation and Assessment Stage

Data is entered into the preliminary assessment desktop tool once the initial requirements have been defined. The first element to be defined is the general data of the light roof subject to strong winds project (project ID, type of project, responsible entity, project manager, etc.). Then, the hurricane category to which the light roof of the house is expected to be exposed is identified in the "Hazard" section. In this case, it is one of the categories three on the Saffir-Simpson scale.

As shown in Fig. 3, the data corresponding to the exposure variable is then entered.

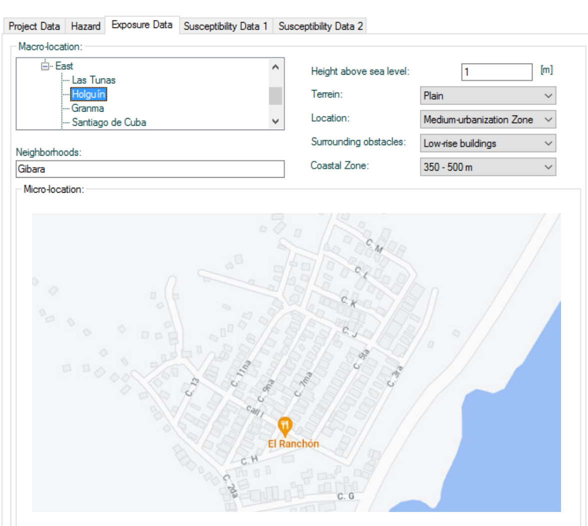

Fig. 3. Introduction of the data of the variable of the exposure

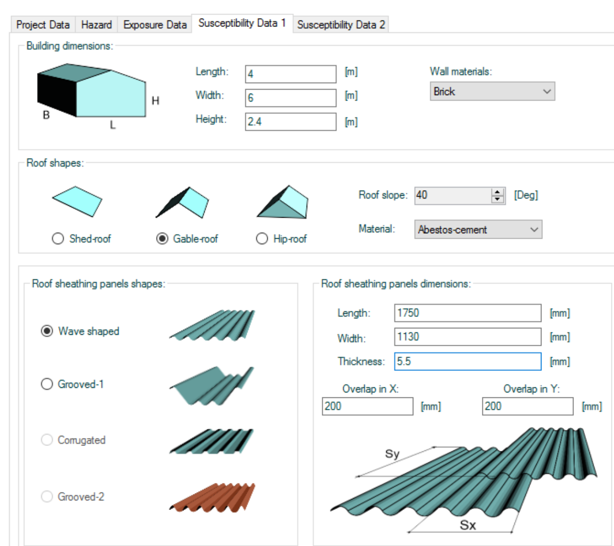

Fig. 4. Introduction of the data of the susceptibility variable

The data related to the susceptibility variable, which correspond to the technical characteristics of the predefined conceptual variant, are entered in two dialogs (Fig. 4 shows the first one).

Once all the data was entered, the desktop application calculated the vulnerability according to equation (1) for the first predefined variant. This resulted in a vulnerability value of 0.81, which is classified as "High Vulnerability" (Fig. 5).

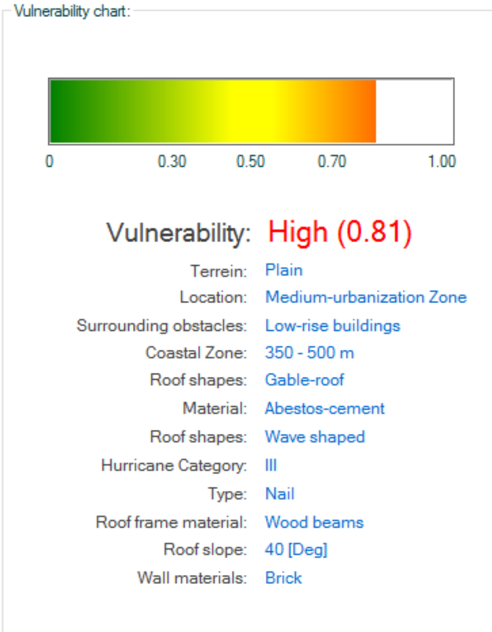

Fig. 5. Vulnerability assessment of the conceptual variant 1

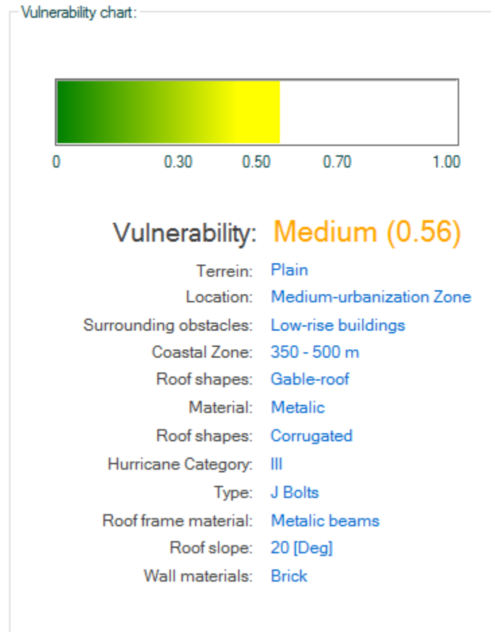

Fig. 6. Vulnerability assessment of the conceptual variant 2

3.4 Improvement Stage

In the last step, the predefined variables of the first variant are modified. A new evaluation is performed. This process is an iterative one and can be repeated as many times as it is necessary. In this case, five indicators were modified. They correspond to the vulnerability variable: roof material, roof shape, fastener, support surface, and roof slope. With this modification, the vulnerability was recalculated. The result was a value of 0.56, which is classified as "medium vulnerability" (see Fig. 6). A summary of both design variants and their resulting vulnerabilities is shown in Table 6.

Table 6. Comparison between the two variants of the light roof construction

Variables	Variant 1	Variant 2
Roof Material	Asbestos-cement	Metallic
Roof Panel	Wave shaped	Corrugated
Roof Frame Material	Wood beams	Metallic beams
Roof Slope	40 [Deg]	20 [Deg]
Anchorage Type	Nails	J Bolts
Vulnerability	**High (0.81)**	**Medium (0.56)**

In this way, it was possible to obtain a preliminary evaluation of the light roof design variants for a conceptual residential project. This allowed the "a priori" definition of the least vulnerable light roof conceptual solution to strong winds.

4. Conclusion

This article presents, in the conceptual stage of the process, a vulnerability assessment methodology for the design of light roofs for residential buildings exposed to high winds. The indicators selected for the characterization of the sources of vulnerability in this type of light roofs are described. The weighting of the indicators and the aggregation of the indicators into a single index are then demonstrated. A desktop application based on the described methodology is presented. It can be used by the design team of project companies to apply it in the conceptual phase of development. The Kano-based weighting can be improved by the inclusion of other tools for preliminary analysis, and more indicators should be considered. For example, the presence of objects that behave as projectiles. Finally, the interaction between strong winds and other factors, such as the amount of precipitation, should be studied.

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