Journal of Architectural Sciences and Applications
JASA 2023, 8 (1), 85-99.
Research article
e-ISSN: 2548-0170
https://dergipark.org.tr/en/pub/mbud

Wood-Based Hybrid Construction Technology

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Abstract

Although the use of different building materials in a single construction system is a well-known technology and the design principles of hybridization are similar from the past to the present, they are explained with different concepts in literature, and there is no single comprehensive systematic classification. This study, which is open to development in this respect, classifies hybrid structures whose main material is wood according to hybridization levels and the parts they are used in the building, and each category is evaluated in detail. In determining the measures, parameters affecting the building's performance were taken into account. In the research, secondary data gathered with quantitative approaches were evaluated using a qualitative method. The study aims to create a comprehensive technical guide on wood-based systems and to achieve linguistic unity in the related literature. In this context, the difference between the uses of a single building material and a hybrid system is evaluated with their strengths and weaknesses in the context of factors such as heat, humidity, acoustics, and fire. The hybrid systems presented in the study are modern systems that are frequently applied today and are open to diversification through development.

Keywords: *Wood-based construction, hybrid construction technology, timber structure.*

Ahşap Esaslı Hibrit Yapı Teknolojisi

Öz

Yapı malzemelerinin tek bir yapım sistemi bütününde bir arada kullanılması yeni bir teknoloji olmamasıyla beraber ve geçmişten günümüze hibritleşme tasarım prensipleri benzer olsa da, literatürde farklı kavramlar ile açıklanmakta ve kapsayıcı bir sistemli sınıflandırması bulunmamaktadır. Gelişime bu yönüyle açık olan bu çalışmada ana yapı malzemesi ahşap olan hibrit sistemler, yapıda bulundukları bölümlere ve hibritleşme seviyelerine göre sınıflandırılmış ve her bir kategori detaylı olarak değerlendirilmiştir. Değerlendirme ölçütlerinin belirlenmesinde yapının performansını etkileyen parametreler dikkate alınmıştır. Araştırmada, nicel yaklaşımlarla toplanan ikincil veriler nitel bir yöntem kullanılarak değerlendirilmiştir. Çalışmanın amacı ahşap esaslı sistemler konusunda kapsamlı bir teknik kılavuz oluşturmak ve literatürde bu konuyla alakalı bir dil birliği yaratmaktır. Bu bağlamda tek çeşit yapı malzemesi kullanılması ve hibrit bir sistem kullanılması arasındaki fark, güçlü ve zayıf yönleri, ısı, nem, akustik ve yangın gibi etkenler bağlamında değerlendirilmiştir. Çalışmada ortaya konan hibrit sistemler günümüzde uygulanmakta olan modern sistemlerdir ve geliştirilerek çeşitlendirilmeye açıktır.

Anahtar Kelimeler: *Ahşap esaslı konstrüksiyon, hibrit yapı teknolojisi, ahşap yapı.*

Citation: Barış, R. & Gür, N. V. (2023). Wood-based hybrid construction technology. *Journal of Architectural Sciences and Applications*, 8 (1), 85-99.
DOI: https://doi.org/10.30785/mbud.1195433

Received: *27/10/2022* – ***Accepted:*** *07/04/2023*

1. Introduction

A structure is built of the systematic differentiation of all the parts it includes, as well as the construction of these parts while keeping this distinction in mind. This differentiation results in evaluating each section separately and obtaining more systematic data. These sections can be counted as system, building, unit, part, component, and ingredient. This study aims to gather the weakness and strengths of wood hybrid constructions compared to other modern systems. While defining them, their hybridization levels were classified according to the way they come together in different levels such as building-level hybridization, system-level hybridization, and component-level hybridization to become a full-fledged construction. In this article, hybrid wood construction systems are elaborated on by classifying them and taking into account the most suitable parts of the construction, which are the building, system, and components.

As a traditional and well-known construction material, wood has been used with not only conventional methods but also advanced technological methods for decades in many regions all over the world. Given that wood has the potential that can be placed in both the tensile and compression zones of the component, it performs high durability despite its lightness. Therefore, wood can be used in any section considering the sustainability and aesthetic purposes to meet the rigidity and other mechanical performance requirements when it comes to hybrid constructions.

The main purpose of hybridization is to provide and gather the most effective properties of every material in one system. As a result of this process, the system is expected to be more possible to prefabricate, construct/deconstruct, and afford with comparatively higher quality of mechanical properties than using a single material (Schober &Tannert, 2016).

Compared to construction systems consisting of only steel material, it has been understood that a wood-steel hybrid system will perform better, especially in fire, when similar precautions are taken. Compared to the building systems consisting of only reinforced concrete, it has been determined that wood-reinforced concrete hybrid systems perform particularly well in acoustic and thermal insulation, and in most cases, they are more efficient models in terms of reducing the dead load of the structure and increasing the tensile strength of the system, when similar precautions are taken. Compared to only timber structures, with similar precautions, wood-based hybrid systems can perform better or similarly in some respects (for instance, wood-reinforced concrete slabs have the same acoustic performance as wood slabs with less thickness, or similar loads can be carried with thinner column-beam measures in steel-reinforced wood hybrid systems).

2. Material and Method

The study used a qualitative method to assess secondary data gathered through quantitative approaches. A new categorization for wood-based hybrid constructions was proposed after conducting a review of the literature and using content analysis. This study which consists of three stages is a summary of a M.Sc. thesis in which wood hybrid construction technologies are presented and supported by application examples.

In the first stage of the study, a comprehensive review of the literature was conducted to identify applied or wood-based hybrid construction technologies that were suggested based on laboratory tests. These data were used to define the hybridization levels in the second part, and by identifying the relevant evaluation criteria, an evaluation model that contains the necessary design data for each construction system was created. In the third stage, the findings were examined and the strengths and weaknesses of wood-based hybrid construction systems were compared with systems using one-type material (wood or steel, or reinforced concrete). The second and third parts of the study contain a strong base potential for future studies and are open to development.

3. Literature Review

A hybrid is an alliance between two things with different origins. In structural engineering, the term "hybrid" refers to a component, system, or building that combines two different materials or systems to maximize certain characteristics of each and produce a whole that is better than the sum of its parts (Fast, 2014). In literature and application examples, the terms hybrid and composite have both been used to describe this combination method. However, as the term hybrid is relatively new, it is more often used for new technologies.

Moreover, Foster, Reynolds, and Ramage (2016) identified different terms to refer to this technology, such as mixed and composite structures. They created a hybrid category by considering the placement of various materials along the height of the building. If two or more materials are utilized together along the height of the building, it is considered a composite structure. If one material goes through just a few stories and the other stories are built with different materials, it is named a mixed structure.

Alternatively, Salvadori (2021) made a hybridization classification mainly dividing buildings into post and beam systems or panelized systems, taking into account subsystems of the structure such as podium and core. As a result, there are now 32 building categories for mid-rise wood-based construction.

The first attempt to combine concrete and wood was made in 1939 by Otto Schaub, who developed a wood-concrete composite floor system using H and Z-shaped connectors (Ali et al., 2017).

Bella and Mitrovic (2020) researched the acoustic characteristics of cross-laminated timber (CLT) systems. Their study found that in masonry structures, the presence of a CLT-paneled exterior increased strength by 40% and ductility by 100%. Furthermore, when CLT panels were applied in a building that was severely damaged in an earthquake, the system's rigidity can be rephrased to an almost undamaged, pre-earthquake state. When CLT panels were hybridized with reinforced concrete structures via anchored dowel connections, the system showed good performance.

Selle et al. (2010) studied different approaches for hybrid concrete-wood floors. As the adhesion between timber and concrete is critical, the researchers analyzed this parameter by taking into account the connector types and the moisture effects on the timber surface. The results showed that fresh concrete does not pose a danger of moisture damage to wood.

Winter et al. (2016) examined timber-steel hybrid beams and proposed 26 different beam types, which were tested. Simple flanges made from folded steel were found to be easy to produce, transport, and assemble. Additionally, cold-formed flanges were relatively lighter and cheaper than welded beams. In the context of timber-steel combination, reinforcement of the timber with steel is generally applied. To compare the mechanical performance of 5x15 cm timber beams reinforced with steel bars by making 1x1 cm grooves, Soriano, Pellis & Mascia (2016) conducted tests. The bearing capacity of reinforced beams increased from 51.1% to 79.2% compared to wooden beams.

Chang (2015) conducted an experimental test to observe the behavior of two different types of tensioned and joined timber walls related to the technique of strengthening wooden shear walls using the pre-tensioning technique. A U-shaped bent plate (UFP- U-Shaped Flexural Plate) was used to connect the shear walls. The combined shear walls are expected to successfully distribute and absorb energy uniformly.

Schänzlin et al. (2018) studied a timber-concrete hybrid system based on a frictional connection system developed by a Swiss engineering office. It is often called the "Plus-Minus-system" which consists of doweled wooden elements with varying widths of the planks. Lehmann (2004) (Weimar University) conducted some research on increasing the resistance by increasing the friction surface area between wood and concrete plates. He applied bending tests on three different fastening systems.

Dickof (2007) examined the Kanazawa M building, a combination of wood, concrete, and steel at both the structural and component level. The first floor is a reinforced concrete shear wall, the second and fifth floors are steel and wood hybrid frame supported, and the columns and braces of the structure consist of wooden elements reinforced with steel bars in the center. The wood in the beams stiffens and strengthens the beam in bending under gravity loads and prevents buckling under lateral loads and lateral rotational torsion under gravity loads. In the columns, the wood around the steel element prevents buckling and serves as a cover to safeguard the steel from fire. The design is made in the direction of the wood to take the axial load while the steel is deformed.

A new wood-concrete hybrid system (HWC box system) including a combination of solid wood and reinforced concrete for high-rise buildings has been proposed by Tongji University and UBC, taking into account the Chinese fire code limiting wooden buildings to three floors. This system is built on the principle of the main system + subsystem, which is a common structural concept for buildings in China. According to this concept, a reinforced concrete core and frame supported by shear walls on every three floors constitute the main system, while modules formed with a light wood frame system constitute the subsystem. The connections between the main and subsystem are critical units as they hold the system together and transfer shear and axial forces between the concrete and wood members. With the bolted joint, the connection of the modules with the reinforced concrete core is ensured. In this system, the connections (bolts) form the third line of defense of the system in case of an earthquake and are designed to not bend before the shear walls and reinforced concrete elements, but to keep the two systems completely connected (Kaushik, 2017).

Loss et al. (2016) studied connections for steel-timber hybrid buildings. According to this study, as the first joint typology in a wood-steel hybrid structure, there are “fully dry” mechanical joints (A-type), connections using epoxy-based resins (B-type), and mixed mechanical joints combining the resistance properties of the resin with steel elements (type C). With these several types of modular connection solutions, it is provided not only the lightness, easy repair, and reuse possibility of components but also the reduction of costs and time. Kinder & Kingsley (2021) presented some steel-wood and wood-concrete connection solutions in their study. Okutu (2019) included the results of the research in which Blass and Schlager tested the performance of different types of fasteners between reinforced concrete slabs and wooden beams.

Hein (2014) researched hybrid timber construction in terms of sustainability in tall buildings. Various connections between wood beams and reinforced concrete slabs or precast concrete slabs are presented in this study.

Margani et al. (2020) presented a sustainable design model for the seismic retrofitting of reinforced concrete structures. The model involves the addition of cross-laminated timber (CLT) facade panels to the structure to resist lateral loads. A connection detail is also included in the model to act as an energy-absorbing damper between floors, which enhances the earthquake resistance of the structure.

4. Findings and Discussion

4.1. Hybridization Parameters

The strength of the structural system of a building is as important as its ability to resist external factors and offer a comfortable space during use. Wood tends to naturally meet sound and heat insulation requirements due to its structure, but it requires specific design regulations for fire safety as it is a combustible material. Additionally, it is essential to limit the entry of water and moisture into the building and prevent them from getting trapped in the elements. Similarly, when reinforced concrete and steel materials are evaluated, their performance characteristics differ. For instance, steel is a noncombustible material, but it loses its strength by undergoing plastic deformation in the event of a fire. This factor should be taken into account when combining it with wood.

4.1.1. Fire design

Fire safety requirements necessitate that structures be built taking into account the conditions that must be met in case of a fire. These conditions include protection of the load-carrying capacity for a certain period of time, limiting the formation and spread of fire and smoke, restricting the spread of fire to neighboring structures, creating evacuation routes for the building occupants, and ensuring the safety of rescue teams. Wooden structures are generally limited to eight stories due to practical and economic constraints, but this limit can be increased in the case of hybrid wooden structures (Östman et al., 2013).

Structures must undergo fire resistance tests to prevent collapse. The fire resistance of structural elements can be obtained by supporting the design load for the entire duration required by the fire test. However, standard fire tests apply only to individual elements such as floors/ceilings, walls, beams, and columns, and do not cover connections. Under fire conditions, bolted and dowelled joints experience a negative effect on their fire resistance, as the heat transmitted into the wood from the more heat-exposed area of the fasteners leads to a localized reduction in the strength and rigidity of the wooden member (Létourneau-Gagnon et al., 2021).

The timber structure is classified as a combustible structure in IBC (International Building Code) and concrete and steel construction is classified as a noncombustible structure. In IBC, timber structures can be used in Type III, IV, and V structures. Type III, IV, and V structures are limited to low and medium-rise buildings with limited construction area: Type III allows combustible construction for internal load-bearing and non-load-bearing elements. There can be external wall mounts. Fire-resistant wood provided meet a 2-hour fire resistance rating (FRR) or has non-combustible exterior walls. Type IV (Heavy wood) is a construction method based on wood elements with minimal measures, providing a natural FRR (Barber, 2018).

Fire can reduce the cross-section, rigidity, and strength of the timber element on the burning surface, and rapid thermal degradation of wood can occur at temperatures of around 200 °C. The front surface of the charred portion is at a temperature of around 300 °C, and the pyrolysis area could be between 200 and 300 °C (Erchinger et al., 2009).

Despite having a zero fire rating for the structure, low-rise structures up to three floors high can nonetheless sustain considerable damage from a fire. For fire-resistant structures; larger or higher is permitted if it contains fire-segregated compartments, is separated from adjacent structures, or where an automatic sprinkler system is applied. Mid-rise buildings with a roof height of less than 25.91 m (85 ft) are supposed to have a 1-hour FRR (Fire Resistance Rating). Multi-story buildings (75 ft (22.86 m) or more to the highest occupied floor) are supposed to have a 2-hour FRR of primary structure, sprinkler protection, and many additional fire protection features. For buildings higher than 128 m (420 ft), fire ratings of 3 hours for load-bearing structures and 2 hours for floors are required (Barber, 2018).

When steel plates are protected from heat by surrounding elements, connections with slotted steel plates can provide high fire resistance. The rate of heat conduction in the joint zone depends on the relative exposure of wood and steel elements. The low temperature behind the charred layer also prevents the wood from decreasing in strength as it heats up (Létourneau-Gagnon et al., 2021).

During ASTM E 119 fire resistance tests, it was estimated that protected surfaces of plywood sheathed uprights delayed the onset of carbonization by 6 minutes, while surfaces insulated with mineral wool insulation delayed it by 19 minutes (American Wood Council, 2021).

There are various design solutions available for solid wood structures that are suitable for fire design. These can be broadly categorized into three types: fully exposed, partially protected, and encapsulated. In a fully exposed design, structural elements are visible from the start of the fire. In a partially protected design, the structural elements are behind a protective covering, although this coating does not prevent pyrolysis (thermal decomposition of the material) for the entire duration of the fire. In encapsulated design, adequate protection is provided to the underlying structure or substrate to reduce the onset of pyrolysis until combustion.

In both exposure and partial protection, it must be assumed that the structure will become a fuel source at some point during a fire. The implementation of these methods requires demonstrating, by a competent fire engineer with relevant experience, that the likelihood of the structure recovering from combustion is reasonable, taking into account the effect of the burning structure on fire development, the structure's self-extinguishing ability, and the structure's ability to support the loads applied during and after the fire event. Regardless of the solution offered, the residual structural members must be capable of supporting the load for either the duration of the fire resistance or the entire duration of a fire (Hopkin et al., 2020).

4.1.2. Acoustic performance

The greatest blocking of sound coming from the source of sound to the people in a place is referred to as sound insulation. If the sound source and the listeners share the same space, acoustic comfort is provided by sound absorption methods, and if they share different spaces, acoustic comfort is provided by insulation methods. If the noise associated with the insulation primarily affects the air, it's called air sound; impact sound if the sound affects a structural element; and if walking affects parts of the building such as flooring, footsteps occur (Neufert, 2014).

Wood, which is a highly absorbent material, is utilized indoors for acoustic purposes. When arranged in pieces with holes, it can absorb the proper medium or high-frequency noises (Avlar, 1995). The installation of a floating screed layer or a soft fiber covering material (such as wood) on a jointless insulating layer, which can be used for all flooring types, is a proven method of reducing the effect of footsteps that directly vibrate floors (Neufert, 2014).

Achieving sound insulation efficacy heavily depends on the many ways that CLT panels are connected, even if they have the same mechanical properties as the joint. The potential to use appropriate fastening methods to lessen vibrations that are conveyed through joints allows the transmissions to be controlled and, consequently, prevents significant acoustic insulation losses (Bella & Mitrovic, 2020).

Pitts (2000) conducted a research project aimed at identifying solutions to improve the acoustic performance of timber frame structures. The test results showed that standard wooden beam floors met the minimum Building Code standards. The addition of a drywall layer to the floor reduced airborne sound by 1-2 dB and impact sound by 3-4 dB. Wooden I-beams and metal mesh/wood flanged beams with the same other layers exhibited the same performance as solid wood beams in airborne sound insulation but performed 2 dB better in impact sound insulation.

Martins et al., (2015) tested the acoustic performance of wood flooring and wood-concrete hybrid flooring using five different samples. The study revealed that the acoustic performance of hybrid flooring solutions was better than that of wood flooring. In terms of airborne sound insulation, the difference between reinforced concrete and wood solutions without ceiling covering was 13 dB and 12 dB for the same samples with suspended ceilings. Regarding impact sound insulation, when comparing solutions with and without ceiling cladding, a 27 dB gain for wood flooring and a 21 dB gain for hybrid flooring was achieved. The study also found that simple solutions without ceiling coverings did not meet the air and impact sound insulation requirements in 24 European countries, whereas the criteria for airborne sound insulation in five European nations were achieved by wood flooring with ceiling cladding. Hybrid floors with ceiling coverings were shown to provide air and impact sound insulation in almost all countries.

4.1.3. Thermal comfort

Natural wood has a porous structure, which generally categorizes it as an impermeable building material in terms of heat conduction. However, this property may change depending on the type of wood (lighter woods conduct heat less) and the direction of the fibers (heat conductivity is relatively higher in the direction parallel to the fibers). The calculation does not account for the shrinkage and swelling of wood caused by temperature changes (Erkoç, 2004).

The thermal conductivity of wood depends on factors such as density, moisture content, fiber orientation, and knots. The thermal conductivity in the radial and tangential directions is almost the same, while the conductivity parallel to the grain is higher than the conductivity perpendicular to the grain (Glass & Zelinka, 2010).

The thermal conductivity of a building material alone cannot determine environmental comfort during the summer months. In this case, the building components' ability to absorb and release heat as a whole plays a crucial role. Therefore, it is necessary to evaluate quantities such as specific heat, periodic thermal permeability, and phase shift. A low-mass building usually has more thermal emissions than a high-mass building, meaning that there will be higher maximum temperatures inside the building during the summer months. However, wooden walls and insulation layers can improve this situation (Bella & Mitrovic, 2020).

Wood has six times more thermal insulation properties than brick, 15 times more than concrete of equal cross-section, and 400 times more than steel due to its nature. Therefore, heating/cooling costs may be high in structures built only from steel or concrete. The use of wood, which reduces the amount of energy consumed for heat management in buildings, can also prevent moisture condensation from occurring on cold surfaces (Tokyay, 2017).

Different properties of materials that may be involved in hybrid structures should be carefully examined during design. For example, for wood-steel hybrid structures at the component level, design gaps can be left between wood and steel to prevent uneven load distribution due to hygroscopic and temperature mismatches between the two materials.

4.1.4. Moisture management

Moisture poses no threat to wood or wood-based structures as long as the detailing of the buildings is done carefully. Moisture management solutions are necessary for hybrid structures, especially in the junction area details.

It was stated by Aklan (2021) that humidity management was successfully completed in the Pyramidenkogel observation tower, which was built in 2012 by Rubner Holzbau in Tyrol, Austria. Moisture management is required for the hybrid attachment points of the structure, which consists of Glulam bar members, CLT panels, and steel cross and support beams, and for areas of wood exposure to precipitation. For example, at the top ends of the columns, there are metal caps fixed to the column at intervals (to allow the wood to breathe inside) (Figure 1a). Droppers have been added to prevent water from entering the screw gaps at the wood-steel connection points (Figure 1b). The same insulation solution is found on the upper surfaces of the tower frames of the Mjøstårnet structure (Figure 2).

Figure 1. a; metal caps for columns, b; dropper detail (Aklan, 2021)

Figure 2. Metal caps for the top frame (CTBUH, 2021) (Photo: Moelven)

Indoor air contains moisture that varies with temperature. In cases where detailing is not successful, humidity in the air may cause condensation on the surface of building elements. It is crucial to prevent condensation-induced water from damaging the building elements, particularly in hybrid wooden structures where there is a risk of metal connection corrosion, weakening of wooden elements due to excessive moisture absorption, and separation of finishing layers from supporting layers.

To prevent such damages, thermal insulation must be successfully applied. The moisture barrier layer should also be positioned correctly, and designs that prevent thermal bridges should be selected (Neufert, 2014).

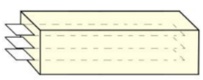
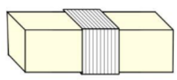
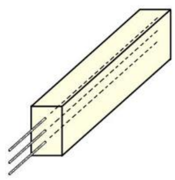
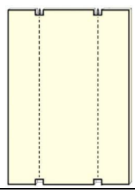
4.2. Hybridization Levels

It is possible to examine hybridization at different levels within a building. For example, this can include analyzing a component that contains two materials, a system that contains various components made of different materials, or a building that contains diverse elements made of various materials in different parts of the structure (Schneider, 2015).

4.2.1. Hybridization at the component level

Hybridization at the component level involves using two or more materials to create a single component that maximizes the benefits of each material. Examples include wood hybrid columns, hybrid beams, and hybrid wall panels. For instance, in the wood-steel hybrid system, steel is used for its tensile strength, while wood is utilized for its compressive strength. In contrast, in the wood-reinforced concrete hybrid arrangement, wood provides tensile performance, while concrete provides compressive performance. Table 1 outlines four different types of hybridization at the component level.

Table 1. Hybridization at the component level (Barış, 2022)

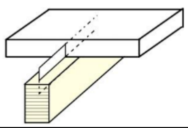
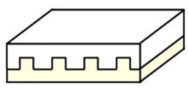
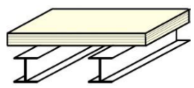
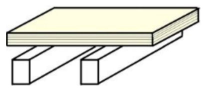
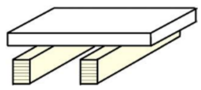
	Flitch Beam Steel plate beams are assembled inside the wooden element. Available in sheet, box, and H profile	**Belted timber** It is applied as a belt to existing wooden elements to increase the rigidity of the element	**Post-tensioned timber beam** The bars placed in the gaps in the wooden element are tensioned without being attached to the element	**Post-tensioned timber curtain wall** After being fixed in place, the rods are tensioned in the prefabricated panels where the rod positions were previously designated
				
Fire	The steel pieces are protected from fire when the wooden section proportions around the steel plate are intended for fire	The steel belt cannot fulfill its function by flowing during the fire since the element is bare	A fire design should be created to guarantee that the wood is damaged before the steel	Steel tension rods in the gaps of wooden panel components should not be left exposed and fire insulation should be made
Acoustic	Like wood-beam floors, this system provides minimum standards, and better performance can be achieved with an additional layer of drywall	It does not require an additional acoustic arrangement as it is usually applied to the individual elements in the building	The performance of the acoustics is unaffected by the steel volume's thinness	The hollow spaces where the tension rods are should also have insulation continuity
Thermal Comfort	The fact that the system consists mainly of wood requires precautions to be taken into account in wood elements	It does not require an additional thermal arrangement as it is usually applied to the individual elements in the building	The fact that the system consists mainly of wood requires precautions to be taken into account in wood elements	Massive timber panels offer adequate thermal insulation, while additional insulation in the tension holes might be necessary

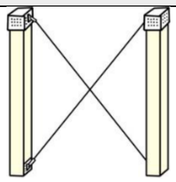
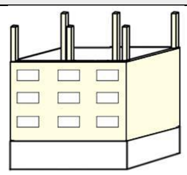
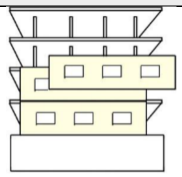
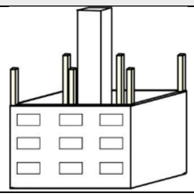
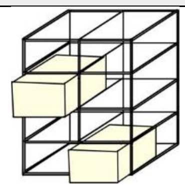
Moisture	The wooden components that surround the steel must be joined in such a way that water vapor cannot contact the steel	When employed indoors, the location's moisture insulation must be successfully applied	Especially in the case of steel, detailing in the joint regions of the elements should be planned to prevent moisture absorption into the gaps	The panels must have a permeable covering, and moisture must not accumulate where the panels attach to the tension rods

4.2.2. Hybridization at the system level

Hybridization at the system level involves integrating several components made of different materials to improve a system's effectiveness, economy, and efficiency. This approach can be used for various systems in a building, including floors, roofs, facades, cores, frames, and main/subsystems. For instance, hybrid wood bridges use this approach. Another common application is building the structure, other than the core structure, with timber and the core structure with incombustible material such as concrete due to building code restrictions for fire in some regions. Table 2 outlines ten types of hybrid construction technologies categorized at the system level.

Table 2. Hybridization at the system level (Barış, 2022)

	Timber-Concrete Ribbed Floor	**Timber-Concrete Floor Plate**	**Steel Frame with Timber Floor**	**Concrete Frame with Timber Panel**	**Timber Frame with Precast Concrete**
	It is constructed by paving fresh concrete with mesh reinforcement over wooden beams with notched screws or metal plates (HBV)	Mesh reinforcement and fresh concrete are applied on eccentric located laminated wood elements, nails as connectors between concrete and timber	Wooden panels are placed on steel beams or can be internally and externally suspended from steel H profiles	Wooden panels are positioned in these locations after the prefabricated reinforced concrete frame (or reinforced concrete precast) details of the junction points with the wood are completed	Precast reinforced concrete slabs that have joints that have been modified are fastened to the beams at the predetermined locations
					
Fire	In non-insulated solutions, wooden beam sections should be designed in measures to allow the carbonization layer/ribs can be closed with fireproof plasterboard	Fire retardant materials can be applied to the wooden part of the section measures can be designed according to the fire	The suspended ceiling or the connection details with the wooden panels can be built to leave the least amount of steel exposed, preventing direct exposure of the steel elements to the fire	The cross-sectional measures of wood flooring are significant and may have additional layers of insulation, but a reinforced concrete frame does not require any precautions	No additional insulation is needed for the concrete part since the cross-sectional measures of the exposed wood frame members are built with the carbonization layer in consideration

Acoustic	Reinforced concrete slab, insulation between ribs, and cladding board (OSB) provide good sound insulation. The concrete cross-section can be increased on uninsulated floors	This system, which exhibits better acoustic performance than solid concrete slabs, exhibits higher performance by increasing its cross-section	A timber saddle can be placed between the wooden panel system located on the metal to absorb the vibration / insulating tape can be used to separate the floor system from the walls	It shows a better acoustic performance than solid reinforced concrete floors and in insulated solutions, the acoustic layer should be continued in the wall-floor junction areas	The continuity of the sound insulation between the wooden elements should be ensured along the gaps and joints
Thermal Comfort	A thermal insulation layer can be added between the wooden ribs by supporting it with a wooden panel from below	It doesn't need an additional thermal insulation layer because of its thermal insulation property, but concrete can still receive an additional layer if necessary	The thermal insulation layer can be added between the H profiles or on the wooden floor panel; an additional insulation layer may not be necessary if the wood cross-section is thick.	The thermal insulation layer can be hidden in the suspended ceiling or applied over the wooden flooring. Thermal insulation measures are applied in reinforced concrete structures for external walls.	For both walls and flooring, an insulation layer comes between the linear wooden elements, for floors, the insulation remains inside the suspended ceiling
Moisture	There should be a film between the wood and concrete that prevents moisture in the fresh concrete from penetrating the wood section	Wood prevents moisture condensation from occurring on cold surfaces due to its high thermal insulation feature	Moisture insulation is applied between the wooden floor and the floor covering in wet areas and with a vapor barrier in the roof system	Moisture insulation is applied between the wooden floor and the floor covering in wet areas and with a vapor barrier in the roof system	There is no risk of moisture transfer from concrete to wood as it is installed with dry joints on site. Normal waterproofing is applied for wet areas
	Steel Braced Timber Frame Wooden elements and steel braces with metal caps are fixed with bolts, screws, metal connectors, or screws in timber frame systems	**Podium Structure** The system includes a podium whose first floor(s) is constructed of reinforced concrete or steel, connectors for the connection line are created simultaneously with the construction of the podium	**Facade System** They are buildings with varied materials and production processes used to create the building's structure and facade system. The carrier system is built initially, followed by the facade system	**Core Structure** The construction of the core system and the construction of the wooden construction can continue simultaneously	**Modular System** Dry jointing is used to secure the prefabricated timber modules to the field-installed steel/reinforced concrete frame structure. Except for module production, the assembly order may differ depending on how complex the system is
					

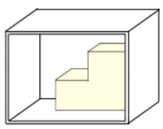
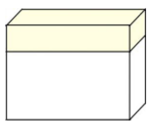
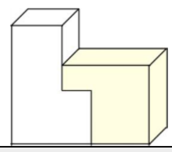
Fire	One of the methods applied to protect steel from fire is to cover the braces with a wooden sheath, fire-retardant paint can be applied to wooden and steel elements	Each material has separate fire regulations. For the hybrid system, the same regulations apply for the connections on the podium and wooden connection line as for the fire regulation required for wood	The wooden facade system doesn't exhibit a destructible feature in a fire in situations when the façade is not load-bearing. Pay close attention to the cross-sectional measurements and consider using fire retardant paints	The construction of fire-escape stairs from non-combustible materials provides an escape route during a fire without the need for additional precautions.	The frame supporting the modules must allow 120 minutes of fire escape during the fire; however, because the wooden modules do not serve as carriers, the fire has no destructive effects
Acoustic	Acoustic layers are applied to the façade, floor, and wall systems because they are typically created as a part of the exterior wall, building envelope, or lattice frame system in timber-framed structures	Insulation should be continued in the connection line between the podium and the wooden structure	It is applied in combination with the acoustic insulation facade system. The acoustic insulation layer should be continued in the junction areas of the facade panel modules	Additional layers should be applied uninterruptedly for the insulation of vibration-induced (machine, elevator, etc.) sounds between the core system and other sections	When modules are placed side by side on internal walls, the acoustic performance improves as the massiveness of the double wall increases. For exterior walls, the acoustic insulation is removed from the module walls or additional insulation is added to the facade
Thermal Comfort	The floor, wall, and facade system to be combined into the system must contain thermal insulation layers	Wood-concrete; The insulation is located between the wooden elements, an extra layer of insulation can be added for the exterior walls and continued along the reinforced concrete podium	Thermal insulation is applied in combination with the facade system. For wood-filled facades, an extra insulation system may not be required when the insulation layer is wood composite panels with insulation, such as SIPs	The wooden construction system is designed to subject to thermal insulation regulations in the relevant building code	For exterior walls, the thermal insulation is dissolved between the studs inside the module walls or constructed with self-insulating composite panels. An additional insulation layer may come under the cladding on the facade

Moisture	Protective caps, droppers, etc., must be kept intact if the construction is situated in an area subject to environmental conditions	For wood-concrete systems, there must be a separator layer (timber saddle, moisture barrier, etc.) to prevent moisture transfer at the podium junction line	In timber facade systems, there should be a layer that provides moisture control between the plywood and the cladding / when the wood is applied as a filler on the facade, sealing should be provided at the junction points with the structure	To prevent moisture transfer from reinforced concrete walls to wooden elements (if there are no additional measures), the dry joint is recommended	If the wood becomes wet, there needs to be adequate room between the modules so that it can dry out. Additionally, the structure and connections of the modules shouldn't be left exposed, and the facade might acquire an additional layer of insulation

4.2.3. Hybridization at the building level

Hybridization at the building level typically involves adding to the building while reusing historical structures to enhance adaptability. While wood is a common choice for added structures due to its lightness, the existing structure can also be made of wood. Table 3 outlines three types of hybrid construction technologies categorized at the building level.

Table 3. Hybridization at the building level (Barış, 2022)

	Add-on module into the structure Benefiting from the advantage of easy workability and assembly, the wooden attachment is formed as semi-pre-production or fully supported in place or mobile	**Additional storey** The existing structure is generally made of a more rigid material (concrete, brick, etc.). For wooden additional floors, in some cases, the attic floor is demolished and additional floors are added to the load-bearing system with a support system	**Add-on module from outside** In most cases, the existing structure and the add-on act as two different structures, so the connections are not rigid
			
Fire	Fire retardant liquid can be applied and sprinkler systems can be integrated for wooden attachments, which are usually bare for aesthetic reasons	They are built according to the height limitations of the fire regulations, they do not pose a destructive risk in fire, as they do not form the carrier system of the whole building, and they may require an additional fire escape route	Fire safety designs of existing and add-on parts are handled separately. Care should be taken to ensure that the dilatation space between the two structures is not airtight
Acoustic	Impact sound insulation is not needed, precautions should be taken at the connections for airborne sound insulation	A floating screed or a soft fiber coating can be applied on the insulation layer, especially in the first layer of flooring added	Acoustic solutions dissolve in themselves and do not affect each other, since the existing and add-on often act as two separate structures with dilatation

Thermal Comfort	Because the extensions are located indoors and the heat insulation feature of the wood, it performs well and does not require additional insulation	Since the mass of the structure to absorb the heat is increased, the thermal oscillation of the wood used should be calculated according to a hybrid whole by paying attention to the properties such as thermal permeability, density, and phase shift	Since some of the façades of the existing building that absorb and release the heat are covered by the add-on part, the thermal release of the new building is recalculated
Moisture	Indoor ventilation must be done well to prevent condensation on wooden surfaces	The connection line between the existing and new module must not be exposed and must have a vapor barrier layer under the facade cladding and a minimum gap	The connection line between the existing and new module must not be exposed and must have a vapor barrier layer under the facade cladding and a minimum gap

5. Conclusion and Suggestions

The systems discussed in this study include construction technologies that have been applied in the context of modern wood hybrid construction or have been tested in laboratory environments and put forward by scientific studies as suggested systems. Each presented system also includes inputs from new wood construction technology. The findings and results of the study, which has the potential to contribute to the development of hybrid wood construction systems, are as follows:

The efficient design of a wood-based hybrid system requires attention to the design of connection and joint details, which play a critical role in the construction.

A wood-steel hybrid system, when similar precautions are taken, performs better than construction systems consisting solely of steel material, particularly against fire. Wood-reinforced concrete hybrid systems, when similar precautions are taken, perform well in acoustic and thermal insulation and are more efficient in reducing the dead load of the building and increasing tensile strength in earthquake design, compared to building systems consisting solely of reinforced concrete material. When similar precautions are taken, wooden hybrid systems can perform better or similarly in some respects compared to only wooden structures. For example, wood-reinforced concrete slabs have the same acoustic performance as wood slabs with less cross-sectional thickness, or similar loads can be carried with fewer column-beam measures in steel-reinforced wood hybrid systems.

Hybridization at the component level involves using wood as a sheath for the steel element to increase the fire resistance of the system. It provides the same level of performance as wooden construction systems in terms of acoustic and thermal insulation and requires similar regulations. Water and moisture management are important considerations, and care must be taken to prevent water from entering the structure from the end points of the hybrid elements.

When it comes to hybridization at the system level, design principles should be applied by evaluating the suitability of each material for fire resistance, and metal connections should be designed in such a way that they do not yield before any of the hybrid elements. It is also essential to ensure the continuity of the insulation layers in the junction lines to ensure acoustic comfort. Water and humidity management are critical, especially at connection points, which should be designed with hidden joints to prevent water exposure.

It has been determined that the movement of the building as a whole is important in hybridizations at the building level, and in some cases, articulated joints may be the most efficient way to connect two separate volumes. Each module must be properly designed for fire resistance, heat, humidity, and acoustic performance, and must meet individual regulatory standards. In the context of the data obtained as a result of the research, it is possible to conclude that wood-based hybrid structures built with modern technologies offer more efficient and economical construction models in the long run than traditional building technologies in most cases.

This study facilitates the understanding of wood hybrid construction technology and provides a basis for future research. In the future, the study can be improved by expanding the classified systems.

Acknowledgments and Information Note

This study is based on the M.Sc. Thesis of R. Barış titled "Modern Ahşap Hibrit Yapı Teknolojisi ve Uygulama Örnekleri" prepared in Mimar Sinan Fine Arts University, Graduate School of Natural and Applied Sciences.

The article complies with national and international research and publication ethics, and ethics committee approval is not required for the study.

Author Contribution and Conflict of Interest Declaration Information

All authors contributed equally to the article. There is no conflict of interest.

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