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Empirical Study of the Relationship of Architectural Form Details to the State of Conservation of Modern Heritage Through Damage Maps †

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† This article is a revised and expanded version of a paper entitled "Impact of architectural form and construction details on the state of conservation of a flat roof", which was presented at Construction Pathology, Rehabilitation Technology and Heritage Managemenent—REHABEND, Gijón, Spain, 7–10 May 2024.

Abstract: The Sustainable Development Center of the University of Brasilia is one of the modernist buildings that make up the Darcy Ribeiro campus. The architectural project contains several recommendations for the execution of a flat roof waterproofing system, as well as details for rainwater runoff and drainage, which reveals the architect's concern with watertightness. This research seeks to identify the relationship between the pathological manifestations recognized on the roof and the details of the semicircular shape of the building, assessing the state of conservation using damage maps as an auxiliary analysis tool. This study is based on a field survey using aerophotogrammetry with a drone, the application of vector drawing software for graphic representation and discussion of the possible causes, and the agents and mechanisms of degradation at work. The results show the importance of mechanical protection for the good performance of the waterproofing system, as well as the need for correct sizing of expansion joints to absorb and relieve the stresses caused by hygrothermal variations. The incorporated methodology proved to be effective and economical in diagnosing and monitoring pathological manifestations, making it possible to plan maintenance actions that extend the useful life and preserve the intrinsic characteristics of building systems.

Keywords: conservation; maintenance; performance; building inspection; constructive details; damage map; flat roof; service life

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Correction Statement: This article has been republished with a minor change. The change does not affect the scientific content of the article and further details are available within the backmatter of the website version of this article.

1. Introduction

The Sustainable Development Center of the University of Brasília—CDS/UnB, located at the Darcy Ribeiro campus in Brasília and designed by Cláudio Queiroz in 1998, stands out as a notable work of modernist architecture built in 2010. This academic building, at 1860 square meters spread over two floors, is presented in two offset semicircular blocks connected at the ends, forming a garden in the center. It is characterized by its exposed reinforced concrete, glazed panels, and brise-soleil, in addition to promoting natural ventilation through upper louvers made of fixed inclined glass [1,2].

Unlike the other buildings on the Darcy Ribeiro campus, which have similar roofing designs—waterproofed slab, metal roofing, concrete gutters with water downspouts, and parapets—the architectural project of the CDS details an efficient roofing system, designed to manage rainwater—from collection to drainage—in order to ensure the integrity and longevity of the building, in accordance with Brazilian standard NBR 9575 [3].

This flat roof is made up of a solid concrete slab, a leveling layer with a minimum slope of 1% for drainage, drip edges in an embedded galvanized sheet, a waterproofing layer of asphaltic membrane, and a mechanical protection layer of mortar. All these architectural and engineering elements together create a system that helps prevent pathological manifestations on the roof and in the interior of the building.

The Modern Movement brought great innovations, especially to architecture: new materials, new forms, and new techniques were incorporated into designs and constructions, seeking new aesthetic standards with pure colors and textures, comfort, and balance in their compositions [4]. The architectural geometry of a building must be executed with a delicate balance between aesthetics and utility, functional efficiency, flexibility, modularity, and meticulous attention to detail. The minimalism and rationalism of compact, simple forms with clean lines, devoid of ornamentation, contrast with traditional architecture, yet integrate the building's user into its design [4].

Thus, the design of buildings with a circular/semicircular plan demands special attention regarding watertightness, given the influence of the architectural shape on the direction of rainwater, in addition to the tensions and structural efforts inherent to its geometry.

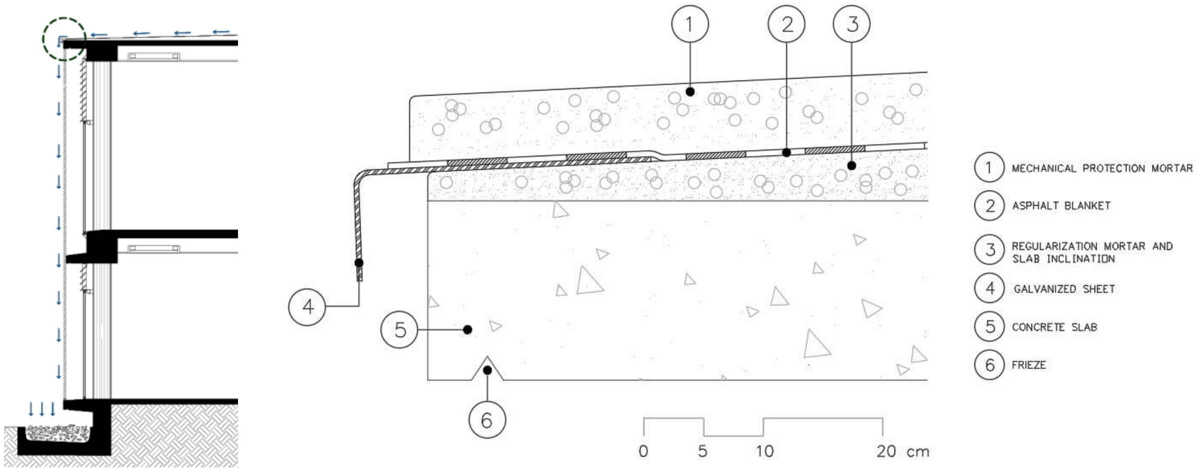
Studies in architectural conservation often highlight that the form and design of a building can significantly affect its susceptibility to deterioration. For instance, buildings with complex geometries or extensive ornamentation may experience different patterns of wear compared to simpler, more streamlined designs. This is because intricate forms often have more surfaces exposed to environmental factors, such as wind, rain, and sunlight, which can accelerate degradation processes. Additionally, complex forms may create areas that are more difficult to access for maintenance, leading to neglect and further deterioration over time [5].

The impact of form on building deterioration is evident in the materials used and how they interact with the building's design. For example, concrete, a staple of modernist architecture, can be prone to cracking and spalling if not adequately protected from moisture. On the other hand, traditional materials used in historical buildings, may, for example, weather more gracefully but require specific conservation techniques [6].

In addition to weathering, the degradation of concrete structures and surfaces is generally associated with rebar corrosion and is related to cracking, surface erosion, and spalling. When considering the repair and preservation of these concrete structures, structural integrity is critical, but aesthetic aspects are visually fundamental to the design intent and appearance of the building [7].

In general, pathological manifestations are the expression of the result of a degradation process, generally classified as biological attacks (stains from colonies of fungi, mosses, algae, vegetation, or accumulation of animal waste); cracks (caused by movement or occasional overloads acting on the element); stains (when there is a change in the color of the element, which may be caused by moisture, efflorescence, or dirt); and spalling (when there is excessive wear of the surface of the concrete element, causing the loss of its superficial layer) [8].

In terms of management and drainage, the configuration of the CDS roof directs the flow of rainwater to the ends of the mechanical protection, where it falls freely into a drainage channel located next to the first floor (Figure 1a). However, this solution is integrated with other details and specifications in the architectural design to ensure the required watertightness and prevent damage and anomalies, such as rainwater infiltrations, which reduce the functional aspects of the building and increase its risks to the users. This applies to the construction detail of the drips, which are installed all around the perimeter of the roof—both on the inside and outside edges (Figure 1b). Made of galvanized steel sheets (fragmented into rectilinear segments to adapt to the semicircular shape), they are inserted between the regularization layer of the concrete slab and the mechanical protection of the waterproofing, under the asphalt blanket, to guarantee their efficiency and prevent their attachment points on the slab from becoming possible points of water percolation and infiltration.



(**a**) (**b**)

Figure 1. (**a**) Schematic section of the CDS/UnB: rainwater flow from the roof (highlighting the drip edges, (**b**)). Source: Oscar Niemeyer Planning Center—CEPLAN/UnB. (**b**) Built detailing of the CDS/UnB drip edges, made of galvanized steel sheets. Source: the authors.

Another solution that appears is to use friezes (small indentations on the bottom edge of the slabs), as well as slopes on intermediate eaves and marquees. These perform the function of a second gutter and redirect the flow of rainwater in the event of galvanized sheeting malfunctioning or even splashes caused by the action of winds during rain events—thus protecting the frames of the circular façades.

The floor gutters (with an independent structure and sloping towards the collection drains) are waterproofed to prevent trapped moisture from rainwater collection from compromising their integrity. On the other hand, the reuse of gray water for garden irrigation, after treatment in its own plant, has not been implemented—despite being planned and dimensioned in the project.

The waterproofing plan (Figure 2) presents recommendations for the execution of the roofing system, including the mechanical protection sheets defined based on the slope diagram (with the watershed at the center) and the expansion joints in positions coinciding with the structural joints. Another specification is the arrangement of asphalt membrane strips, overlapped in the transverse direction and following the curvature of the building, to prevent the return or percolation of water through the joints.

Thus, the constructive solution developed for the drainage system, which involves all the elements that make it up, in addition to intercepting and moving the rainwater away from the façades, was designed to dispense with the need for traditional drainage pipes and tubes which, in areas with intense tree planting (as is the case with the UnB building park) are constantly obstructed by vegetation [1,2].

The concern for watertightness, however, continues to be the main feature of both the architectural concept of the Sustainable Development Center and the future interventions carried out in this building. Recently, the University of Brasília approved the installation of photovoltaic panels on the roof to generate clean electricity to be consumed by the department.

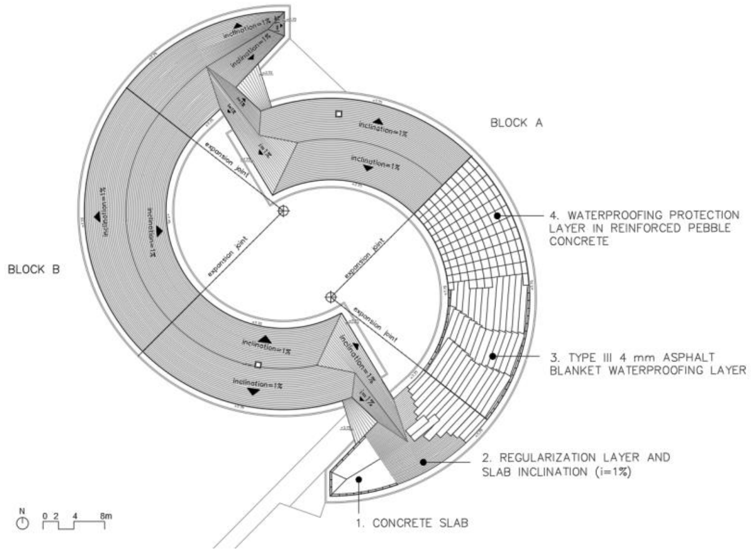


Figure 2. Executive roof waterproofing project and drainage diagram. Source: Oscar Niemeyer Planning Center—CEPLAN/UnB. Source: the authors.

In addition to ensuring watertightness, the integration of the photovoltaic panels with the waterproofing system and the slab was meticulously planned to maintain their structural integrity. The supports for the solar panels' metal profiles are fixed to concrete blocks positioned on the mechanical protection layer. These blocks are set with mortar, providing a solid and stable base for the supports and obviating the need for direct perforations in the waterproofing layer or the slab itself, as shown in Figure 3a.

(**a**) (**b**)

Figure 3. Fixing the photovoltaic panels to the roof: (**a**) construction detail; (**b**) dxecution photo. Source: the authors.

This approach safeguards the waterproofing system against potential damage that could compromise watertightness. Thus, each component—the panels, the waterproofing system, and the slab—works synergistically to maintain the building's energy efficiency and the waterproofing system integrity, contrary to what was reported by Lucchi [4], when mentioning the absence of protective elements in buildings with pure geometry. The proposed details can be seen in Figure 3.

Among the systems that make up the envelope, the roof performs important functions in buildings and directly interferes with the durability of the elements that make it up. Morgado et al. [9] state that a significant portion of the pathologies associated with flat roofs are due to deficient detailing in the design phase, errors in technical execution, inadequate or non-existent maintenance, and exposure to adverse conditions. The building envelope acts as a protective shell for buildings against environmental conditions and is therefore more exposed to these conditions and therefore more susceptible to deterioration [10], particularly the roof.

In this sense, it is essential to carry out regular building inspections to monitor the state of conservation of the building and to plan the necessary interventions to ensure its good performance and prolong its service life [11]. In recent years, the use of image acquisition technologies—especially drones—has enabled improvements in inspections and data collection, as well as contributing to decision-making.

The concern regarding the impact on the performance and durability of constructions caused by pathologies is of great significance in the fields of engineering and architecture. Throughout its service life, a building is subjected to various agents that cause damage, and depending on the level of exposure and its duration, these agents can lead to the degradation of construction elements or even entire systems. Therefore, they must be properly addressed to prevent their spread and further damage to other parts of the building [12,13].

The evaluation of the structural and functional aspects of the building is the objective of an inspection, which allows for the identification of pathological manifestations and leads to the elaboration of a maintenance and management plan of the building. Emerging methods for building inspection incorporate advanced technologies, notably the utilization of UAVs and sensors capable of capturing high-resolution imagery, thereby facilitating a more effective investigative process [12–15].

Digital photogrammetry is a well-established in situ and non-invasive technique for data acquisition in architectural and conservation surveys of built environments [5,9,13]. In cultural heritage, especially in buildings without up-to-date project documentation, this technique is highly capable of capturing measurements and details [1,2,10,14–20].

However, the wealth of detail in damage maps is only possible using digital technologies, especially aerophotogrammetry, which allows inspections to be carried out quickly, safely, and accurately using high-resolution images taken by unmanned aerial vehicles (UAVs or drones). The cost savings associated with carrying out building inspections should also be considered, especially in areas that are difficult to access, making it a valuable tool [10,14,17].

Aerial photogrammetry using drones is often used to inspect facades, as it is difficult to carry out a visual inspection with the naked eye, without the need for supporting infrastructure such as scaffolding, ladders, and turntables [21]. Photogrammetry makes it possible to represent the actual shape of a building's façade or roof, as in this case study, since the shape is constructed from photographs that depict the characteristics of the materials at the time the image was taken [18].

However, it is essential to carefully define the parameters prior to the inspection, including the flight altitude, distance from the object, capture angle, and image overlap, among others. These preliminary steps are crucial for conducting a thorough inspection with the aircraft and for obtaining high-quality data for later analysis [12,14,15,19].

Conceptually, a damage map is a detailed graphical representation document that records all existing and identified damage in a building [16], observed during an inspection. It is a tool of great importance for the maintenance and conservation actions of buildings, because it represents visually and simply the synthesis of the existing pathologies, leaving no room for different interpretations related to the type of damage. The use of graphic symbols associated with pathologies clearly indicates what was seen during the inspection, provided there is a good basis and description in the captions [13].

Damage maps are graphical tools that help to understand the current state of deterioration of the building and to select appropriate repair or intervention methods for each type of damage identified. They represent the relationships between the agents causing degradation of the building elements and their respective causes over time, allowing for the physical recording of the evolutionary state of conservation [16,22].

In this context, the main objective of this study was to investigate the relationship between pathological manifestations on the flat roof and the architectural details of the building's semicircular shape, assessing the state of conservation of its elements and components, as well as the influence of structural design, construction processes, environmental factors, and active degradation mechanisms. In addition, the study produced qualitative damage maps to visually represent the evidence.

The research into the relationship between the details of architectural form and the state of conservation of a modern architectural building is a relevant contribution to the compilation of an atlas of recurring pathological manifestations in modern heritage, as has been widely published for historic heritage.

A damage inventory contributes to the preservation of cultural heritage by facilitating the documentation and analysis of typologies. In particular, the research contributes to a comprehensive approach to identifying and understanding the factors that affect the sustainability of flat roofs, thus providing valuable knowledge for improving the maintenance and prolonging the service life of such structures.

2. Materials and Methods

The methodological approach used to investigate the flat roof in this study combined an aerial survey using a drone equipped with a high-resolution camera and visual inspection by an expert. A project analysis was carried out to complement the drone and specialist inspection data. The procedures ensured a comprehensive and accurate analysis of the conservation condition of the flat roof.

The images captured provided a panoramic view of the flat roof and identified potential areas of concern such as deformations, debris accumulation, and signs of surface wear. The physical presence of the inspector on site allowed for the identification of details and conditions inside the building and under the canopy. The integration of these two methods was carefully planned. Preliminary information from the drone guided the inspectors to specific points that required a more detailed inspection on site. This approach ensured the accuracy and reliability of the survey results for a global analysis of the state of conservation of the building's flat roof.

Digital processing of the images into a single plan, representing the flat roof in its entirety, allowed the damage to be mapped (Figure 4). Considering the dimensions of the building under study, this was a successful method of obtaining the as-built condition, necessary for recording and analyzing the damage.

Based on the explained process, the following is a case studied with the application of the methodology to produce damage maps from images acquired by aerophotogrammetry with a drone applied to the flat roof of the CDS/UnB equipped with an RGB sensor, which forms images from three bands in the visible light spectrum—blue, green, and red—that create a clear and high resolution image when combined. This type of sensor, compared to LiDAR, multispectral, or hyperspectral sensors, is usually readily available on the market and at a more affordable price [14].

This qualitative study is outlined in the following stages: (i) building inspection and field survey through aerial photogrammetry using a drone; (ii) creation of damage maps in vector representation software; and (iii) assessment of anomalies through identification of the causes, agents, and mechanisms of degradation at work—data acquisition; structure behavior; and diagnosis [23].

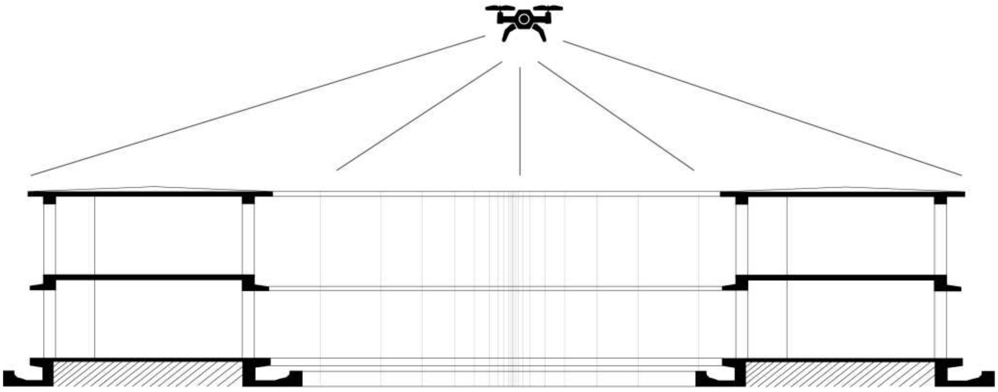


Figure 4. Illustration of taking a single aerial photo with the use of a drone for the representation of the roof plan of the CDS/UnB. Source: the authors.

The use of a drone (DJI® Mavic Air 2S model) for the roof inspection was considered to reduce the safety risks associated with inspectors (since the building has no parapet). In addition, the technique allows high-definition images to be obtained, whose processing allows for greater accuracy in mapping pathological manifestations [24,25].

In a more simplified preliminary analysis, such images were captured in two distinct periods, under different weather conditions: the first orthoimage, taken at the end of the rainy season, on February 16, 2023, was captured at a height of 56 m relative to ground level (at 49 m from the roof). The second orthoimage, taken at the beginning of the dry season, on 15 May 2023, was obtained at a height of 45 m from the ground (approximately 38 m from the roof). The choice of these periods is justified by the possibility of assessing the effects of humidity and temperature variations on the state of conservation of the building's flat roof.

For the creation of the damage maps, the drawing software AutoCAD® was chosen due to its ease of handling, interactive interface, and its widespread use by designers and professionals involved in conservation.

Regarding the graphic representation of pathological manifestations, the standards developed by Lima and Zanoni [18] and Carvalho [8] for damages in reinforced concrete structures were incorporated here, with certain adaptations, as indicated in Table 1.

Table 1. Graphic representation standards of pathologies, adapted from Carvalho [8].

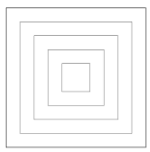
Phatological Manifestation	Graphic Representation	Simbology
Crack	Linear representation	
Spalling	Hatching formed from geometric repetition, in concentric polygons of varied sizes, outlining the area of the pathological manifestation	

Table 1. *Cont.*

Phatological Manifestation	Graphic Representation	Simbology
Biological attack	Hatching formed by point symbols	
Soiling and moisture stain	Hatching formed by point symbols	

Finally, to complement the diagnosis, an inspection of the roof was conducted by the inspector, for the photographic recording of the existing pathologies, anchored in the visual identification method defined in the Brazilian standard for building inspection [11].

3. Results

Drone imagery enabled an initial visual and qualitative evaluation to assess the extent of damage and potential risks linked to the roof components. Alongside the aerial images, the roof orthoimage offered a comprehensive overview of the roof, even in a single picture.

Based on the defined methodology, damage maps were created that graphically represent the pathologies expressed in Table 1 identified on the building's roof. These were produced from the graphical overlay of the obtained orthoimages, which occur, above all, in the layer of mechanical protection of the waterproofing.

Figure 5 shows the damage map constructed from an orthoimage captured with the drone at the end of a rainy period. It identifies the main stains affecting more than 50% of the roofing system area, with emphasis on soiling stains from particle deposition and differential washing, as well as moisture stains resulting from the accumulation of rainwater due to problems in directing the flow. The lighter-colored stains, from the center to the edges, across the entire extent of the roof, are those caused by the carrying of dirt, while the darker-colored stains, which are deposited along the edges of the curves that shape the building, signal points of moisture retention.

The damage map in Figure 6, developed from an orthoimage captured with the drone at the beginning of the dry period, shows anomalies identified as cracks, spallings, and stains from biological attacks.

The area of the building exhibiting moisture stains and dirt covers approximately 780 m^2, which represents 48.75% of the total area. It can be observed that both sections of the building, the north and south, display similar levels of staining. However, there is a slightly higher incidence of this type of pathological manifestation on the northernmost roof, attributed to differences in roof slope caused by execution errors.

Among the cracks, transversal cracks from one edge to the other, longitudinal cracks next to the water divider (ridge), and cracks distributed along the edges of the mechanical protection, in both the inner and outer curves, stand out. Their width varies between 1 mm and 5 mm, and their depth oscillated between 1 mm and the entire thickness of the protective mortar layer.

Spalling generally occurs alongside cracks and along the edges of the flat roof, in sections where hygrothermal variation causes tensions that break the mechanical protection layer. During the inspection of the waterproofing system, the process of detecting the spalling of the protective layer was conducted entirely through visual means. This implies that the evaluation was carried out by directly observing the surface, without the use of specialized equipment or tools that could verify the loss of adhesion between the waterproofing layer and the underlying substrate.

Figure 5. Damage map of the roof of the Sustainable Development Center: highlighting soiling and moisture stains. Source: the authors.

This visual method relies on identifying evident signs of spalling, as well as the presence of cracks or any other type of irregularity on the surface of the layer. However, it is important to note that without appropriate tools, such as adhesion testers, the detection of less visible spalling or that which has not yet manifested on the surface may not be entirely accurate. This limitation can hinder a full understanding of the extent and severity of the spalling, as underlying issues may not be immediately apparent to the naked eye. Therefore, in situations where the integrity of the waterproofing is critical, the use of complementary methods might be recommended for a more comprehensive evaluation.

Biological attack typically occurs in proximity to existing trees and is primarily caused by the decomposition of organic matter, such as leaves and small branches, which accumulate on the surface of the mechanical protection. This process is exacerbated by the presence of a moist and shaded environment, which provides ideal conditions for the proliferation of microorganisms or even the growth of vegetation. The roots of this vegetation can penetrate the mechanical protection layer, causing cracks and spalling, which further contribute to the degradation of the protective layer.

Figure 6. Damage map of the roof of the Sustainable Development Center: highlighting cracks, spallings, and stains from biological attacks. Source: the authors.

The association or overlay of the damage maps from Figures 5 and 6 can also assist in diagnosing internal pathologies of the building, such as infiltration points and efflorescence stains, identified mainly in certain sections of the upper floor's plaster ceiling and in the intermediate slabs connecting the blocks. These pathologies denote the rupture of the waterproofing membrane and water penetration through the cracks defined by the cracks, indicating more severe damage.

Table 2 gathers the main pathologies identified during the in loco inspection, as well as the relationship between the possible causes, agents, and mechanisms of degradation at work.

Table 2. Summary table: Pathological manifestations and cause–effect relationships [1]. Source: the authors.

Pathological Manifestation	Commentary	Photo
Soiling and moisture stains	Resulting from the carrying of dust particles and/or pollution adhering to the surface by the action of rainwater or the punctual retention of moisture due to drainage deficiencies and technical execution errors, which result in the presence of mold, fungi, and dark stains across the entire extent of the roof, especially in the final portion of the curves that shape the building.	

Table 2. *Cont.*

Pathological Manifestation	Commentary	Photo
Transversal cracks from one end to another	Hygrothermal variation combined with a limited number of expansion joints leads to significant structural movement stresses, causing transversal cracks in the mechanical protection mortar, which span from one end of the building to the other. This occurs to subdivide the mechanical protection layers of the roof.	
Rhythmic transversal cracks (inner curve and outer curve)	Throughout the building's perimeter, at the ends of the mechanical protection, transversal cracks with regular length, thickness, and spacing are identified along the internal and external curves, especially at the changes in direction of the surface. The presence of dark stains near these cracks indicates susceptibility to infiltration.	
Spallings	The stresses arising from structural expansion due to hygrothermal variation reach such intensity in some sections that they can cause displacement of the mechanical protection layer and rupture of the waterproofing membrane, as indicated by the infiltration and moisture stains found in the gypsum ceiling (roof) of the upper floor.	
Biological attack	Due to its location in a region of intense tree coverage, some leaves that settle on the mechanical protection layer in shaded areas and with localized moisture retention end up promoting biological colonization and the development of molds, mosses, and vegetation.	

4. Discussion

The term "conservation" encompasses different processes related to the "protection" of heritage and its significance, including preventive measures, repairs, restoration, reconstruction, and maintenance, with conservation itself being a much more complex process [26].

The execution of periodic evaluation of the state of conservation contributes to the planning of strategies and actions for preventive and corrective maintenance measures, considering efficient solutions for the repair of pathologies, extending the service life of the construction systems, and preserving the architectural attributes of the building [9,14].

Flat roofs, common in modern architecture, can suffer from poor drainage and water accumulation, leading to leaks and structural damage. In contrast, the steep roofs of some architectural forms typically allow for better water runoff, but their joints and seams can be vulnerable to water ingress if not properly maintained. Understanding the relationship between form and deterioration enables the implementation of preventative measures that can extend the service life of a building and preserve its aesthetic and historical value.

The extent, shape, and dimensions of the soiling and moisture stains recognized in the damage map indicate that, in certain sections, the runoff and drainage of rainwater occur as anticipated in the project, as it is possible to identify, through the uniform stains, the path taken from the ridge towards the drip edges at the ends of the flat roof. Moreover, there is no puddling of water on the roof, since rainwater is not directed to gutters, but to edges that project it into freefall to the ground.

On the other hand, the configurations of the moisture stains, which have dark coloring and irregular shapes and are concentrated along the edges of the blocks, point to deficiencies in runoff and moisture retention which, if not corrected, can lead to water percolation and infiltration problems. Observing the configuration of the stains, it is noted that the runoff of rainwater begins to follow the semicircular shape of the building, moving according to the irregularities of the surface.

The damage map also indicates that the transversal cracks at the ends of the mechanical protection follow a certain frequency and rhythm, since the spacing, length, and thickness are uniform. Being located between the straight segments that form the curvature of the building, always at the change of direction of the panels, their occurrence is related not only to the effects of hygrothermal variation but also to the different movements due to geometry, which tend to open or expand in a non-linear way in structures with a circular/semicircular shape. Another possible cause is the differential expansion between the mechanical protection mortar and the galvanized drip sheet along the perimeter of the roof, whose tensions can lead to spalling.

In instances where transversal cracks extend from one edge to the other, strategically situated roughly at the midpoint of the span delineated by the building's structural expansion joints, their specific arrangement, thickness, and occurrence provide insights into the operational behavior of the structure. This phenomenon appears to be an effort to effectively divide the roof into smaller, more manageable panels. The purpose behind this segmentation is likely aimed at mitigating stress and enhancing the overall stability and integrity of the roofing system, thereby accommodating natural movements and adjustments within the building's framework.

The mechanical protection layer contains only four expansion joints, which align with the building's structural expansion joints. This configuration leads to tension from hygrothermal variations, causing shifts in the mechanical protection layer and damage to the waterproofing membrane. The presence of moisture stains on the gypsum ceiling below indicates where the membrane has broken in some sections.

Other cracks are also identified in the sections corresponding to the water dividers and close to the structural expansion joints of the building. The presence of dark stains signals water percolation through the cracks, making the roofing system susceptible to moisture and the deleterious action of fluids. This finding reinforces the need for proper sizing of expansion joints, both in the slab and in the mechanical protection layer, to combine the tensions from structural movement due to hygrothermal variation, thus reducing the risk of cracking.

Despite its potential benefits, this approach remains uncommon in waterproofing projects. This is primarily because the Brazilian standard ABNT NBR 9575:2010, while advising the incorporation of expansion joints within the mechanical protection layer, falls short of detailing the specific dimensions that should be implemented. As a result, the absence of clear sizing guidelines within this standard leads to hesitation and variability in the application of such critical structural elements in waterproofing endeavors, underscoring the need for more precise directives to enhance the effectiveness and reliability of these projects.

Knowledge about the pathologies that compromise the state of conservation of the flat roof and consequently endanger its integrity has come to be considered and incorporated, especially when analyzing future interventions in this building. This is the case with the detailing proposed for the installation of photovoltaic panels, recently approved and executed by the university, which sought to avoid perforations on the waterproofed surface to prevent problems with water percolation and infiltration. The solution reveals that the concern for watertightness continues to be a central feature of the architectural design of the Sustainable Development Center, as well as the conservation and maintenance actions of this building.

The methodological procedures adopted for field survey and elaboration of damage maps, given the safety, accuracy, ease, and speed they represent, can be easily applied for the periodic assessment of the conservation state of flat roofs of other buildings, especially due to ease of access and low cost of the equipment, contributing to the development of ongoing studies in identifying pathological manifestations in buildings [14,27].

The research into the relationship between the details of architectural form and the state of conservation of a modern architectural building is a relevant contribution to the compilation of an atlas of recurring pathological manifestations in modern heritage, as has been widely published for historic heritage [28–30].

AutoCAD® can be used as a tool for mapping damage from frame images, with each layer (AutoCAD layer) representing damage identified by personal codes. Two-dimensional models can be imported into 3D BIM modelling, for example, in Revit®, ACCA®, ArchiCAD®, and improve semantic information and its management, including automation, which is fundamental for a sustainable heritage conservation. Three-dimensional BIM modelling can extend the user interface and its requirements by associating software and its plug-ins, such as Dynamo®, Rhinoceros®, Grasshopper®, Navisworks®, and Matlab®, among others [31–37].

Importantly, this methodology can be adapted for use in buildings across various climates and architectural styles, broadening its applicability and value in the field. In colder climates, drones equipped with different imaging cameras can identify heat loss or moisture ingress, while in warmer regions, they can detect sun damage or material degradation due to high temperatures. For buildings with complex architectural forms, UAVs can navigate intricate designs and capture data from challenging angles, offering insights into unique structural features. By tailoring the integration of in situ and aerial inspections to different environmental conditions and architectural complexities, this methodology provides a versatile framework applicable to a wide range of scenarios, making the findings relevant and valuable across diverse contexts [14,27].

While UAV (unmanned aerial vehicle)-based inspections offer significant advantages in terms of coverage and accessibility, especially for large or difficult-to-reach structures, several limitations must be considered to provide a balanced view of their reliability. One of the primary challenges is their susceptibility to adverse weather conditions. High winds, rain, snow, or fog can severely impede the drone's ability to capture clear images or maintain stable flight, affecting the quality of the data collected and posing risks to the UAV's safe operation. Consequently, inspections may need to be rescheduled, which can cause delays and impact project timelines [15,22].

Operating UAVs requires a certain level of skill and expertise. Pilots must be adept at maneuvering the drone and responding to unexpected situations, such as sudden weather changes or technical malfunctions. Additionally, interpreting the data collected, often in the form of high-resolution images and videos, requires further expertise to accurately identify structural issues.

Regulatory restrictions add another layer of complexity, as UAV operations are subject to various rules that can vary significantly by region. These regulations often include limits on flight altitude, no-fly zones, and requirements for special permits or licenses, which can be complex and time-consuming to navigate, potentially delaying inspections or restricting their scope.

Another technical limitation is the battery life and flight time of most UAVs, which restrict the duration of each flight. This limitation may necessitate multiple flights to cover large areas, adding to inspection times and logistical complexity. Additionally, managing battery life can be particularly challenging in cold climates, where batteries tend to deplete faster.

The limited payload capacity of most drones restricts the types and number of sensors that can be deployed simultaneously. This limitation affects the comprehensiveness of data collected in a single flight, potentially requiring multiple flights with different sensor configurations.

While UAV-based inspections offer valuable benefits in terms of efficiency and coverage, acknowledging and addressing these potential limitations is crucial to maximizing their effectiveness. Developing strategies to overcome these challenges, such as training programs for operators and planning inspections around weather forecasts, can enhance the reliability and success of UAV-based inspections.

Moreover, monitoring pathologies can assist in planning corrective or preventive maintenance actions that extend the building's useful life. The costliest administrative resource will depend only on the acquisition of roof images with the drone, a service that is already outsourced and offered by various companies in the market, but can also be performed by the university itself, through the acquisition of equipment and training of its technical professionals.

5. Conclusions

The monitoring and inspection of building roofs through aerial photogrammetry and the construction of damage maps offer significant contributions to understanding the relationship between architectural form and conservation. Aerial photogrammetry allows for the capture of high-resolution images that reveal precise details of building surfaces, enabling the identification of pathologies and damages that may not be visible to the naked eye.

The elaboration of damage maps of a building's roof using aerophotogrammetry with drones in vector drawing software allows for greater agility in monitoring anomalies, enabling high-definition visualization of pathologies and the performance of preventive or corrective maintenance interventions quickly, precisely, and assertively, to preserve the intrinsic characteristics of the building, and serve as valuable tools for the analysis and documentation of the conservation status of architectural structures.

By providing a comprehensive and accurate visualization of a building's conditions, these maps help to understand how different architectural forms can influence the occurrence and type of damages. For instance, certain roof shapes may be more susceptible to the accumulation of water or debris, which in turn can accelerate degradation processes. Understanding these relationships is crucial for developing effective conservation strategies that consider the specificities of each structure.

Moreover, the use of aerial photogrammetry and damage maps can inform future studies by providing empirical data on the effectiveness of different conservation techniques concerning specific architectural forms. These data can be used to compare the durability of materials and design solutions in different contexts, contributing to the development of more robust conservation guidelines.

In practice, this approach can also be applied to the preservation of modernist architecture, which often features innovative forms and experimental materials that require specific care. The precise and detailed documentation provided by aerial photogrammetry can help preserve the aesthetic and structural integrity of these buildings, ensuring that conservation interventions respect the original intentions of the architects while extending the buildings' service life.

A damage inventory contributes to the preservation of cultural heritage by facilitating the documentation and analysis of typologies. In particular, the research contributes to a comprehensive approach to identifying and understanding the factors that affect the sustainability of flat roofs, thus providing valuable knowledge for improving the maintenance and prolonging the service life of such structures.

The case study of the Sustainable Development Center at the University of Brasília highlights the importance of the mechanical protection layer for the good performance of the waterproofing system, reducing pathologies that compromise the structural integrity of the flat roof and the interior of the building. However, its effectiveness will depend on the correct sizing of expansion joints and the characteristics of the applied material, as it is the constructive element most exposed to environmental conditions.

To ensure effective building conservation, it is essential to adopt a proactive approach that includes regular inspections, the use of durable materials, and design improvements that mitigate environmental impact. It is recommended to conduct comprehensive inspections every season—spring, summer, winter, and fall—to identify and address issues before extreme weather conditions exacerbate them. Additional checks should be carried out after severe weather events, such as intense storms, to assess any potential damage or deterioration.

To enhance drainage, flat roofs should be considered as the first option during the design phase, or larger gutter and downspout systems should be installed to efficiently manage heavy rainfall, thereby reducing overflow and water accumulation around the foundation. Installing green roofs can also aid in absorbing rainwater, reducing runoff, and providing additional insulation, thereby improving both drainage and energy efficiency.

However, different regions with varying climatic conditions often require specific construction typologies. In areas with heavy snowfall, flat roofs may not be feasible due to the risk of overloading the roof slab, making steeply pitched roofs a preferable choice.

Implementing these recommendations and following a systematic research on the building, studying its documentation, current condition, materials, construction systems, and pathological manifestations for conservation purposes can significantly enhance the longevity and integrity of buildings, minimizing deterioration while optimizing maintenance efforts. Regular evaluation and adaptation of these strategies, based on specific environmental conditions and building designs, are crucial to ensuring their effectiveness in conservation efforts.

Lastly, through the analysis by overlaying different damage maps, monitoring is facilitated to ease the understanding of associations and cause-and-effect relationships between different damages caused by pathologies over the aging of the building. Thus, the ease of application of the proposed methodology can also be practically utilized, such as for the documentation of other buildings and the development of a management, maintenance, and conservation plan for the structures, always adhering to the principles of minimal intervention, authenticity, reversibility, and compatibility.

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