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Durability by design of outdoor timber walkways and pedestrian bridges

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1. Introduction

The goal of this study is to explore the specifics of timber construction technology for pedestrian bridges and walkways that are subjected to maritime and urban exposure environments. Both an on-site survey and a literature revision have been made, with the focus to emphasize on the main wood characteristics and important issues concerning the construction processes. Different designs and types of wooden structures have been examined closely to categorize their potential. The sites visited are located in the periphery of Lisbon and Sintra in Portugal.

Thanks to its singular characteristics, timber has always been an essential part of contemporary architecture, and nowadays is gaining popularity again in various construction sectors as the markets embrace the material. Historically, it has been used frequently in earthquake active regions providing a good solution for constructive elements under tensile loads for housing and infrastructure projects. Examples for this can be found in multiple historical sites located in earthquake active regions, such as the timber structures found in Japan. Old concepts of construction that have been often forgotten over time are rediscovered, and with the application of modern technology they offer crucial constructive solutions. Contemporary architecture adapts to the traditional techniques and together with an increased precision in production and an advanced understanding of mechanics, new design principles are possible (Anagnostou, 2018).

With the focus on profit and sustainability, especially nowadays it is vital for the construction industry to have a material on the market that is relatively cheap as well as environmentally friendly. A good price implies that the labour work has to be limited and the workability favourable.

2. Properties and pathology of timber structures

Since the main area of focus is humid and saline environments, these structures demand particular analysis and treatment. Therefore, the properties and the appropriate usage of wood are examined.

To make timber a more appealing solution for structures, characteristics such as sustainability, cost and appearance are constantly improving. The biggest advantages of such elements are the blend of a lightweight construction combined with satisfying load bearing capabilities, sustainability and sufficient serviceability. The market offers various timber products, such as solid construction timber or glued-laminated timber and each type exhibits distinct characteristics which can be advantageous in throughout the life cycle of the structure. The use of additional materials such as metallic parts in connections and concrete in the foundation proves to be beneficial for the durability and strength capabilities of the constructions when designed and maintained adequately (Kleinhenz, 2012), (Ramage, *et al*., 2016).

Wood also prevails as one of the most sustainable construction materials on the market. The growth of the trees and the consequent production of wood allow more CO_2 to be consumed than emitted, while cement and steel are responsible for 15% of the global CO_2 output at the moment. In the past years, the worldwide production of steel is almost doubling and of cement more than tripling (van Ruijven, *et al*., 2016).

Durability is defined as the ability of the structure to provide a defined performance over a predetermined amount of time. Directly related with this prospect are aspects such as the material characteristics and the environmental and operating conditions. The exposure of a structure represents the harshness of the moisture and temperature conditions that benefit the growth of organic material (Thelandersson, *et al*., 2011).

Furthermore, the durability of wooden structures is mainly dependent on how well the applied material performs over time in the environment of the respective section of the structure. Constructive solutions are a straightforward way to ensure long-term durability. With the objective to encourage the prevention of moisture attacks and the formation of anomalies, the wooden elements must be kept in a dry condition through satisfying ventilation, drainage and end grain protection mechanisms. With different methods of preservation such as the appropriate treatment of the surfaces, the use of wood types with a higher durability and strength, and the suitable use of structural and constructive solutions, it can be assured that the elements meet the level of durability needed. Regular maintenance is demanded in order to provide the desired performance during the lifespan of the structure (Kleinhenz, 2012), (SÉTRA, 2006 (2007)).

Typically, constructive solutions include:

- Roofing
- Boarding

- End grain protection
- Inclined surfaces
- Protected connections
- Well ventilated joints that allow sufficient drainage
- Metal profiles and concrete foundations ensuring clearance of the wood to the soil

For a successful investigation it is essential to detect the entire volume of irregularities. Depending on the type of anomaly, the cause can be specified. Through the passage of time and depending on the environment, components are impacted by human action and other natural agents.

Dryness, humidity and salts are all indicative for natural parameters that require attention when designing an element. Therefore, it is necessary to ensure that the material properties coincide with the setting so that the effects of the actions can be limited. The anomalies caused by nature are divided into three main groups: atmospheric, chemical and biological agents (Cruz & Nunes, 2012).

Anomalies caused by atmospheric agents are mainly related to fluctuations in the moisture content and in combination with direct sunlight (ultraviolet light), the lignin of the timber is degraded in a quicker rate, accelerating the effect of bleaching on the timber surfaces. By chemical agents it is often referred to corrosion of the connecting parts, caused when under damp conditions. Finally, biological agents can be fungi or insects such as wood borers or subterranean termites. Likewise, they appear in specific conditions that are frequently related to the moisture content of the affected element being above 20% (Nobre & Nunes, 2007).

All of the mentioned agents can be combatted with certain methods. When applying treatments with preservatives, especially in sections where the timber is covered or is not getting hit by the sun regularly, the design must allow the water to escape. In addition to the design, chemical treatments can be advantageous in the eradication of organic attacks by insects or fungi. Such preservatives come in three classes: oil based, water based and organic solvents (Nations., 1986).

The maintenance of timber structures should be carried out systematically. Typically, all constructions require regular maintenance work, but since wood is a material that changes constantly over time, it is particularly important to focus on the budgeting and on the procedure of the repair actions required. The design process should respect future activities on the construction and enable maintenance to be carried out in a secure and efficient way (Crossman & Simm, 2004).

3. Methodology

The aim of this dissertation is to analyse timber structures in maritime and urban environments in order to optimise the design and save costs in the later stages of the structure's life-cycle. The information used in this report was collected from literature referred to in the references and site visits that were concluded during the year of 2020. The qualitative data was collected from various visits by the author with the focus on gathering observations without intervening. All the sites are located within a perimeter of 40km from Lisbon. It was necessary to visit different constructions in order to witness each of the studied phenomena first hand. Non-destructive testing was carried out with the use of:

- a moisture meter for measuring the moisture within the material
- a screwdriver for testing the firmness of the surfaces
- a scale for measuring the width of cracks and knots
- a camera for taking pictures and using them as visual evidence for the observations

With this approach, deterioration mechanisms can be identified without damaging the existing structures and so securing a harmless testing routine.

Following the compilation of all the data from written sources, a number of walkways were visited in the broader area of Lisbon. The selected structures are situated in different areas (Figure 1), each with a distinct environment. The visits were divided in three different case studies.

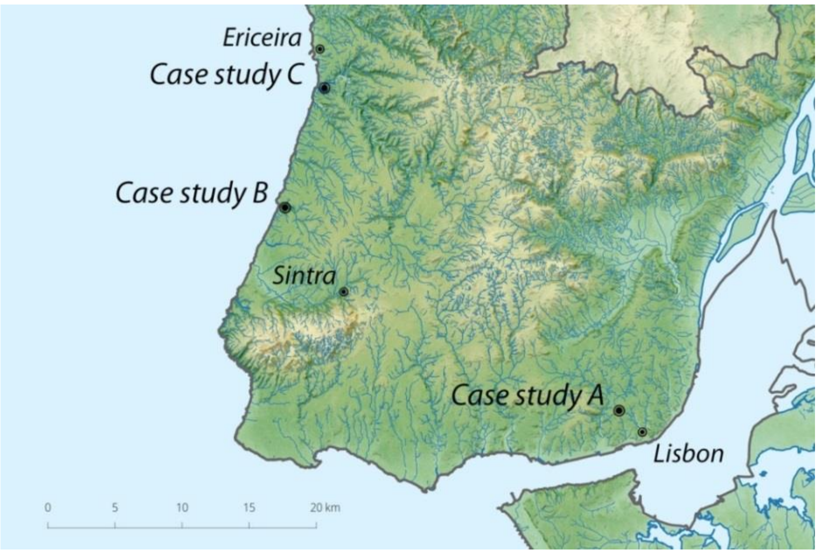

Figure 1. Map of the Lisbon and Sintra area including the location of the case studies [W1].

Case study A is located within the city of Lisbon, while case studies B and C are located on the Atlantic coast of Portugal. Each environment affects the wooden structures in a particular way depending on parameters such as humidity, direct exposure to the sun or the presence of salts. The impact of various climatic conditions and different construction methods will be inspected with the objective to identify the advantages and disadvantages of each approach. A different setting implies variations of the results that were to be expected, since the conditions change to a large degree within small distances. Walkways generally displaying similar design approaches, the components got divided in classes such as cladding, handrails, connecting parts, supporting columns and beams. The parts close to the soil normally portrayed different signs of deterioration than the ones on the top part of the structure. Following the literature review, anomalies such as moisture problems and biological attacks were expected in the lower section and deterioration by the dryness of the sun and the usage by the public on the top side.

It was possible to visit different sites, since this method of construction is applied frequently in Portugal. The environment along the coasts is very harsh, making each structure an optimal specimen for research concerning durability-based design of timber structures. Each structure was visited at most twice, once in spring and once in fall.

In Portugal there is a temperate maritime climate, with hot summers and wet winters being affected by the Atlantic and Mediterranean currents [W2]. The collected information is valuable for getting a better understanding of the impact under these particular conditions and provides the necessary insight to be referenced in future studies.

The analysis was divided in two parts; the preliminary stage and the detailed stage. As depicted (Figure 2) both of these phases include various aspects to consider during the investigation. While the preliminary stage presents a more general approach of investigating the objects, in the detailed stage specific features are examined with the assistance of the equipment.

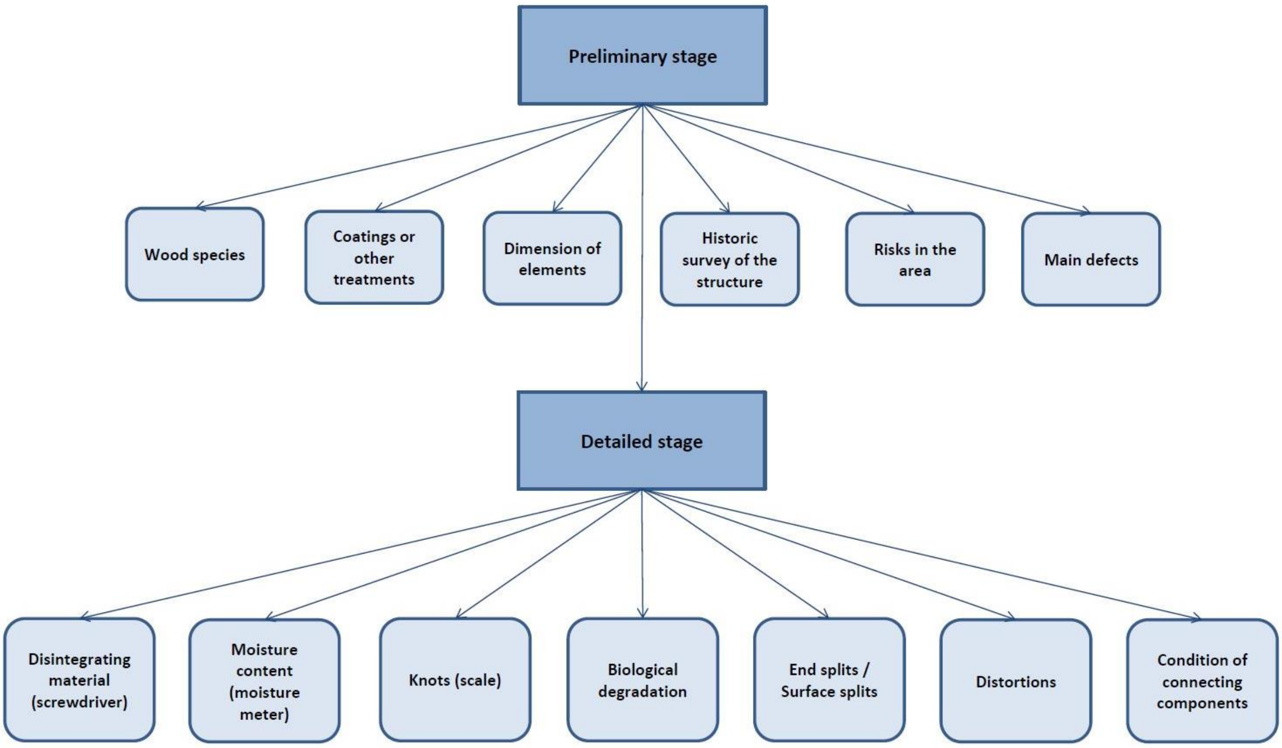

Figure 2. The main aspects of the inspection.

Before the visits an inspection datasheet was completed to facilitate the survey (Table 1). It served as a checklist on site classifying all the necessary anomalies to be detected.

Table 1. Example of inspection sheet used for case study C.

Nº of Case Study:	**3**		**Date: 17/07/2020**
Location	Praia de foz do Lizandro		
Type of structure	Timber walkway / Beach access		
Time of the day	Morning (10 o'clock)		
Weather	Sunny		
Wind	18 km/h		
Temperature (°C)	<5 ☐	between 15 and 20 ☐	>20 ☒
Humidity (44%)	Low ☐	Medium ☒	High ☐
Year of construction	2018		
Length of structure	≈330m		
Proximity to the ocean	<100m		
Exposure to the sun	Low ☐	Medium ☐	High ☒
Type of sorroundings	Beach / Parking lot		
Type of timber	Scots Pine		
Type of timber products used	Solid construction and glued-laminated timber		
Treatment	Fully dipped		
Coating	Oil or bituminous paint		
Connecting elements	Steel bolts and L-profiles		
Inclined surfaces on top deck	Yes ☒	No ☐	
Clearances between elements	Small ☐	Medium ☐	Large ☒
Main risks in the area	Salts, humidity, sun		
Moisture content on top deck	<10%		
Moisture content close to the ground	40%		
Anomalies			
Presence of soft degrading material	Yes ☒	No ☐	
Type of element	Horizontal support of staircase, W*H*D≈ 2,00*0,25*0,10m		
Location	Behind the staircase of central ramp, ≈30cm above ground		
Presence of rot fungi	Yes ☒	No ☐	
Type of element	Horizontal support of staircase, W*H*D≈ 2,00*0,25*0,10m		
Location	Behind the staircase of central ramp, ≈30cm above ground		
Presnce of degradation caused by insects	Yes ☐	No ☒	
Presence of salts	Yes ☒	No ☐	
Type of element	Footing		
Location	At the lower part of the footings		
Biggest knot in supporting element	35cm, on column in the corner of cross section		
Presence of shakes	Yes ☒	No ☐	
Type of element	Horizontal beam supporting the deck		
Location	Under the extending ramps		
Presence of surface splits	Yes ☒	No ☐	
Type of element	Especially apparent on columns		
Location	Under the main deck		
Presence of end splits	Yes ☒	No ☐	
Type of element	Especially apparent on columns		
Location	Under the main deck		
Presence of distortions	Yes ☐	No ☒	
Presence of corrosion	Yes ☒	No ☐	
Type of element	Steel bolts		
Location	Under the deck		

4. Analysis of case studies

Case study A is a timber pedestrian bridge that spans over a distance of 90m and is located in the heart of Lisbon. Being part of the Monsanto Green corridor, it is serving as a connection between the Monsanto Forest Park and the Eduardo VII Park. Timber products in form of solid construction timber and glued laminated timber were both present on this site and investigated in terms of degradation. Anomalies were mainly noticeable on the top part of the construction in form of cracking, detached parts and faded colouring in various sections due to the effects of direct sunlight and precipitation. The lower construction including the load bearing elements was visibly in a better condition.

Case study B is located on a beach close to Sintra, stretches over a length of 850m and encompasses two different structures; one that has existed for years connecting the beach to the road, and a new part added recently. In the survey both parts were inspected with the newer being located in particular close proximity to the ocean and the existing segment being further from the sea and surrounded by trees. While deterioration patterns regarding the effect of saltwater and direct sunlight on timber were tested on the beach, further inland the impact of reduced ventilation in sections that are covered by vegetation could be evaluated. Eventually, a comparison could be made between elements that were in use for a relatively much shorter time in an environment with strong fluctuations of the moisture content and in the presence of salts, with parts that are in service for longer but are in a setting of comparably much reduced fluctuations of the moisture content.

Case study C spans over 280m and is situated in the centre of a beach south of Ericeira, enabling an organized access to the ocean. It was designed by the architecture studio Concepsys in Lisbon, in the year of 2006. The walkway is used on a daily basis by a number of surf schools and cafes that have their stands situated on the upper deck Salts and high moisture contents were generally frequently present because of the close proximity to the sea and the structure was subjected directly to the sun since any form of shelter was not present. Also, in this case study timber products in form of solid construction timber as well as glued-laminated timber were present. The design of the upper part of the walkway included multiple features that allow protection from the direct sunlight, an appropriate ventilation and drainage from the water. Therefore this structure displayed a number of exemplary design solutions in terms of durability-based design. Sections located closer to the ground and exposed to moisture contents above 20% demonstrated in similar fashion a limited amount of anomalies.

5. Discussion of results

After completing all of the surveys on site, the focus went towards the interpretation of these findings by outlining and evaluating the key aspects considered. The focus is mainly aimed towards analyzing the causes of encountered deterioration patterns and their possible impact on the durability of the respective case study, whilst improved constructive propositions are discussed. Concerning the research itself, the limitations of the work along with recommendations are pointed out, so that there is a transparent blueprint for future studies to build on.

Subsequently, with the Methodology of the inspection explained and all of the visits completed, the gathered information was re-evaluated in order to examine the reasoning behind degradation patterns so that the possibilities of improving the durability of the designs can be later discussed. Having the most notable anomalies encountered during the visits categorized, the attention is aimed towards the causes, in order to obtain a better understanding of each individual case and its influence on the structure. In this manner, it will be possible to identify each of the solutions that should have been adopted in order for them be applied in future constructions.

Concerning the decay patterns, a closer look has been given into the consequences of these findings and how they compare to the information collected. Possible distinctions along with correlations are discussed while the attention is aimed on securing additional facts based on the existing evidence.

Generally, the case studies cover a large variety of degradation patterns since the environmental conditions are typically alternating within short distances. In areas where there is direct exposure to the sun and dryness is prevalent, anomalies on the upwards facing and more exposed side of the structure are primarily investigated. In addition, sections in corners, close to the ground or water source, ordinarily were examined in terms of the presence of soft surfaces or an indicative colouring that could signify the presence of a kind of fungi or another degrading agent. When constructive or non-constructive solutions were detected, and information on their nature was available from the references, they were compared to each other as well as with alternative cases where these solutions are absent.

6. Conclusion

The usage of timber products has been historically significant and finds purpose in numerous fields in exterior and interior applications. Modern and expedient testing methods allow a better understanding of its properties, and along with contemporary construction techniques the limits of this material can be stretched.

This research focuses on the accumulation of the key aspects concerning durability-based design of timber structures and having all the observations from the case studies analysed and compared with previous research, a conclusion can be established about the effects of the examined environmental conditions along with the most advantageous design choices.

Ultimately, the concluding thoughts are that timber structures demonstrate a great number of characteristics that justify their construction in environments of extreme moisture and dryness and that much consideration has to be given to environmental and durability related issues during the design phase, in order to save costs in the course of the structures service life. The analysis has shown that effective solutions for these concerns are often related to the optimization of constructive details and the correct choice of material and protective measures, which demands expertise and the appropriate research to provide the desired information.

Encompassing a variety of specific climatic conditions this work paves the way for future examinations in the same field of study.

7. Acknowledgements

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