T.C.

ANTALYA BILIM UNIVERSITY

INSTITUTE OF POSTGRADUATE EDUCATION

CIVIL ENGINEERING

THESIS PROGRAM

DAMAGE ASSESSMENT AND FAILURE MECHANISM OF BUILDING AFTER WILDFIRE BASED ON MANAVGAT

DISSERTATION

PREPARED BY

ISMAIL SAIT SOYER

ANTALYA – 2022

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ASST. PROF. DR. HAMID FARROKH GHATTE

ANTALYA – 2022

APPROVAL/NOTIFICATION FORM
ANTALYA BILIM UNIVERSİTY
INSTITUTE OF POST-GRADUATE EDUCATION

ISMAIL SAIT SOYER, a master student of Antalya Bilim University, Institute of Post Graduate Education, Civil Engineering with student number 2023103, successfully defended the thesis/dissertation entitled "Damage Assessment and Failure Mechanism of Building After Wildfire Based On Manavgat", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Academic Tittle, Name-Surname, Signature

Jury Member (Chairman) : ……

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Director of The Institute : ……

Thesis Submission Date : …….
Thesis Defense Exam Date : …….

PREFACE

The hereby master's dissertation of Civil Engineering covers the issue of wildfire effects on building. Within the framework of this study, a literature review has been completed and various studies regarding the topic have been investigated. I would like to thank my dissertation advisor Asst. Prof. Dr. Hamid FARROKH GHATTE for guiding me during the preparation of this study. I also would like to thank my family and friends for supporting me.

22/06/2022

İsmail Sait SOYER

ÖZET

Orman yangınları gibi, yüksek sıcaklık üreten yangınlar, yapılar üzerinde olumsuz etkiler meydana getirir. Binaların yangın boyunca performansının değerlendirilmesi ve yapı elemanları için yangın güvenliği önlemlerinin sağlanması, yapı tasarımının önemli bir bölümüdür. Kurak mevsimlerde, tüm dünyada, yanıcı bitki örtüsünün bulunduğu alanlarda orman yangınları meydana gelmektedir. Orman yangınları, kontrol altına alınamadığında yerleşim yerlerine sıçrayarak, binalarda çeşitli hasarlar meydana getirebilmektedir. Bu tez kapsamında, 26 Temmuz 2021 tarihinde başlayan, ülke tarihinin en büyük yangını olan Manavgat Yangınının etkilediği bölgelerde bulunan yapılardaki, yangın etkileri irdelenmiştir. Yangın süreci boyunca, farklı yapısal sistemlerde meydana gelen hasarların mekanizmaları incelenmiştir. Yangın karşısında birbirinden farklı, çatı tiplerinin, yapı malzemelerinin, yapısal sistemlerin davranışları farklı açılardan araştırılmıştır. Yangınının etkilediği çeşitli bölgelerde bulunan, 210 adet farklı yapının performansı yapısal hasarlar açısından incelenmiştir. Orman yangınına yönelik olarak, binalar için yangına dayanıklılık tasarımı, yeterli güvenlik sağlayacak şekilde revize edilmelidir. Son olarak, orman yangını bölgelerinde bulunan binalar için, hasarlardan korunmak veya azaltmak amacıyla bazı öneriler sunulmuştur.

Anahtar Kelimeler: Betonarme binalar; yapısal hasarlar; yığma binalar; çelik binalar; orman yangını.

ABSTRACT

High temperatures producing fires, like forest fires, adversely affect structures. Evaluating the performance of buildings during a fire and providing fire safety measures for building elements is vital to building design. During dry seasons, forest fires occur universally in areas with combustible vegetation. When forest fires cannot be controlled, they can spread to settlements causing damage. In this thesis, the fire effects of the Manavgat Wildfire, starting on July 26, 2021, on the buildings in the regions affected by it are examined. During the firing process, the mechanisms of damage in different structural systems were investigated, as well as the fire-resistant building materials, roof types, installations and systems. Performances of 210 buildings in various fire regions are examined for structural damage. For forest fire, revised fire resistance designs should be provided for adequate safety. Finally, recommendations are presented for buildings located in forest fire zones to prevent or reduce damage.

Keywords: Concrete buildings; failure mechanism; masonry; steel; structural damage; wildfire.

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ABBREVIATIONS

GM **:** Google Maps

RC **:** Reinforced Concrete

CHAPTER ONE

INTRODUCTION

1.1. Overview

During the dry seasons, many areas in all of the world are subjected to combustible vegetation. These fires can spread disastrously, destroying everything residences included in their path and endangering human lives.

The Manavgat fire, which was recorded as the biggest fire in the history of Turkey and occurred in 2021, caused great damage to the residential areas as well as the damage to the forests.

Manavgat wildfire started at four different points in Manavgat on July 28 at 11:30 am, spread to some neighborhoods of Akseki, Gundogmus, Ibradi and Alanya districts. High temperature (37 centigrade degrees), low humidity (14%) increased the spreading of the fire. A strong wind blowing (50 km/h) allowed the fire to spread and grow rapidly. It took place in 21 different locations just in a day and 59 neighborhoods were severely damaged. After 220 hours of struggling and trying to control with different methods, it was brought under control at 15.30 on 6 August and the cooling works continued for having the sustainable condition. Based on the governmental information, 8 aircraft, 2 UAVs, 19 helicopters, 2 management helicopters, 1 unmanned helicopter, 1915 vehicles and 8,155 personnel took part in the fight against the wildfire. Additionally, a large number of volunteer citizens came to the area to help the people subjected to the fire. As a result of the wildfire; 7 people lost their lives, 821 people were affected by smoke, thousands of hectares of forest and agricultural land areas were damaged, as well as many animals have been lost their lives.

1.2. Aim of the Research

It is to examine the damage mechanisms of the buildings affected by the wildfire according to the building types and to illuminate the points to be considered regarding the structures to be built in the fire zones.

1.3. Motive and Significance of the Research

It is known that natural disasters have an uncontrolled and destructive effect. Facing any of these disasters unprepared results in serious loss of life and property. Contributing to minimizing the loss of life and property in a fire disaster is the most important motivation source of this study.

1.4. Limitation of the Research

There are a number of limitations in this study. The fact that the fire and fire extinguishing work continued during the research has limited the number of buildings examined.

Moreover, the fire happened in the hottest and driest days of the summer months which led to experiencing even higher ambient temperature felt along with the heat caused by the fire. This situation, combined with smoky air, limited the time spent in the research areas.

Additionally, the rapid demolition of the hazard causing heavily damaged structures not only made it rather hard to study the mentioned structures but also decreased the number of study subjects.

And finally, the Covid-19 situation and restrictions it brought with itself have caused difficulties in transportation and communication.

1.5. Wildfire History in Manavgat

The wildfires that took place in Manavgat go down in history as the biggest fires of Turkey. In the forest fire that started 13 years ago, on July 31, 2008, in the Taşağıl town of Manavgat and lasted for 6 days; 16 thousand hectares of land were destroyed, 77 houses and 88 barns, 1 primary school, 1 mosque and 1 village mansion were severely damaged.

CHAPTER TWO

LITERATURE REVIEW

2.1. Articles On the Effects of Fire on The Structure

It is crystal clear that preventing wildfires from spreading is a vital issue. A series of factors influence the wildfire that it is not easy to keep under control, such as weather conditions (wind in terms of speed and direction; humidity; temperature) [1].

The wildfires can destroy the buildings and infrastructure of a subject community. On the other hand, several factors can influence building through the wildfires, including its location, the material's flammability and the design and buildings materials [2].

In the areas surrounded by combustible vegetation, fire protection of the structures is one of the main issues. So many design codes consider the safety of the structures in case of fire [3].

A proper structural analysis provides the tools to design a structure to support its loads safely. Most of the current design codes are mainly based on seismic actions and natural disasters as well as improving their performance for these purposes [4, 5].

However, another main issue is the consideration of fire since the ability of the structures to maintain their strength and stability throughout the fire have the same importance as well. Investigations related to the structural damage in wildfires are extremely limited [6].

The main focus in literature in the field of the behavior of buildings during the fire is the using models of buildings as well as the examination of conditions exposed to the fire [7].

Improving the fire performance of structural insulated panel core materials has been investigated by Li et al. [8] and the results showed the use of flame-retardant adhesives can lead to a sufficient fire safety level for the core material without affecting its functions. The effect of geometry and dimensions on the upward fire spread in U-

shaped structures has been investigated by Chen et al. [9] and the study provides a theoretical guide for the fire protection design of u-shaped structures covered with insulation materials in practical engineering. The behavior of a full-scale steel frame building has been investigated by Lamont et al. [10] in terms of structural stability. On the other hand, a fire model was used for the evaluation of the development and displacements of the strain in structural elements subjected to the fire. Numerical modeling and finite element models have been employed for structural and thermal numerical investigation based on a full-scale building subjected to fire test. Similarly, an investigation has been conducted by Wald et al. [11] based on the distribution of forces within different structural members of a steel-concrete composite frame construction through the fire test. Foster et al. [12] investigate the thermal and structural performance of a full-scale composite building subject to a severe compartment fire. Numerous damage assessment studies of the structural elements and connections that have been conducted after earthquakes provide invaluable data to investigate the performance of buildings during the seismic actions [13, 14], to the evaluation of the code criteria. In the case of understanding the damage assessment after a wildfire, few investigations have been done in the last decade [15].

The detailed damage assessment studies provide examples of deficiencies observed in various buildings. Furthermore, the countries are updating their codes and standards by introducing performance-based fire safety design provisions. In the case of the effect of high temperature on compressive strength, fire protection and materials as well as the modeling by using different methods a series of studies have been done to estimate or improve the understanding of their performance throughout the fire [16-19].

As modern technology, automation in fire safety engineering using Building Information Modelling (BIM) had a dramatic impact on the construction industry over the last decade [20]. The results showed significant changes with increasing temperature and cause a remarkable deterioration in the microstructure and compressive strength. In terms of the structural performance of flexural and shear responses of prestressed concrete slabs under fire conditions, as well as fire behavior of hollow-core concrete slabs, have been investigated considering a finite element model that exploited solid elements [21-23]. Results from the parametric studies showed that the specification of the slabs like

depth, load level, loading pattern, axial restraint, level of prestressing as well as fire scenario has a significant influence on the fire response of slabs and failure mechanisms.

2.2. Results of the Literature Review

In light of the above-mentioned literature review, it is crystal clear that the understanding of the fire effects on different types of existing structures and materials as one of the most critical topics considering climate changes that cause wildfire in all of the world was not studied extensively in the literature. In this research the results of 210 different buildings in Manavgat, Turkey were examined in terms of the performance and structural damage conditions that exposure to wildfire. Therefore, the behavior of different construction materials and systems are investigated as a case study. This wildfire was one of the deadliest wildfires that have occurred in Turkey on July-August 2021. On the other hand, the seismic performance of the existing buildings after a wildfire is another vital topic, since turkey is subjected to big earthquakes as well. Moreover, it seems presenting the basic guideline for wildfire and protection methods will prevent or reduce the efficiency of wildfire on buildings.

CHAPTER THREE

BUILDINGS AND FIRES

3.1. Design Parameters

Lightning, damaged power cables and people's activities are the main reasons for a wildfire that can spread uncontrollably, destroying a large residential area. The performance of a building subjected to fire relies on different parameters, including materials, the temperatures improvement and the continuance of fire. A nominal fire is represented as a curve of gas temperature with time (e.g., ISO 834-1 [24]). This is independent of fuel and conditions for ventilation and continues with time without decaying. A simplified method can be employed for the prediction of the gas temperatures, such as one or two-zone models and computational fluid dynamics. Nominal fires are usually used for design purposes.

In structural design, fire is treated differently all over the world, where the material is so talented to burn the efficiency considered higher than other places that this capacity is not that high. Structures exposed to fire loads generally are examined mainly in the ultimate conditions and it is sufficient to only analyze parts of the structure without the need to examine the whole generally without consideration of wildfire.

3.2. Behavior Of Construction Material In Fire

In this section, a summary of the properties, behavior and investigation of the resistance of fire for any construction materials composing the structural systems of the buildings is represented. The efficiency of a fire on the performance of materials can also be identified as the effects of fire actions directly and indirectly. Generally, the damages from indirect fire actions occur in case of thermal expansion and deformation. In the following section, the behavior of concrete, steel, timber and masonry material was discussed mainly in terms of structural materials.

3.3. Concrete and Reinforced Concrete Expose to the Fire

The behavior of concrete is directly related to aggregates, cement and water. For reinforced concrete, the behavior of rebars will be another issue. The low thermal conductivity caused to considered to be noncombustible. When it consists of carbonate or lightweight aggregates the fires can improve. Below 500 °C as a temperature of concrete, is not affected on concrete strength while above 500 °C, the compressive strength of concrete begins to reduce based on the direct fire effect. This reduction of strength is higher in the case of high-strength concrete. In terms of modulus of elasticity the same condition is happening and it will reduce with an increase in temperature, mainly at temperatures lower than 200 °C. By cooling down the temperatures of concrete, it starts to regain the main part of its strength. Rebars are protected by the cover concrete if it is still in place. Therefore by spalling the cover this efficiency cannot be available anymore. When they are exposed to fire, their yield strength is reduced dramatically above 400 °C. When rebars cool down, they regain the main part of their strength [25]. The color of the concrete after exposure to the fire can give a good estimation of the temperature of the surfaces. Although there is no real color change below 300 °C, above 300 °C and below 600 °C, the color can be almost pink; between 600 and 900 °C, the color can change to gray; and above 900 °C it is buff-yellow. Smutting of the concrete can appear even below 300 °C. By increasing the temperature if thermal expansion is restrained the probability of the large axial forces will increase. Spalling of the cover concrete is the main damage type that can occur in reinforced structures and cause the corrosion of rebars. The pore pressure in the cement paste is the main reason for this phenomenon. Diagonal cracking in continuous beams, sagging of beams and slabs and cracking of columns are other kinds of damage. In the case of concrete, the fibers are melting under high `temperatures, by creating passages for the vapors to escape. It should be noted that by increasing the cover thickness the protection capacity of the rebars increases. Additionally, using fire-resistant materials can increase the capacity and safety of the buildings exposed to fire.

3.4. Masonry Buildings Expose to the Fire

In the case of comparison of the different buildings exposed to the fire, masonry buildings had better performance than reinforced concrete, steel structures, or timber structures. Leading to flaking and discoloration of the layers especially the outer layer

generally happening in the masonry building exposed to high temperatures. The material that has low porosity experiences more disruption than the material with is porous. Bricks above 400 °C experience a decrease in strength and the modulus of elasticity. The direct fire action is based on both shoot deposition and thermal oxidation of iron-containing minerals [26]. Stability in masonry structure deteriorates due to loss of mortar bond strength at high temperatures. Starting of thermal oxidation can happen at temperatures around 250–300 °C. In masonry buildings, various minerals produce different types of colors. Although this kind of action does not comprise the stability of structures, it can generate aesthetically damage and change the appearance.

3.5. Timber structures Expose to the Fire

Although, the sustainability of timber building is one of the main reasons for increasing the global demands in the recent decades due to the combustible capacity of wood, timber structures and timber materials are vulnerable to fire. When a timber structure is exposed to fire, behave differently based on the heavy and light conditions of timbers. The large-dimension members (heavy timber structures) [27] have better performance compared to the light ones in fires. When the cross-section of a timber element is big the surfaces start to burn and for a long time prepare a layer to the protection of the inner wood. The inner moisture of the wood below evaporates above 100 °C and at 200 °C, the wood starts to thermally decompose. The estimated charring temperature considered about 300 °C [3]. In the case of the direct fire action, the modulus of elasticity and strength of wood in timber structures are reduced by increasing the temperature. For increasing the resistance of smaller-dimension members against fire, protective materials such as gypsum boards and fiber cement panels can be employed. Moreover, the joints can be protected not only by being inside the wood section but also by enclosure by a gypsum board. All of the wooden plates have poor performance in the fire if they are not protected properly.

3.6. Steel Structures Expose to the Fire

Generally, steel elements are relatively thin and with high thermal conductivity compared to the other building materials. The steel members mainly perform poorly if they are subjected to fire. The yield strength and modulus of elasticity steel drop dramatically about 300 °C. In the case of direct fire action, stiffness, as well as strength

decrease almost to half values. Furthermore, restriction of thermal expansion causes large deformation and the buckling of the steel elements. The mechanical properties like strength and modulus of elasticity return to their initial conditions after cooling down when the temperature does not exceed 700 °C. When the steel elements are subjected to temperatures above 700 °C for more than 20 min, the process of oxidation will start on the surfaces, as well as loss of the cross-sectional thickness. At temperatures more than 870 °C, the features can not return to the initial conditions. Moreover, the steel elements will have less ductility and high strength and hardness. For aiming the protection of the steel elements from the fire so many methods are available; the application of certain coatings, encasement with concrete and enclosure with boards.

CHAPTER FOUR

METHOD

4.1. Case Study

The case study consists of the effects of wildfire in Manavgat-Turkey (July-August 2021) on various structural systems. In addition, the damages caused by high temperature on structural elements were investigated in different structural systems. The evaluation of the cases was made in four categories according to the structural systems: steel, masonry, reinforced concrete (RC), timber and mixed structures considering different roof types.

4.2. Location of the Occurrence of the Wildfire

Manavgat is located in the Antalya region, 75 km away from the city center of Antalya in the southern Mediterranean region. Manavgat included of 2.283 km² area with a population of 241011 people according to the 2019 datasets. One of the important tourism centers with 64 km coastline and many ancient - historical places (Figures 1-4).

Figure 1. Satellite photo of Turkey and the wildfire-affected areas (G. M.)

Figure 2. Satellite photo of Antalya and the wildfire-affected areas (G. M.)

Figure 3. The three-dimensional position of the wildfire affected areas (G. M.)

Figure 4. Close view of the first area (G. M.)

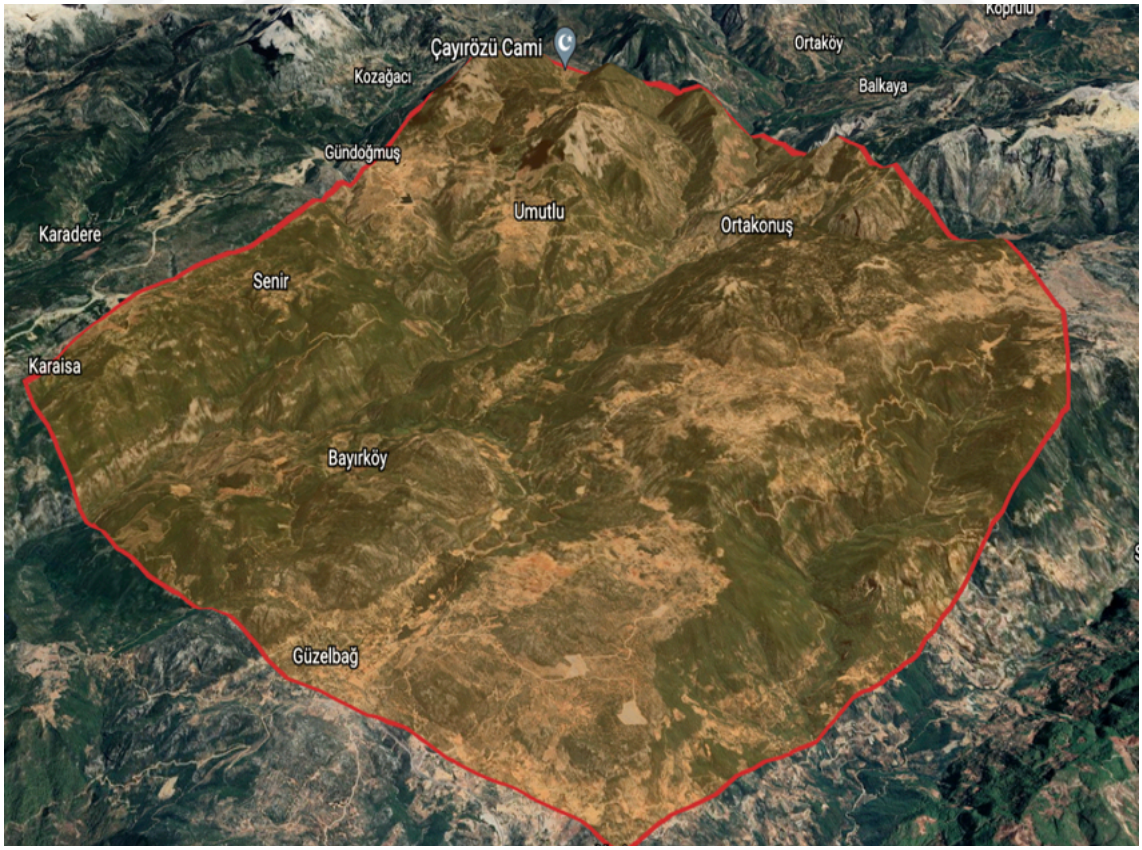

Figure 5. Close view of the second area (G. M.)

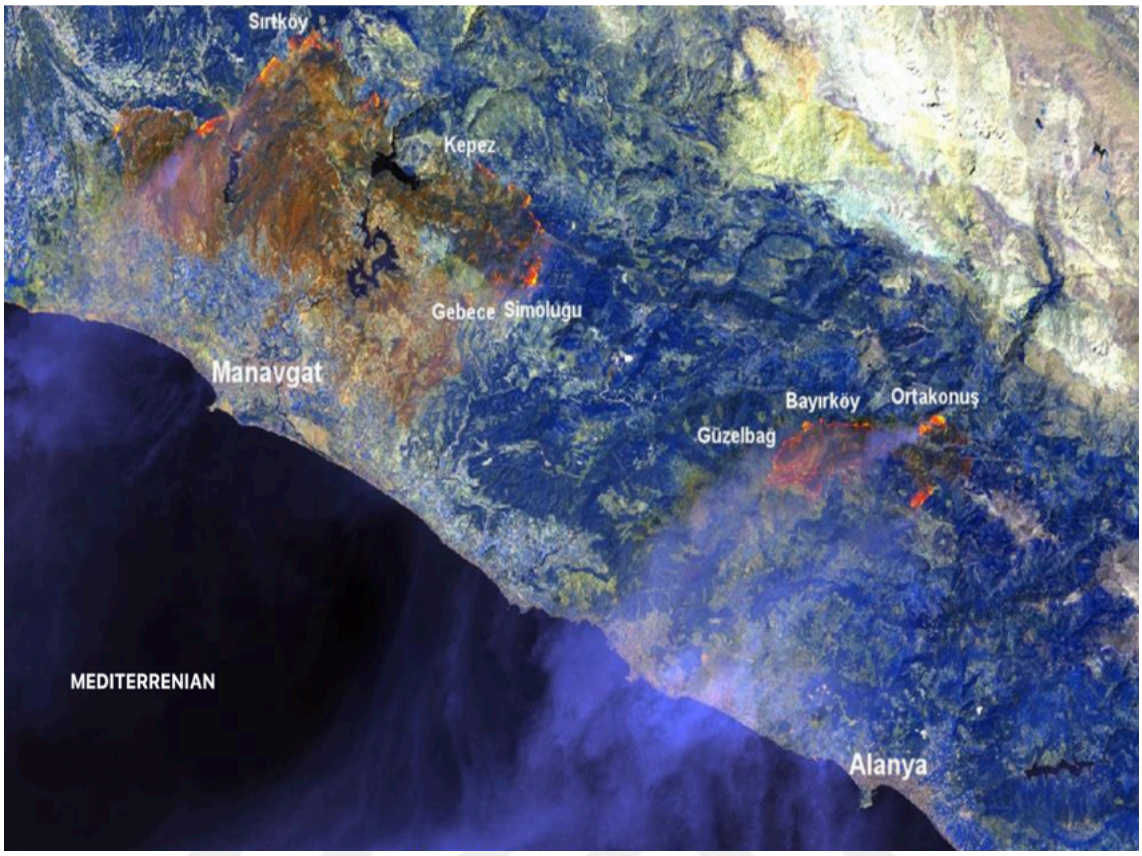

Figure 6. Real-time satellite image of Manavgat wildfire (July 31, 2021)

It was analyzed using image processing techniques on Landsat-8 OLI satellite images dated July 31, 2021, served by the US Geological Research Center (USGS) to determine the changes that occurred in Manavgat, where the fire had the greatest impact. As a result of the analysis of the Landsat-8 thermal image, it was seen that the surface temperature reached 95 °C in the areas where active fires were observed in the region where the fire incident occurred, while the seawater temperature was around 27 °C (Figure 6). Based on the analysis, it was determined that a total of 83 thousand 810 hectares of land were burned, including 56 thousand 663 in Manavgat, 12 thousand 935 in Marmaris, 11 thousand 898 in Bodrum, 1629 in Koycegiz and 685 in Gundogmus. During the last two decades, the big wildfires in the Antalya region are Manavgat and Taşağıl region in 2008 with approximately 16 thousand hectares burned area. Considering this data, the 2021 Manavgat wildfire, which caused the burning of approximately 57 thousand hectares, has been recorded as the biggest fire disaster in Turkey [28]. Many strategies and methods have been employed to control the wildfire and one of them was using the roads (Figure 7).

Figure 7. The road separates the forest area to better control fire.

A significant part of Manavgat (Figures 6-8) is covered with red pine trees, which are common in the Mediterranean climate and are highly flammable. Strong winds (between 40 km/h and 60 km/h) carried the fire to the area uncontrollably. The roads separating settlements prevented the fire from spreading in some places, but most could not prevent the fires due to the pinecones blown by the wind.

(a)

(b)

(c)

(d)

Figure 8. A part of settlements that were affected by the wildfire (a-d)

(a)

(b)

Figure 9. A part of the forestland was affected by the wildfire (a - b)

4.3. Case Study Specifications

The local structural systems in Manavgat are generally masonry and stone structures with wooden beams. During the last three decades, this style has been modernized and changed to the proper structural systems like RC frames and steel structures. Building types in general are; concrete frames with brick infill walls, masonry with wood/concrete roofs, light steel structural and mixed structures.

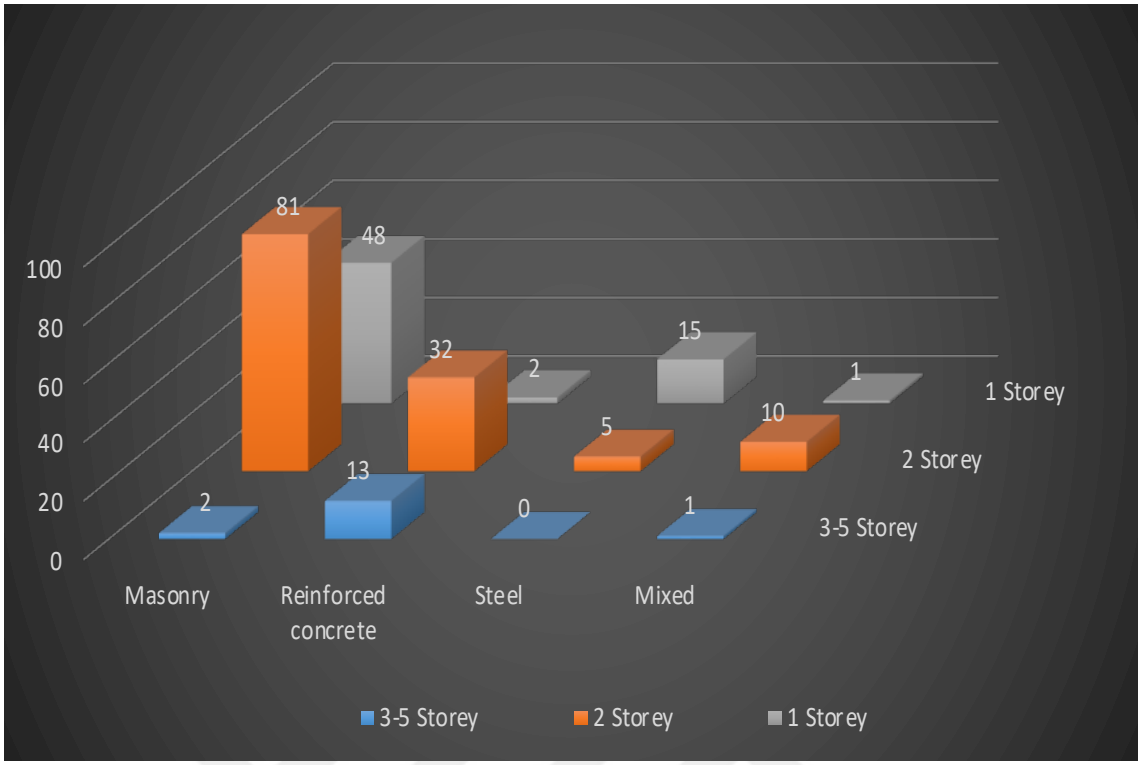

Figure 10. Number of stories and number of the buildings

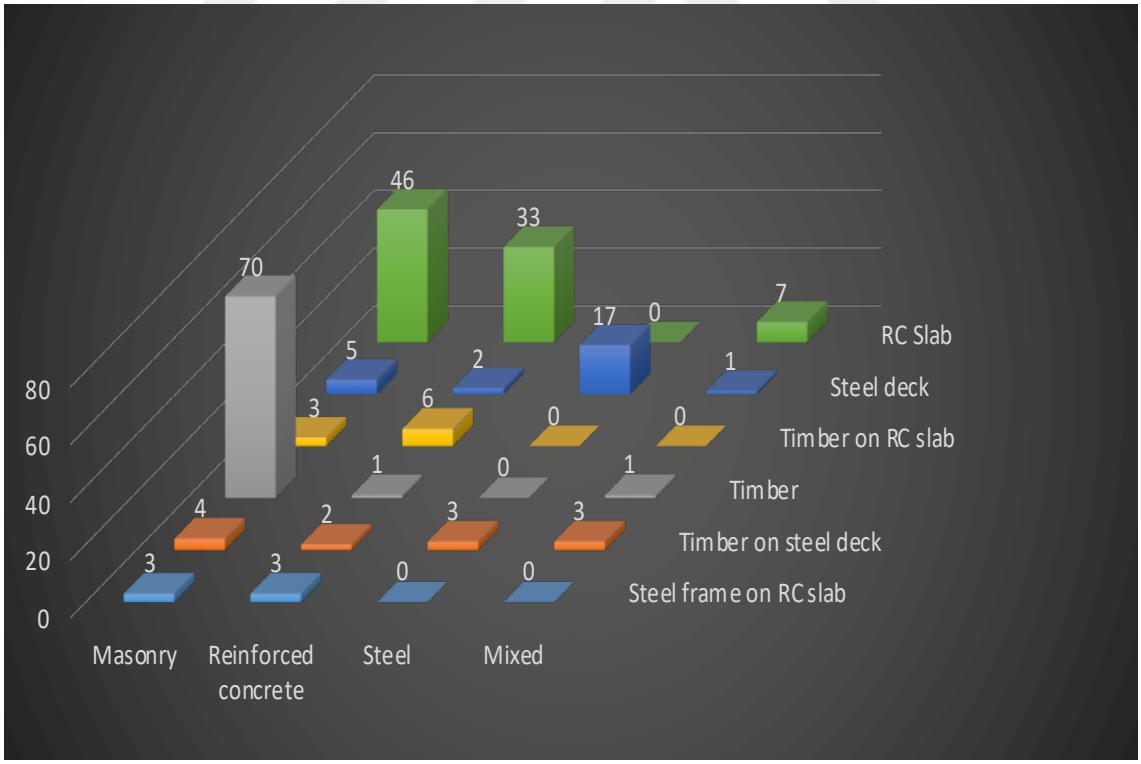

Figure 11. Number of buildings, structure types and roof types

A total of 57 neighborhoods affected by the “Manavgat wildfire” were combined with a line on google maps and the affected areas were represented in Figure 3. Therefore, two regions were investigated (Figure 3). To investigate the damage caused by the wildfire in the structures, 18 neighborhoods in 4 districts (Manavgat, Alanya, Akseki, Gundogmus) were considered that were affected by the Manavgat wildfire. 210 different buildings in various areas that were heavily damaged in the wildfire were examined. Most of the buildings affected by the wildfire were 1-2 story buildings based on the situation in forested areas and settlements close to the forest. Near to the city center, the number of the story in the buildings increases. Among the 210 buildings, in terms of quantity, the first part is 1-2 story masonry buildings, the second part is 2-5 story RC buildings, the third part is 1-2 story steel buildings and the fourth part is mixed structures. (Figure 10). Figure 10 shows the distribution of story numbers of the 210 examined buildings in terms of types of structure. The buildings were mostly without any design project and engineering control during the construction process. For this reason, by the time people have made an addition to the existing buildings based on their needs and possibilities. Masonry, reinforced concrete and steel structures mainly were the different types of building systems. Structures within two types of structural systems are considered as a scope of mixed systems. In the buildings examined in this study, it has been observed that the roof systems have great importance on the effects of fire on the building. It has been observed that fires reaching the building from outside, such as forest fires, start from the most vulnerable part of the building and spread. The strength of the building and its exposure to fire is closely related to the starting point in the building. The fire mostly reached the residential areas through trees. In buildings with wooden roofs, the fire mainly started from the roofs. In buildings without RC slabs under the roof, the fire could penetrate easily enter the building. By burning the inside items in the building, the exposure time of the structure system to fire and their efficiency increased. In this study, the classification of roof types were made as follows; RC slab (an RC slab covers the top of the building), Steel deck (Light steel profile and sheet material cover the top of the building), timber on RC slab (a wooden roof on the RC slab), Timber (only a wooden roof covering the top of the building) and timber on steel (wooden boards placed on a light steel profile cover the top of the building). Steel frame on RC slab (there is a light steel roof above the RC slab that covers the building). The majority of masonry buildings have timber roofs and RC roofs at the same time which has a great effect on spreading

the fire. While RC slab and wooden roof simultaneously could control the spreading better than wooden roof by itself. Most of the RC buildings have RC roofs that had a better performance than wooden roofs during the fire. In the case of compatibility of structural systems and roofs, most of the steel buildings had steel roofs, while most of the mixed structures have RC roofs. (Figure 11)

4.4. Damages and Failure Mechanisms

In the following section, damage mechanisms of structural elements with all of the observed details have been investigated in the Manavgat wildfire in their categories.

4.4.1. Reinforced Concrete Structures

Fire deformation in RC systems mostly occurs in reinforcing bars after spalling of the concrete cover as a secondary effect of fire. This condition is much more important in the case of less covered bars with concrete. Due to the low heat resistance of reinforcing bars, it deforms in high temperatures fires. Although it is protected because it is inside of the concrete, its deformation becomes inevitable as the exposure time increases. Reinforcing bars located in the regions of bearing elements (beams, slabs) were subjected to tensile stresses that have undergone deformation due to high temperature. Therefore, it has been observed that bending deformation happened due to the decrease in strength in the regions where tensile stresses are high. (Figure 12). In some cases, as presented in Figures 11 and 12 superficial vertical and horizontal cracks happened in the faces of the structural elements as well as the color of the surface was changed according to the exposure time to high heat. In other cases, it was observed that shell concrete was spalled in some reinforced concrete columns where high temperature negatively affects the continuity between bars and concrete and the concrete on the surface deforms faster due to the exposure to fire. As can be seen in Figures 13 and 14 the plaster which was made to obtain a flat surface on reinforced concrete was separated from the concrete surface when subjected to the effect of high temperature. Therefore, high temperature disrupts the continuity between concrete and plaster. Moreover, it was observed that there were separations and deep cracks in columns to shear walls, beam to the wall and slab to wall connections. It shows that high temperature changes the properties of the mortar bonding material and causes separation, especially in cold joints. In addition, the separation of

structural and nonstructural elements has been reported severally and caused many continuity problems (Figure 15).

(a)

(b)

Figure 12. Deflection in horizontal bearing elements- slabs and beams (a and b)

(a)

(b)

Figure 13. Damages in vertical bearing elements-column (a and b)

Figure 14. Vertical and horizontal cracks

Figure 15. The separation between walls and frame

(a)

(b)

Figure 16. Spalling plasters and damages on concrete (a and b)

4.4.2. Masonry Structures

In masonry structures, fire primarily destroyed roofs, wooden beams and floors. The burning of the timber structural elements used the changing of the balanced condition of the system. The unbalanced situation causes the disconnection of the joints and local failures. In many cases, reinforced concrete floors lost their capacity and collapsed or had deformation based on the instability conditions of the masonry walls. Due to the low heat resistance of reinforcing bars, it deforms in fires in high temperatures. Although it is protected because of the cover of concrete, its deformation becomes inevitable as the exposure time increases.

The local structural system of masonry buildings in Manavgat is mainly based on masonry stone walls with wooden beams located inside of the wall (Figures15, 16 and 17). Unfortunately, when the beams were subjected to fire, the stability of the masonry walls dramatically led to failure. In some cases, the slabs (reinforced concrete slabs) could control the rate of fire in the safe direction where the wooden roof and beams were quickly subjected to fire and failure.

The observation of the cases showed that the separations and deep cracks in wall-to-wall connections, slab to wall joints happened severally in masonry buildings (Figure 19). Therefore, high temperatures destroy the properties of the mortar and bonding materials and caused the separation of the walls especially in terms of vertical and horizontal separation in wall joints (Figure 15,16). Another observation expressed that the plaster, which was made to obtain a flat surface on walls, was separated from the walls based on the effect of high temperature. It shows that high temperatures destroyed the cohesion between the wall and plaster not only on the inside of the building but also on facades (Figure 20 and 21). Generally, all of the structural systems are subjected to spalling of plasters in the facade as well as inside of the buildings based on the different temperatures and materials. (Figure 16)

(a)

(b)

Figure 17. The collapse of the RC slabs based on the failure in the walls (a and b)

(a)

(b)

Figure 18. Timber beams, slabs and roofs have been destroyed by fire (a and b)

(a)

(b)

Figure 19. The materials lost their qualities, deep cracks and separations (a and b)

Figure 20. Deep cracks in the facade

Figure 21. Inside spalling of plaster

4.4.3. Steel Structures

In the case of steel frame structures, fire mainly damaged timber slabs and roofs, then horizontal steel elements. Vertical steel elements had less interaction with fire compared to the horizontal elements resulting in fewer damages. As the cross-sectional ratio of the steel elements increases the fire resistance is increased as well to cause a better performance during the wildfire.

Buckling in the steel columns has been observed severally in steel structures. It should be noted that most of the steel structures have not been supported by the current seismic design codes. In addition, vertical steel elements had buckling due to high temperature and losing their compressive strength.

The deformation of the structural elements increased by increasing the exposure time to the fire (Figure 22). Deflection in steel beams was severally observed on the horizontal steel elements that were subjected to bending moments and high temperature at the same time. This kind of element lost its tensile strength and the deformation increased by increasing exposure time to fire. (Figures 23-25.)

Another failure type in the case of steel structures was damage to masonry walls and steel beams. The timber slabs and roofs were burned by fire and drywall sheets were separated from the structural parts and spilled because of the fire.

(a)

(b)

Figure 22. Deflection and buckling in steel elements (a and b)

(a)

(b)

Figure 23. Damages in walls and slabs (a and b)

(a)

(b)

Figure 24. Damages in partitions, walls and roofs (a and b)

(a)

(b)

Figure 25. Damage and deflection in steel elements

4.4.4. Mixed Structures

Although the main kind of structural systems was reinforced concrete, masonry and steel structures, a group of buildings had more than one structural system. Therefore, the buildings that have two structural systems were considered mixed structures. These buildings consist of four different materials: brick wall, stone wall, briquette wall and light steel, as well as mixed structures, consisting of reinforced concrete and masonry stone walls as well.

Separation at wall-to-wall joints and structural irregularity were observed. (Figure 26-27). At the connections of the reinforced concrete and steel structure, the concrete separated from the rebars due to the high temperature.

It has been observed that in the mixed system consisting of masonry (brick and stone) and reinforced concrete with different materials, deflection occurs in horizontal reinforced concrete elements (beam, slab) more than other elements (Figure 28).

Another observation showed that the slab in the buildings consisting of masonry and reinforced concrete with stone walls lost its stability and collapsed based on the deflection of beam and slab that subjected to the fire (Figure 17). Deep cracks and separations in the load-bearing stone wall are severally observed in this kind of buildings (Figure 29).

In the mixed system consisting of masonry walls and steel, the plasters on the walls were separated from the steel section and steel elements had big deformation exposed to the fire (Figure 30). As seen in the photos (Figures 26-31), different types of structural materials presented the numbers as different systems.

Figure 26. Damages in the mixed materials (four types of materials)

Figure 27. Damages in the mixed materials (two types of materials)

Figure 28. Damages in the mixed concrete structures (slab)

Figure 29. Damages in the mixed structures (beam and slab)

Figure 30. Damages in the mixed materials (two types of material)

Figure 31. Damages the in the mixed materials (two types of material)

4.4.5. Evaluation of the Roofs

As a main component of the building during the wildfire, the roof has been investigated separately based on the different types of roofs and their performance throughout the fire action.

In buildings without reinforced concrete slabs under the wooden roof, the fely destroyed the roof and the elements inside of the roofs filed throughout the buildings and timber slabs (Figure 32).

In buildings with reinforced concrete slabs under the wooden roof, it has been observed that although the wooden roof was destroyed, less destruction occurred compared to the buildings that had not no reinforced concrete slab under the wooden roof (Figure 33).

In addition, in reinforced concrete slabs with low strength concrete and low reinforcement ratio collapse and failure happened severally (Figure 34).

It has been observed that timber roofs on steel decks were burned and the tiles were collapsed or deformed. By increasing the fire exposure time, deformations increase in steel elements with the insufficient cross-sectional area (Figure 35).

Generally, as the cross-sectional area decreases in light steel roofs, the resistance to heat decreases and visible deformations occur in the steel bars that are mainly not designed properly based on the updated design codes (Figure 36).

(a)

(b)

Figure 32. Timber roof without reinforced concrete slab (a and b-totally destroyed)

(a)

(b)

Figure 33. Timber roof with RC slab (a and b-destruction)

(a)

(b)

Figure 34. Reinforced concrete slab roofs (a and b)

(a)

(b)

Figure 35. The timber on steel roofs - totally destroyed (a and b)

(a)

(b)

Figure 36. Light steel roofs-totally destroyed (a and b)

CHAPTER FIVE
CONCLUSION

5.1. Findings

1. The main failure mechanisms in reinforced structures; spalling of the cover of the reinforced concrete, losing or decreasing the bending capacity of the beams and slabs that caused main deflections and high temperature changed the properties of the bonding materials. Vertical and horizontal disconnection and deep cracks in column-wall, beam-wall, slab-wall joints.

2. The main failure mechanisms in masonry structures; fire primarily destroyed roofs, wooden beams and floors then disconnection of the joints and local failures, separation at wall-to-wall joints and structural irregularity the stability of the masonry walls had dramatically led to failure, high temperature destroyed the cohesion between the wall and plaster.

3. The main failure mechanisms in steel structures; vertical steel elements had less interaction with fire compared to the horizontal elements resulting in fewer damages, vertical steel elements were subjected to buckling due to high temperature and losing their compressive strength, the timber slabs and roofs were burned by fire and drywall sheets were separated from the structural parts and spilled.

4. The main failure mechanisms in mixed structures; are separation at wall-to-wall joints and structural irregularity, plasters on the walls were separated from the steel sections and the steel beams had big deformations, losing the stability and collapsed based on the deflection of beam and slab.

5. In buildings with reinforced concrete slabs under the wooden roof, although the wooden roof was destroyed, less destruction occurred compared to the buildings that had no reinforced concrete slab under the wooden roof.

6. Generally, in all of the structural systems separation of structural and nonstructural elements has been reported.

7. In many cases, reinforced concrete floors lost their capacity and collapsed or had deformation based on the instability conditions of the masonry walls and wall to wall or beam to column connections.

8. In buildings with steel roofs, wooden materials were burned and the steel elements that were subjected to the fire had a great reduction in terms of resistance and caused irreversible deformations especially in thin-section steel elements.

9. Almost in all of the structural systems, spalling of plasters in the facade as well as inside of the buildings is severally observed based on the different temperatures and materials.

5.2. Results And Suggestions

In light of the observations, the effects of extreme temperatures on various structural systems and materials were reported during the wildfire in Manavgat, Turkey (July-August 2021). A group of 210 different systems of buildings was examined in terms of the performance and structural damage mechanisms that occurred in the buildings exposed to the above-mentioned wildfire.

The seismic performance of the existing buildings after a wildfire is another vital topic since Turkey is subjected to big earthquakes. Moreover, it seems presenting the basic guideline will prevent or reduce the efficiency of wildfire on buildings.

Fire resistance design code for the buildings that enthuses natural disasters should be revised to have enough safety in life and economy.

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