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THE CLIMATE IMPACT ON TIMBER STRUCTURES

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ABSTRACT

In the last fifty years the climate change has become an important problem with high social and economic impact. Sadly, there are plenty of events that evidence the risks that the climate-change carries on our own lives, but also on our built environment. One of the most important and oldest building materials used by humans is the timber. Being a natural material it has a direct interaction with the climate factors, therefore it is impacted by the phenomenon of the climate change, as well.

Besides other characteristics, the moisture content of the wooden cells is one of the most challenged properties by the global warming. It is a basic requirement that all wood products are made from raw materials with a moisture content that is the expected equilibrium wood moisture at the point of use, otherwise the finished product may be damaged due to greater swelling or shrinkage, pronounced deformation and cracking, making it unsuitable for its intended use. Thus timber buildings older than forty-fifty years, witness to the global warming can be seriously affected by changes in characteristics like strength, stiffness, hardness, high deformation values or appearance of biologically active compounds. In order to protect these structures an understanding of the nature of these changes and setup a series of methods is necessary, without damaging the cultural heritage sites.

The aim of the present review is to summarize the impact of the environment, climate and climate-change on timber buildings, and to present the most important analytical methods from the literature, used for the study of wooden material.

Keywords: climate change; temperature; humidity; moisture content; timber; heritage.

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1. INTRODUCTION

Wood is a construction material that has been widely used over the history, therefore it can frequently be found in the historical monuments and ancient structures as indoor (floors, indoor frames) or outdoor (roof, frontage, outdoor frame) building element [1, 2]. The use of wood for buildings and other timber structures in the different climatic regions is generally related to the environmental conditions, however theses same conditions are the main causes of the different types of deteriorations found on the timber elements of these buildings.

Temperature, wind and natural hazards, growth in temperature and precipitation quantity are the main causal agents of – in some cases extensive and severe – damage of the historic built surrounding [3, 4]. It has been considered by specialists [3] that many extreme events that have been recorded in Europe in the recent years – which include floods, tornados and heavy rains – are effects of the so called climate change [5].

The results of damage evaluation in structures made from large span timber indicate a type of damage that causes cracking in the lines of glue and glulam timber lamellae [5]. Damage of timber is often connected to low or high moisture content (MC) and rapid changes in temperature [6]. Conditions of low or high MC over a given period of time can be attributed to the local conditions; however climatic conditions and variations have an increasing effect. The strength of wood is often affected by varying equilibrium level of moisture content and temperature, and changes in wood products' moisture content can cause shrinkage, swelling and variations in strength and elastic characteristics of even before they are integrated as building elements. For example the effect of shrinkage means a reduction in the cross-sectional area, moment of inertia as well as the sectional modulus of the member.

In a research done by Ranta-Maunus [7] it was shown that the strength of the bending and compression of the timber increased when the moisture content decreased below the saturation point of fiber of the wood. Tension strength did not depend much on moisture content, making this dependence to be ignored. The definition of the various effects of moisture on the timber was simplified to a percentage value that expresses the change of a physical parameter per one percent of moisture content change [7].

Dry wood is known to have higher strength as compared to wet wood, however, there is a minimum limit moisture content value that wood cannot exceed when drying, and otherwise the timber can become even weaker. This limit is similar for all the wood species, the maximum strength is about 10% of MC. Reduced strength values can occur as a result of wood having low moisture content from long-term exposure to high temperatures. For example, higher temperatures than 60 ^{o}C lead to a degradation of wood and a permanent reduction of its strength [7].

This paper aims to give a short literature overview on the impact of the environment, climate and climate change on timber structures. First, timber as a frequently used material in construction is presented. Then climate change is discussed in details. Various tests and several techniques are presented – such as ultrasonic and sonic wave techniques, electrical and x-ray methods – that serve as analytical methods characterizing the timber structure. A conclusion that summarizes the whole work is drawn at the end.

2. TIMBER, AS CONSTRUCTION MATERIAL

Timber is a construction material with a significant complexity. It has been in use for decades [2, 8] and it has applications that form part of our collective heritage [8]. However its application has not ceased, it is still widely used today as new structural component of buildings and as new infrastructure element that presents dimensions that were never considered before [2]. Timber as a structural material has various benefits, it can be recycled, it is superior in thermal insulation and is excellent in its dynamic behavior, and therefore it is frequently used with success in regions with high earthquake hazard. Material-based design principles are required for the new applications/use of timber as a structural material.

According to a report by Vardoulakis and coworkers [9] multi-story timber buildings have a variety of structural systems which are categorized in two categories. The first includes the historic timber buildings in which timber has had uses for centuries which include the Asian multi-story pagodas, the Scandinavian stave churches as well as combined timber alongside masonry buildings in the various European cities. The second category contains the traditional heavy timber frames which are described by beams with large dimensions and columns joined together using timber [9]. The second category contains construction forms that are common in historical timber buildings mostly in North America. Glulam, sawn timber and rough types made from logs are the most common timber beams and columns used for this category. Light timber frame is another multi-story building material and is the most commonly used form. It involves the use of small sawn timber to act as wall studs and floor joints; the cross-section of this joint can be from 90x40 mm^2 to 250x50 mm^2 or even more. It is common in North America and normally is referred to as wood frame construction.

Cross Laminated Timber (CLT) is also becoming common in Europe for the prefabricated multi-story buildings [10]. CLT panels are timber panels that are large in size, are of solid wood, and are produced from sawn timber layers which are alternative in nature [9]. Timber structure behavior is influenced by two major parameters: the viscoelastic orthotropic behavior and variability because of temperature and moisture content [11].

2.1 Viscoelastic orthotropic timber behavior

Timber can be considered as viscoelastic orthotropic timber when its mechanical behavior depends on both elastic and viscous (regarding time) properties. Its behavior depends strongly on the direction of cross grain having large mechanical property differences like elasticity modulus or strength in between the respective values that are parallel and perpendicular to the direction of grain [11, 12].

Tension is also an important aspect in the study of the viscoelastic behavior of timber [11]. Timber shows almost linear elastic brittle failure under the conditions of tension while when under compression, the stress-strain diagram hardening part is non-linear and has limited ductility up to final stress which is then followed by a softening part which is mild in nature [13]. Furthermore, compression which is perpendicular to the direction of grain results into densification of wood followed by increase of yield strength [12].

Today, in timber structural design, failure mechanisms also need to be taken into account, in order to assure that there will be no occurrence of brittle failure prior to the ductile component plasticization. It is necessary to design the brittle timber members for the ductile rigid as well as semi-rigid connections over strength.

2.2 Effects of moisture content and temperature on timber

Wood is termed as a hygroscopic material because it often attempts to be at equilibrium with the surrounding climate conditions. The result of dynamic moisture equilibrium can be the twisting and distortion of solid timber and laminated timber when exposed to variations in climate [11, 14]. Based on this, the wood is characterized by its moisture content, which highly affects the strength of the wood component.

The Fiber Saturation Point (FSP) is the moisture content at which the free water (i.e., the cell cavity water) has been completely dissipated. Wood tends to shrink by losing water from the cell walls below the FSP, which is usually between 25% and 35% moisture content for many wood types (i.e., the bound water) [15].

The Equilibrium Moisture Content (EMC) is the moisture content at which the moisture of the wood portion is matched with that of the ambient environment, usually exists at a moisture content of between 10% and 15% for most wood types in the controlled area [15].

It is possible to determine the moisture content of wood using a portable moisture meter. The strength of the wood decreases as the moisture content rises to the FSP, and as the moisture content decreases below the FSP, the strength of the wood increases, but this improvement can be compensated by a decline in strength due to the shrinkage of the wood fibers [15].

A wood member's Moisture Content (MC) can be measured as:

$$MC = \frac{Weight\ of\ moist\ wood\ -\ weight\ of\ oven - dried\ wood}{weight\ of\ oven - dried\ wood} \times 100\% \tag{1}$$

Wood is negatively impacted by temperatures above 35 °C. The strength of the wood member reduces as the atmospheric temperature increases above 35 °C. The structural members have ambient temperatures of less than 35 °C in most insulated timber buildings [15].

According to Eurocode 5, the structures are allocated to one of the below service classes. The key objective of the service class system is the assignment of strength values and the measurement of deformation under specified environmental conditions [16].

Service class 1 is distinguished by a moisture content equivalent to a temperature of 20 °C in the components and a relative humidity of just more than 65% in the ambient air for a few weeks each year. The total moisture content of most softwood will not surpass 12%in service class 1. Service class 2 is distinguished by a moisture content equivalent to a temperature of 20 °C in the components and a relative humidity of just more than 85% in the ambient air for a few weeks each year. The total moisture content of most softwood will not reach 20% in service class 2. Service class 3 is distinguished by climatic conditions contributing to higher moisture content than in service class 2 [16].

3. CLIMATE CHANGE

Over the past decades, there has been a significant change in climate which has increased the attention towards the potential effects of the changes especially in urban [17, 18], but also in the rural environment. It is estimated that currently, almost half of the world's population is living in urban areas; however, this number is approximated to rise to over 70% in the next 30 years [19]. Many low-income countries have vulnerable populations that are already suffering from clean drinking water shortages, poor sanitization and frequently, they live in flood plains and coastal zones which are considered high risk areas [17].

Global climate change as stated by the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (TAR), climate change is related to the greenhouse gases emitted by humans to the ozone layer [18]. In addition, the TAR report asserts that a bigger percentage of the global warming are caused by human activities; these activities are further mentioned to continue interfering with atmosphere's composition besides the global mean temperature as well as sea levels rising for many years to come [17]. The urban areas are in the continued hotspot of climate change [10]. The high inter-yearly variation in local weather and confounding aspects, like change in land use or effects of urbanization, make difficult to detect climatic driven trends in individual cities.

Built areas are associated with Urban Heat Islands (UHI) which have temperatures higher with 5-6 °C than the surrounding countryside [10]. Building materials, when compared to vegetated surfaces are capable of retaining more solar energy in the day and cool at slower rates during the night. In addition, urban areas possess lower speeds of wind, lower losses of the convective heat as well as evapotranspiration that yields in more surface warming energy.

There is often an interaction between the built areas physical components as well as human activities and other climatic drivers in the urban setting. For instance, the impervious surfaces impact dramatically on downstream flooding risks and erosion besides changing temperature of rivers and quality of water through storm water discharges that are not controlled. There can also be an increment in the concentrations of urban air pollution during heat waves. The reason for this is that elevated temperatures together with solar radiations stimulate photochemical smog production and ozone precursor volatile organic compounds by some plants [17]. The consideration of specialists is that many extreme occurrences in Europe in recent past years have been a result of climate change [5].

There are a few examples of flooding, tornados and heavy rains [3, 17], which will be described as follows:

i. *Flooding* has raised the attention of the authorities, as its occurrence has increased in Europe and around the world. The future estimates on flooding occurrences are much higher because it is predicted that the climate will change significantly; this will increase flood events severity and frequency. The United Kingdom tragedy of December 2015 is a good example of the flooding and its effects where not less than 500 properties as well as multiple historical buildings were destroyed by Foss and Ouse main rivers [3].

ii. Europe has shown a high rise in *tornados* over the past years as shown in various studies [3, 17]. The occurrence of these extreme events between 2000 and 2014 was more than 242 times as compared to 8 times between 1800 and 1850. Tornados that cause damages to historic buildings have been witnessed in most parts of Europe like Greece, Sweden, Hungary, Germany, UK, France, Portugal, Belgium, Russia among other parts of Europe [3].

iii. Heavy rains are one of the major impacts of climate change. The effects of heavy rains have been recorded in parts of Romania like Arad where a 200-year-old building was destroyed [3]. The cause of this was revealed when a close inspection of the building was done and it was found out that it was due to infiltration of water in the basement as well as fissures.

4. CLIMATE AND TIMBER INTERACTION

From various research on wood and its behavior and characteristics, it is known that wood is very sensitive to changes in climate, shown especially by shrinkage and swelling, but also by properties like stiffness and strength [4, 20].

Timber design guidelines suggest that it is important to take into account the sensitivity of wood to moisture and drying of timber below the average moisture content that agrees with the expected conditions of the surrounding climate [20].

For example, wood that is put into service and has an average moisture content of over 20% will result into a 20% lower resistance than the same wood with low moisture content.

Growth of mold on timber is a phenomenon that also comes with the changes in climate conditions. The propellants of this are the two major climatic conditions: moisture and temperature [21], [22]. The growth of fungi on timber is made possible with conditions of moisture content being 35-50% and that of temperature being around 23-25°C [22]. Exposure time to moisture and temperature changes is also an important factor. Environmental conditions like relative humidity as well as temperature of the environment are never constant for long time frames. These conditions vary over times which then come with favorable and unfavorable fungi growth conditions that lead to mold growth on timber. It is also worth studying the interaction of wood with biogenic carbon dioxide emissions which is the carbon dioxide released from biomass as a result of decay or incineration and it is also part of climatic changes [21], however timber is known to be carbon neutral, because acts as temporary carbon storage material. Through photosynthesis CO_2 is released into the atmosphere by the biomass. Timber production normally leads to a reduction in the level of global biomass stock which then results into a reduction of bio spherical pool of stored carbon. The outcome of this is not carbon neutrality, rather an increased concentration in atmospheric CO_2. Therefore, sustainable timber harvest while maintaining the bio spherical carbon pool is a vital condition for climate friendly timber material.

The interaction can be seen also in the stem of trees in the forests, because the direction of the stem growth depends mainly on the wind direction, and in case of severe winds for example storms and tornados [3, 17] the impact has various forms like crack-forming, break of stems and leaves, and deterioration of the mechanical and physical resistance for the timer as material [15].

It has been discovered that between the climate change effects can be found the change of the thickness and mass of the wood. By comparing wood samples from the 1870s and today's samples with the latest measurement technology, the Weihenstephan School of Life Sciences team was able to demonstrate that the annual-growing wood is gradually becoming lighter by up to 12%. During the same period, tree growth has also accelerated in Central Europe. In other words, despite the production of a large amount of wood today, the wood contains less materials, meaning that it is weaker compared to the wood produced a few decades ago [23].

5. TECHNIQUES AND TESTS APPLIED ON TIMBER

Carrying out a complete analysis on timber can sometimes be challenging, because a number of factors need to be assessed in order to make sure that the timber products are at no risk. An example of such risk is the inclusion of historical timber in the supply chain. The techniques that are widely used to evaluate timber conditions can be of two or three types: non-destructive testing (NDT), destructive or semi-destructive timber testing [24, 25].

5.1 Non-destructive testing

NDT, or non-destructive evaluation (NDE) is the science that can be used to spot or find out the physical as well as mechanical properties, or even defects present in a piece of material such as timber while maintaining their potentials of end use without alterations [2]. According to the work of Tanasoiu and coworkers [24], the techniques of NDT that are utilized in the industry of forest products are applicable in the control and evaluation of quality as well as wood properties and structures and are categorized as follows:

5.1.1 Visual inspections

This is one of the oldest NDT methods that is still in practice, however, it is said to be very subjective [2]. Through this technique, it is possible for someone with expertise to conclude if wood member demonstrates mechanical damage or if it is broken [24, 26].

A deeper inspection can involve listening for hollow sound, normally by using a hammer to knock or using a scrapper to determine degradation depth on a degraded surface [24, 26].

5.1.2 Sonic stress wave

The principle upon which this technique is based on is that the speeds of sound as well as attenuation are dependent on wood strength and stiffness. From this principle, it is possible to calculate the dynamic modulus of elasticity using the formula [24, 27]:

$$E = \rho \cdot v^2 \tag{2}$$

where E is the dynamic modulus of elasticity, ρ is the wood density; v is the measured wave velocity.

Practically, the generation of the used wave is done with the aid of a hammer or by use of an instrument to induce vibration on the wood [24, 27]. This involves mounting two piezoelectric transducers at a distance d at the ends of the specimen of wood, used so that the two transducers determine the time-of-flight t of the stress wave.

Through this, the velocity is determined by this equation:

$$v = \frac{d}{t} \tag{3}$$

where v is velocity of stress wave, d is the distance of the transducers and t is the flying time. Through this relation, it is easy to determine the dynamic modulus of elasticity, E.

5.1.3 Ultrasonic stress wave

Ultrasonic stress wave technique is a similar technique to sonic stress wave, but it operates with higher frequencies. For timber, frequency range is favorable at 20-500 kHz because wood has high attenuation. The strength predictors used in this case are the acoustic velocity as well as acoustic attenuation coefficient. Defects are located by transit time increase between the two transducers [24, 27]. This technique is used for homogenous and nonporous materials. It is also effective for the quality control of laminate structures, localizing delaminated areas because of the ability to concentrate ultrasonic waves in small regions [2].

When the instrument has two transducers, an emitter and a receiver, these are mounted on the two sides of the wooden piece. The ultrasonic signal is generated by the emitter, and if the wave meets a defect on its way, it is partially reflected. The reduced, transmitted signal is measured by the receiver. The ratio of the non-reflected and reflected signals is then used to evaluate the internal defect. In the pulse echo method only a single transducer is employed, which serves the purpose of an emitter as well as a receiver of the reflected pulses.

Environmental aspects and characteristics of wood like moisture and grain direction affect the ultrasound measurements. Therefore, for example, the speed of the ultrasound is high (three times higher) along the direction of a grain compared to across direction in compact wood. This makes possible to detect defects which encompass grain direction changes.

5.1.4 Other alternative NDT techniques

Several other techniques are also applied in the examination and control of wood quality and composites in NDT ways although they have more limited usage [24, 27]. These techniques include; deflection, electrical, isotope/gamma radiation, penetrating radar and the X-ray methods.

The *X-ray technique* is commonly used in laboratories or in the manufacturing line to measure the density of timber. The *electrical method* involves the detection of decay with in-situ evaluation by looking into the relation between MC and electrical resistance of timber.

The *deflection method* is mostly used for products of lumber and pole. The *gamma radiation/ isotope technique* is used in the determination of a trace element for the quantification of preservation distribution in timber. The *penetrating radar technique* is employed in the detection and quantification of the degradation of wood at locations that cannot be accessed.

5.2 Destructive testing

Destructive testing techniques are widely used to classify components, verify production, evaluate defects, and may be a crucial part of essential engineering evaluations. Just as NDT, destructive testing is equally vital, however not always can be used especially in the case of cultural heritage sites.

In order to clarify the performance or material behavior of a specimen, the tests are carried out to estimate the material failure limit. They include different forms of destructive testing, for example the bending test, where the strength, stress and strain can be measured depending on the type of wood and depending on its water content. Deflection and deformation on wood components can also be measured during these tests [25].

Compression test plays also an important role, where compression strength is measured to determine the allowable load resistance, which is significant for the service live of the components. It’s worth mentioning that the results of these tests depend highly on the orientation of the wood cells [15, 25].

5.3 Timber monitoring

According to Cavalli and Togni [8] it is important in construction to do timber monitoring in order to keep the timber structures in good conditions and ensure structural safety. However, another primary goal of monitoring timber in historical buildings is to conserve the originality as well as the integrity of the structural features together with the structural systems. Timber monitoring idea became more important when the ice rink of Bad Reichenhall of Germany collapsed in 2006.

Monitoring is not just for monitoring bridges, but also primarily for monitoring new buildings. To date, the surveillance of historic timber buildings is carried out, at a minimum, precisely by documenting temperature and humidity fluctuations and/or by repeating the on-site inspection.

The on-site inspection is known to be the most effective non-destructive method for the evaluation of timber structures, but it reveals its tacit limit: it takes a snapshot of the state of the timber structure at a given period.

Otherwise, the remote monitoring used by modern systems, based on recent developments and applications, creates the ability of continuous monitoring, enabling all possible external influences have to do with the structure’s mechanical behavior and its conservation status.

As part of the World Cultural Heritage, some of the strategies built for the surveillance of new buildings can be applied to existing timber structures, taking into account the significance of historical structures that need to be protected and managed under safety conditions.

Nowadays, the common method for monitoring old timber constructs is to repeat on-site inspections at frequent intervals, to obtain information on the existing conditions and, finally, to track the progress of alterations such as degradation rates, residual cross-section of the part, stress on the functionality of the joints, as well as the progress of decay in the wood.

The use of emerging technology for remote monitoring of new timber buildings and bridges can be applied to old timber buildings and effectively used to track moisture content or deformation.

6. CONCLUSIONS

The rewarding nature of timber as a building material has made it to be used for so many years. Timber has properties that make it stand out with many benefits compared to other building materials. These properties include its ability to be recycled, its superiority in thermal insulation as well as being excellent in dynamic behavior.

The variations in climate come with changes in temperature, humidity among many other climatic conditions. When these occur, different scenarios arise like the rise in sea levels which can lead to devastating effects such as tornados, flooding and heavy rains which can then lead to damages of buildings and other properties. The interaction of timber with the climatic variations is considered to be based on variation on temperature and moisture.

The strength and resistance of wood are two of the main factors affected by the climatic conditions, therefore the timber elements of a building need to be designed at a moisture content that is within the range that will correspond to the prevailing climatic conditions. Mold growth is the result of increased moisture content, which can be the effect of the increased moisture content and high temperatures related to the climate change. Timber must be taken through a number of tests to avoid the wrong type being introduced into the supply chain.

This work has covered the description of several nondestructive techniques used for analyzing the condition of a timber element of a building, which can serve as inspection methods for a cultural heritage building survey.

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