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RESEARCH ARTICLE

Strength of connection profiles used in cross-laminated timber walls under seismic load

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Abstract

Cross-laminated wood (CLT) material, which has many advantages, has been widely used in architectural designs as a building element and building material in recent years. It has been proven that CLT can also show high performance against ground vibrations, but it is also mentioned in the literature that some problems such as rupture, snagging, and breaking occur in the elements used in the connections of the walls to the floor and the ground. This study was conducted to examine the performance of fasteners used in CLT walls against lateral load. In this context, 4 CLT walls were produced and then 5 metal profiles were designed to be used in the connection of these walls with the foundation ground. CLT wall and connection profiles, created according to ASTM E 72 standards, have been tested in an experimental setup with different detail options. According to the test results, it was observed that some of the CLT walls and connection profiles showed high performance at maximum load, displacement, and stiffness values. As a result, it has been determined that the resistance of the CLT material against lateral earthquake load can be increased with the right fasteners, and the collapse time of the structure in the event of an earthquake can be indirectly extended.

1. Introduction

Human communities have been benefiting from the multifunctional, strong, easy-to-use, aesthetic, sustainable, and renewable advantages of wood for years and use wood as a building material [1]. In the past, wood was used only as a natural building material in residential buildings, but today it is used as a structural element in many different projects [2]. The reason why wood can be used in many areas is its anatomical structure, physical properties, mechanical properties, and chemical properties [3]. Today, with the advancement of technology, wooden materials continue to be developed and gain different properties. With the development of the wood industry, high-rise and wide-opening wooden structures have begun to be built. The world's production and market share of wooden construction and industrial wood materials is also increasing rapidly.

Industrial wood material has been developed in terms of its mechanical and technological properties compared to solid wood material. Thus, solid wood's disadvantages have been advantageous to the newly produced material [4,5]. The first use of cross-laminated started in Switzerland in the early 1990s. In

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European countries, Australia, and, North America, the use of cross-laminated timber (CLT) is becoming increasingly common with new production technologies and has become a construction system used as an alternative to the increasing steel and concrete construction system in the architectural sector [6]. Cross-laminated wood names are used in different abbreviations (CLT, KLH, BSP, X-LAM) around the world [7]. According to the Australian Timber Development Association, the CLT construction system is a structural wood panel system that consists of large-sized, 3, 5, 7, 9, or more lumber boards placed perpendicular to each other (opposite and usually 90°) with fiber directions in each layer and bonded together with formaldehyde-free adhesives [6] (Fig. 1). These panels are rigid components with resistance and dimensional stability, which are adhered to each other from their wide or narrow surfaces under a pressure force of at least 0.6 N/mm2 during the production process.

Solid wood construction uses these panels as wall, ceiling, and roof panels [9]. The lumber used in the outer layers of CLT wall panel applications is typically oriented vertically so that its fibers move parallel to gravity loads and maximize the vertical load capacity of the wall. The timber fibers used in the outer layers of flooring and roof applications are positioned parallel to the direction of the opening [10]. Panel elements of different thicknesses produced with CLT can pass wide openings. It can also pass floor openings up to 7 meters without the need for intermediate support [11]. CLT construction elements, which can be used in structures with different functions such as detached houses, multi-story residences, public buildings, and industrial buildings, can be designed in many forms and scales with lamination technology. These panels produced at the factory prevent the occurrence of manufacturing errors [12, 13]. CLT has many advantages such as being ecological and sustainable, storing carbon, providing healthy spaces, causing less noise and environmental pollution (dust, etc.) compared to traditional construction techniques, providing convenience in assembly, reducing the amount of waste, being resistant to fire and earthquake [14-17].

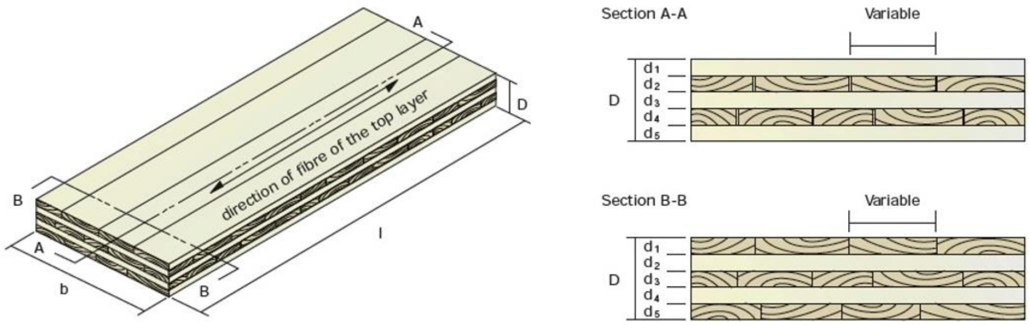


Fig. 1. CLT panel cross-sections and fiber directions [8]

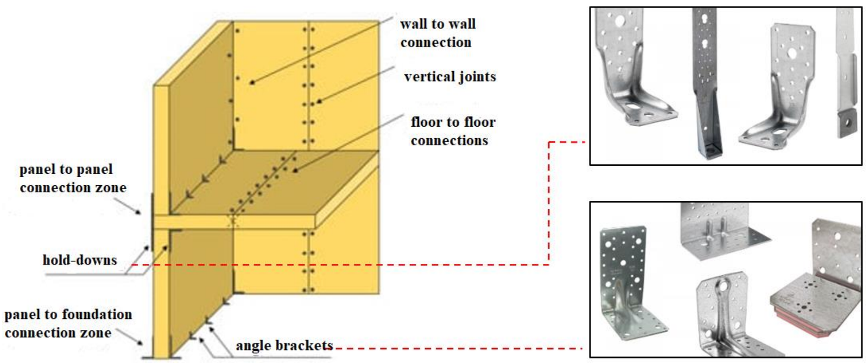


Fig. 2. Connectors (hold-downs and angle brackets) for CLT building [29,30]

2. Seismic performance of timber buildings

The ground motion caused by the earthquake affects the structures on the surface. The earthquake load acting on the buildings horizontally starts at the foundation of the building and shakes the upper points. For the structural system to be resistant to this shaking, the structures must be well-designed [18,19]. The main principles affecting the design of earthquake-resistant structures are strength, ductility, and rigidity. In a building that carries earthquake loads, the structural system and its elements must have rigidity, strength, and ductility to ensure that the earthquake loads are transferred continuously and safely to the foundation [20]. The structure's ductility includes the ability to make excessive shape and displacement and consume energy against the applied force [21]. During the shaking, the energy must be absorbed (absorbed) in the structures whose foundations are on the earth's crust. The more energy that can be spent on different places to increase the earthquake resistance, the less strength is required to be added to the structure. The more rigid (fragile) the building, the greater the severity of the shaking and the higher the probability of damage or even collapse of the structure [22]. One of the general features that should be in earthquake-resistant structures is that the structures should be light. During an earthquake, the weight of the structures and the inertial forces acting on the structure are in direct proportion. The lighter the structure, the less it is affected by earthquake forces [23].

It is known that wooden structures were preferred a lot before reinforced concrete structures became widespread in Turkey. For earthquake-resistant wooden structures to be applicable, the strength of wood material and engineering knowledge must be combined. With the development of technology, the properties of engineered wood materials have been improved [24]. Buildings made with wooden construction have a much better performance in severe earthquakes than other reinforced concrete and masonry buildings (25, 26]. Wood is a flexible material with little deformation. The wooden material can return to its original form as a result of the applied load. Its high strength and light weight make it preferred as a building material in earthquake zones [24]. Due to the properties of wood, it can pass through wide openings. The lightness of wood reduces the effect of forces acting in the horizontal direction. In addition, wood is a material that is resistant to shock and vibration absorption [27].

In seismic-prone regions, cross-laminated timber produced with an industrial system is preferred by architects and users [15]. CLT panels are used in many areas such as walls, roofs, floors, and stairs. Since CLT is a strong, light, and flexible material, its resistance to earthquakes is quite high. Considering that the earthquake loads are proportional to the weight of the building, the fact that CLT is lighter than other building materials provides a great advantage. The earthquake effect (collapse) is less in light buildings. The fact that wooden buildings are 5 times lighter than reinforced concrete buildings increases the rate of preference [28]. Mechanical connectors used in the connection of wall panels in CLT structures to each other, floor panel, roof, and foundation are divided into two groups. In the first group, there are hold-down and angle brackets used to prevent vertical panels from swinging and offsetting. The second group includes small-diameter metal connectors used for panel-to-panel connections or floor-to-wall connections of walls and floors [29] (Fig. 2).

Since studies and standards in this field related to the earthquake performance of CLT in our country are insufficient, the Eurocode, which draws on the experience of North America, is a good example. In Europe, the design of wooden structures has been standardized in Eurocode 5, and earthquake resistance in structures has been standardized in Eurocode 8 [32,33]. The behavior of the CLT under lateral loads needs to be investigated and developed with further experimental studies [34]. It is seen that the CLT buildings of one-to-one dimensions give very good results in earthquake performance tests. Earthquake-resistant CLT structures from 9 to 34 floors can be built [35]. The performance of the CLT structure under earthquake load primarily depends on the properties of the connectors [36,37].

There are many studies in the literature on the performance and properties of these connectors. In the studies by Schneider et al. [38], experimental research has been carried out on a new connector assembly consisting of hollow steel pipes placed inside cross-laminated wood panels. The research presented here has shown that this new fastening assembly for cross-laminated wood panels can be used in seismic regions. Pozza et al. [45] investigated the monotonic and cyclic behavior of cross-laminated wood panel–angle bracket connections with an experimental and numerical study. At the end of all experimental tests, in the case of axial displacement, significant deformation of the steel tie plate and crushing of the wood around the nail shank was found. Ceylan and Girgin [39] experimentally investigated the effect of seismic loads on the axial tensile load in the laboratory environment by using metal joints in the full-size CLT wall-floor connection system. In the study, the displacements of joint plates, metal brackets, and phosphate-coated ring nails were investigated. It has been observed that phosphate-coated nails have a high adhesion ability, and peeling and buckling damages are delayed.

When the experimental studies on the connections used in CLT wall panels are examined, it is seen that the connection layout and design have a strong effect on the seismic behavior of the wall. Lateral loads such as earthquakes applied to the structure try to break the ground connection. Hold-down and angle bracket connections used in foundation joints resist tensile loads and resist shear and rupture of the wall by rising upwards [29,40,41]. When these connectors are designed correctly, they show a significant energy dissipation capacity in the event of an earthquake [42-46]. This study was carried out to encourage the widespread use of CLT wooden construction systems in our country, which is in an earthquake zone, especially because the damage rate of wood against earthquakes is lower than other building materials. With the new connection models examined within the scope of the study, it is aimed to increase the performance of the CLT wall and strengthen the ground connection.

3. Materials and method

The study consists of 3 stages. In the first stage, a literature review was made within the scope of the subject, and the connection details and the problems of the CLT walls were determined. In the second stage, connectors used in the market and mostly imported from abroad were examined, and alternatives in different sizes were produced. Then, CLT wall panels were manufactured with native trees. At the last stage, CLT panel walls and all connectors were tested and compared with different combinations in a lateral load test setup.

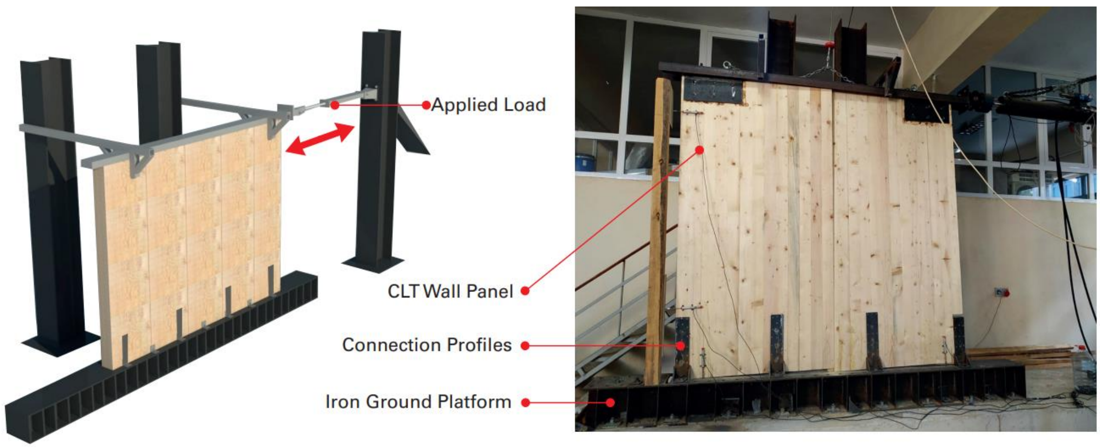


Fig. 3. The examined RC beam (a) Sectional elevation, (b) Cross-section [2]

3.1. Wood materials and experimental test setup

In this study, Eastern Spruce (Picea orientalis L.), a coniferous tree species, which was obtained from a local firm in the Eastern Black Sea Region, Trabzon city, and widely preferred in the construction sector, was used to manufacture CLT walls. These trees were baked and planned to produce four CLT wall panels with a thickness of 54 mm and a size of 2.40 m×2.40 m. The density value of these walls was determined as 0.467 gr/cm^3 according to the ASTM D2395 (2017) standard [47]. The analysis of the performance of the CLT walls produced within the scope of the study under lateral load was carried out under lateral load according to ASTM E 72, 2014 standard [48] in the laboratory of the Forest Industry Engineering Department of Karadeniz Technical University. The schematic representation of the experimental test setup is given in Fig. 3.

According to the load application procedure specified in the ASTM E 72 standard (2014), loads of 3.54-7.12-10.7kN were applied to the CLT walls, respectively, and retracted. Then, maximum loading was carried out until the wall system failed or the total displacement was 100 mm. The displacements on the walls were calculated at each stage. After the tests were carried out, the maximum load-carrying capacity and maximum displacement amounts and stiffness were determined for each experimental group.

3.2. Connection details

When the literature is examined, it is seen that connectors such as bolts, screws, nuts, nails, metal plates, and profiles are generally used in the floors, walls, roofs, and foundations of buildings made with CLT [8,29-31]. In the study, the connection of the CLT wall with the foundation was emphasized. In this context, 6 different connection detail with CLT walls to the foundation were tested in the experimental test setup. While creating these details; angle brackets, hold-down, U-type connection profile, and diagonal connection profile are used. These profiles are specially designed and each of them is made of 1cm stainless iron. 6 different connection configurations and elements used in the test setup are given in Table 1.

Table 1. CLT wall-to-foundation connection details for each experimental test group

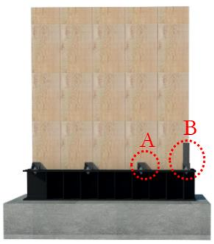
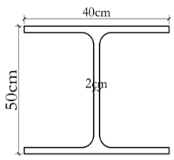
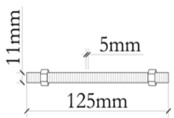
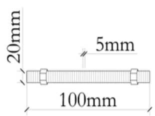
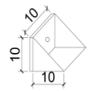
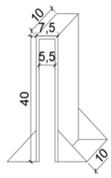
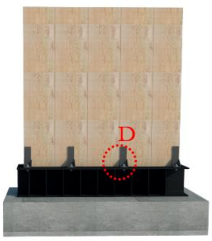
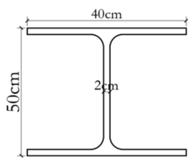
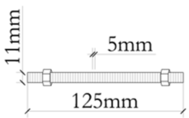
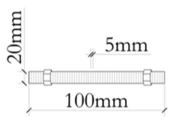
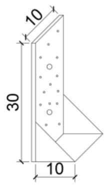
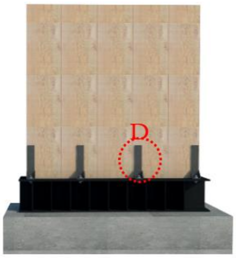
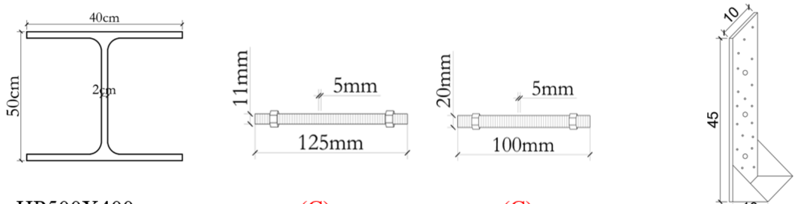
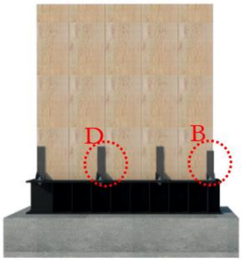
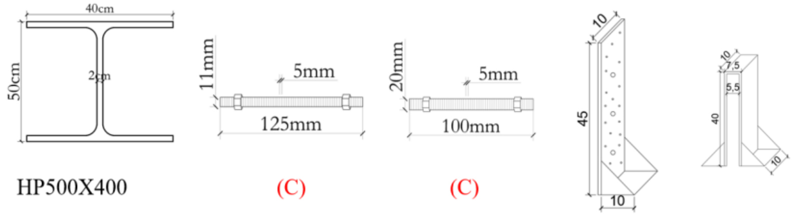
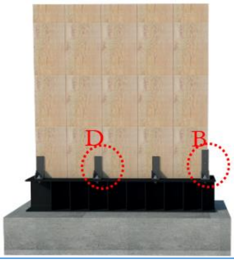
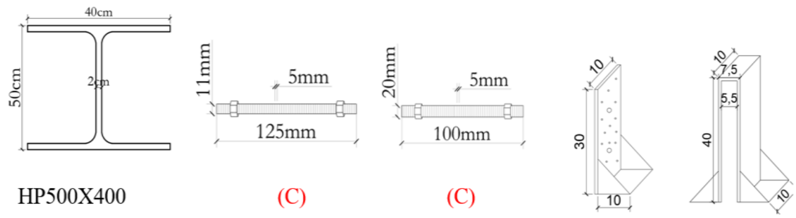
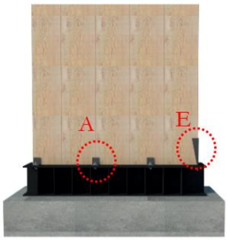
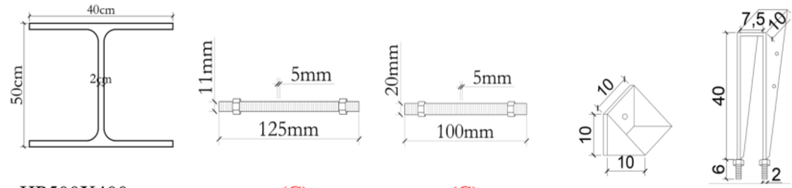
CLT wall test groups		Connection elements: HP steel beam, angle bracket (A), U type profile (B), bolts (C), hold-down (D), diagonal connection profile (E)				
Detail-1		 HP500X400	 (C)	 (C)	 (A)	 (B)
Detail-2		 HP500X400	 (C)	 (C)		 (D)

Table 1. Continued

CLT wall test groups	Connection elements: HP steel beam, angle bracket (A), U type profile (B), bolts (C), hold-down (D), diagonal connection profile (E)
Detail-3 	
Detail-4 	
Detail-5 	
Detail-6 	

In all the details of the study, tests were carried out by placing the CLT wall panel on the HP steel beam and reinforced concrete foundation. In Detail-1, to fix the 240 cm high CLT wall panel to the steel beam, the U-type connection profile (40 cm height) and angle brackets (10 cm height) are placed at equal intervals from the direction of the applied load. The U-type connection profile was inserted into the wall about 10 cm and fixed with bolts and nails. All details are fixed to the steel beam and wall panel with angle brackets, bolts, and nails. In Detail-2, hold-down (30 cm height) is placed at equal intervals from the direction of applied load, respectively to fix the CLT wall panel to the steel beam. In Detail-3, to fix the CLT wall panel to the steel beam, hold-down (45 cm height) is placed at equal intervals, respectively, from the direction of the applied load. In Detail-4, to fix the CLT wall panel to the steel beam, U type connection profile (40 cm height) and hold-down (45 cm height) are placed at equal intervals from the direction of the applied load. The U-type connection profile is fixed with bolts and nails inserted into the wall about 10 cm. In Detail-5, to fix the CLT wall panel to the steel beam, the U-type connection profile (40 cm height) and hold-down (30 cm height) are placed at equal intervals the from direction of the applied load. In Detail-6, to fix the CLT wall panel to the steel beam, the diagonal connection profile (40 cm height) and angle brackets (10 cm height) are placed at equal intervals. The diagonal connection profile is fixed with bolts and nails inserted into the wall about 10 cm.

4. Result and discussion

In this study, six different connection details were placed on the CLT wall panels and examined in the lateral load test setup according to ASTM E 72 standards [46]. In the experiment, the displacements of the wall assemblies under loads of 354 kg, 712 kg, and 1071kg, respectively, were analyzed. Then, the maximum load and displacement results were obtained by applying more load than the last load (1071 kg) tried on the device. The given unit of load, kg, was converted to the unit of load, kN, and the test results were obtained. 1kg is accepted as 0.01 kN. Finally, the connection profiles were tested with different combinations on four CLT wall panels. The deformations of the walls and connections under load are shown in the figures (Fig. 4-9). As a result of the experiments, the displacements of the CLT walls at applied loads of 3.54-7.12-10.7 kN and the maximum load, maximum displacement, and stiffness values were given graphically. The test results of the 6 connection details below are given respectively.

Detail-1 (Angle brackets with U-type profile)

Fig. 4 shows the post-test deformation details of the connections in the CLT wall. In the lateral load test conducted for Detail-1, the U-type connection profile (40 cm) and hold-downs (10 cm) placed respectively from the side where the load applies to the wall remain intact; a break occurred in the part of the U-type profile (Fig. 4, B point). The displacements in the loads applied to Detail-1 are 2 mm at 3.54 kN, 9 mm at 7.12 kN, and 13.5 mm at 10.71 kN, respectively.

Detail-2 (Hold-downs-30 cm)

In the lateral load test conducted for Detail-2, stripping occurred on the nails connecting the hold-downs (30cm) to the wall panel, respectively, from the side where the load comes to the wall. The CLT wall panel has risen above ground level. The displacements at the loads applied to Detail-2 are 2.46 mm at 3.54kN, 5.46 mm at 7.12kN, and 7.46 mm at 10.71kN, respectively (Fig. 5).

Detail-3 (Hold-downs-45 cm)

In the Detail-3 lateral load test, hold-downs (45 cm) were placed on the side where the load comes from the wall, respectively. The displacements at the loads applied to Detail-3 are 1.5mm at 3.54kN, 2.5mm at 7.12kN, and 4.5mm at 10.71kN, respectively. In the test, when the max. load (99.94kN) was applied, and a displacement of 100 mm was achieved without any break in the wall and profile connection points (Fig. 6).

Detail-4 (Hold-downs-45 cm with U-type profile)

In the Detail-4 lateral load test, the wall was broken in the section opened to connect the U-type profile to the wall, which was placed respectively from the side where the load came to the wall (Fig. 7, A point). The hold-downs (45 cm) were not damaged much, but there was a separation from the B point on the wall. The displacements at the loads applied to Detail-4 are 1.5 mm at 3.54 kN, 2.5 mm at 7.12 kN, and 4.5 mm at 10.71 kN, respectively.

Detail-5 (Hold-downs-30cm with U-type profile)

As a result of the Detay-5 lateral load test, there were breaks in the part of U type profile (40 cm height), placed respectively from the side where the load comes to the wall and a small amount of peeling on the nails used in hold-downs (30 cm height). In addition, wall separation occurred at point A (Fig. 8). The displacements at the loads applied to Detail-5 are 1.5 mm at 3.54 kN, 2.5 mm at 7.12 kN, and 4.95 mm at 10.71 kN, respectively (Fig. 8).

Detail-6 (Angle bracket with diagonal profile)

In the lateral load test for Detail-6, a 40 cm high diagonal connection profile (40 cm height) and angle brackets (10 cm height) were placed on the side where the load comes from the wall, respectively. During the applied load, the diagonal profile was broken at the connection point in a short time. The angle bracket is not damaged (Fig. 9). The displacements in the loads applied to Detail-6 are 7 mm at 3.54 kN, 13.5 mm at 7.12 kN, and 17.5 mm at 10.71 kN, respectively.

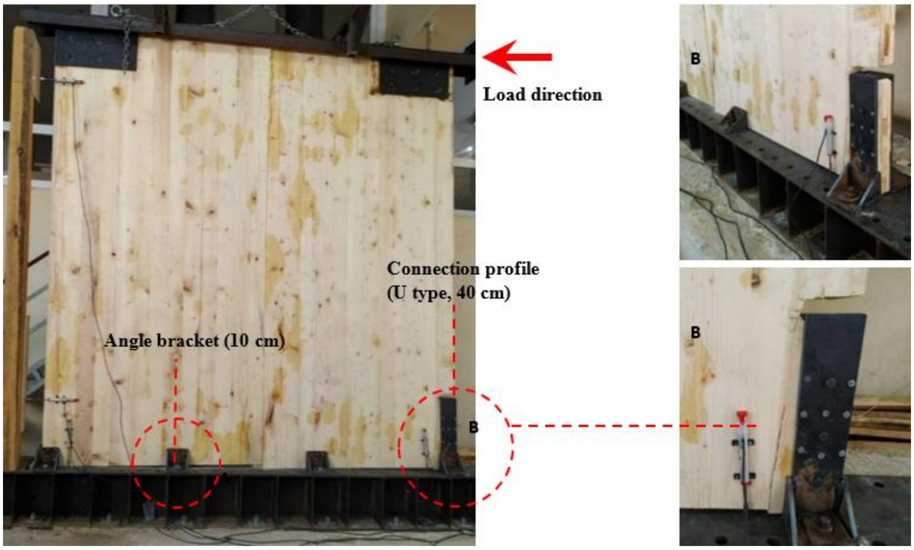


Fig. 4. CLT wall to foundation Detail-1 and deformation of connections

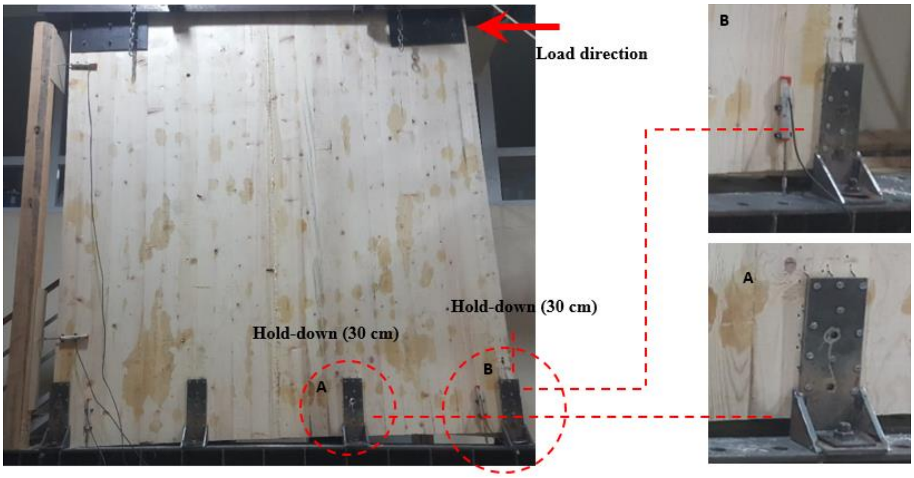


Fig. 5. CLT wall to foundation Detail-2 and deformation of connections

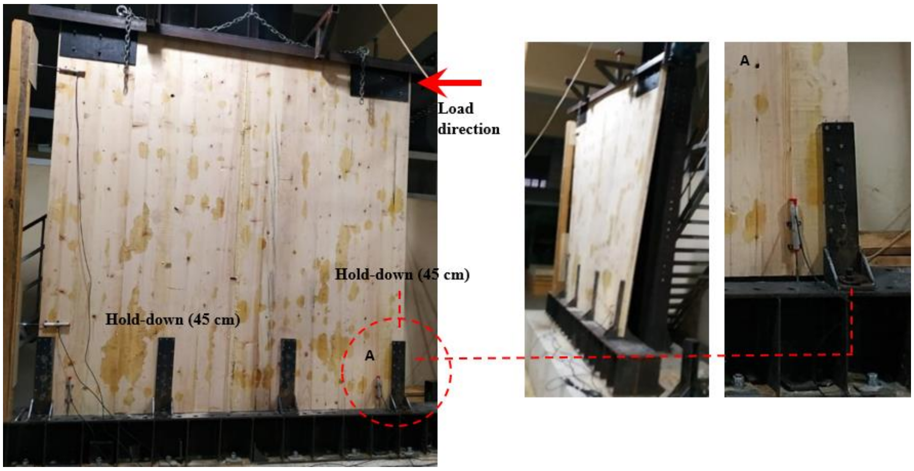


Fig. 6. CLT wall to foundation Detail-3 and deformation of connections

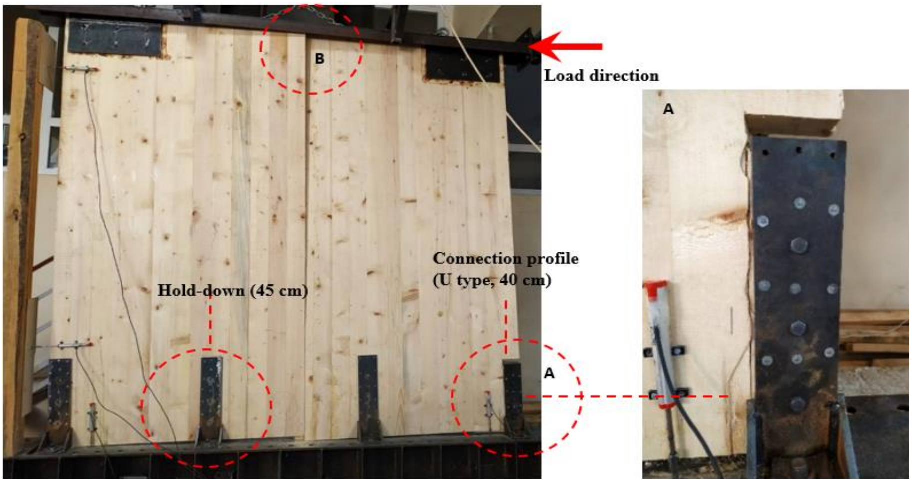


Fig. 7. CLT wall to foundation Detail-4 and deformation of connections

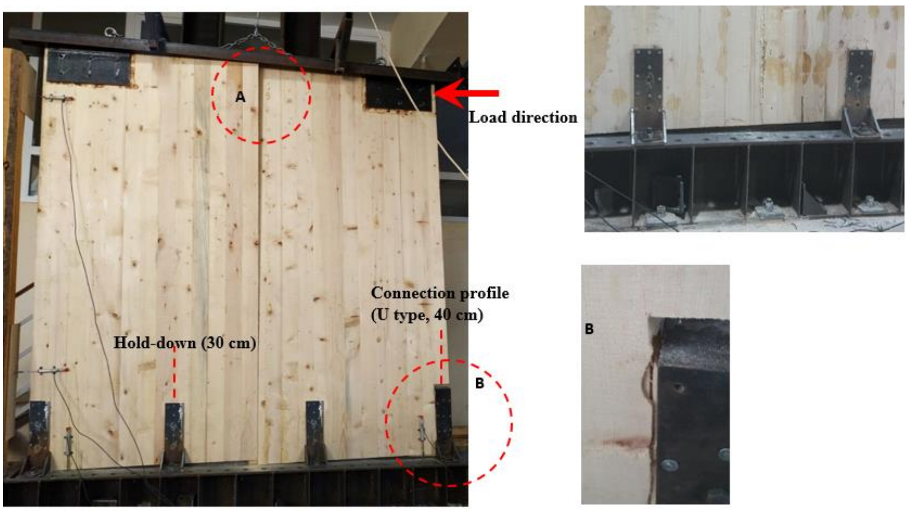


Fig. 8. CLT wall to foundation Detail-5 and deformation of connections

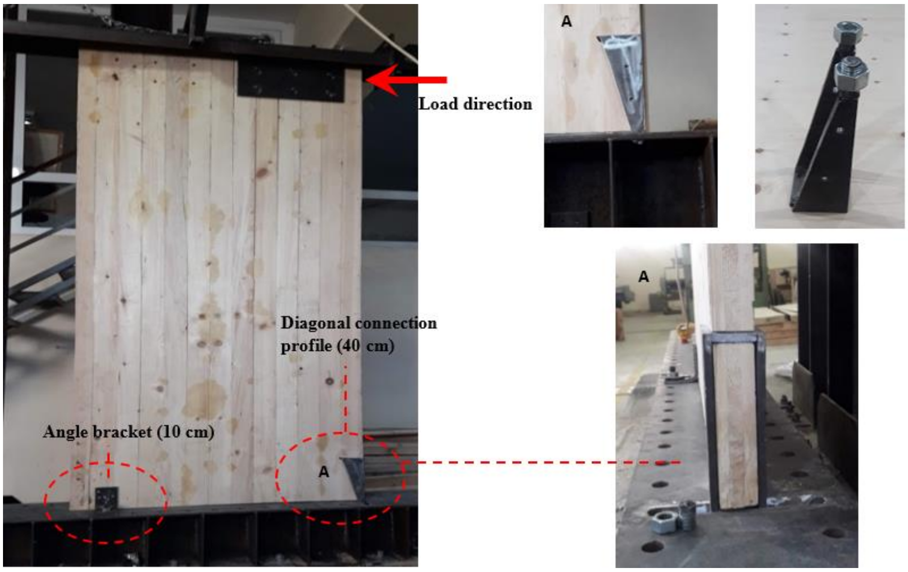


Fig. 9. CLT wall to foundation Detail-6 and deformation of connectors

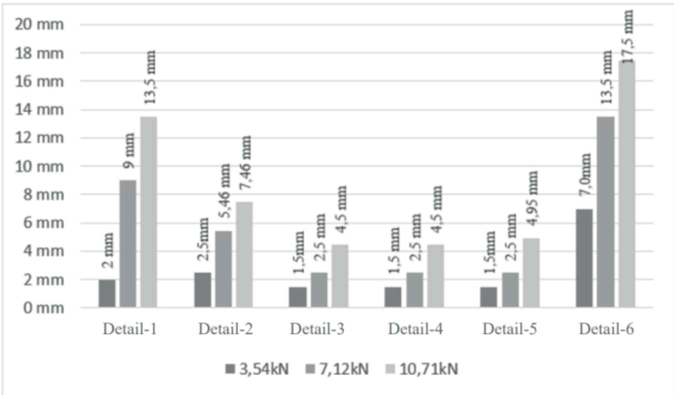


Fig. 10. Load–displacement graph of CLT wall details

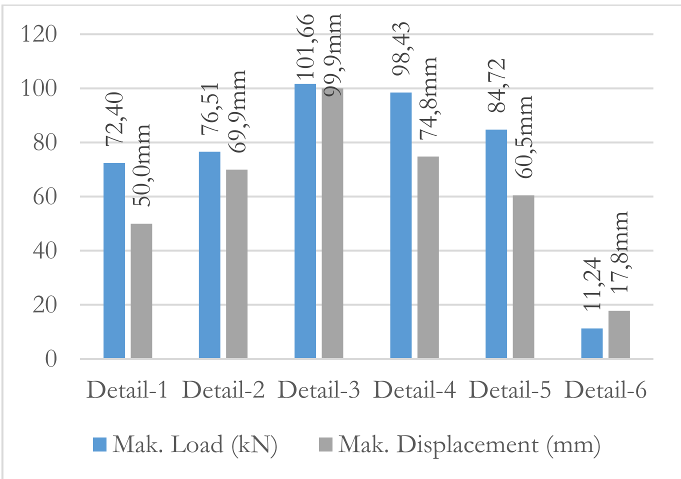


Fig. 11. Max. load–max. displacement graph of CLT wall details

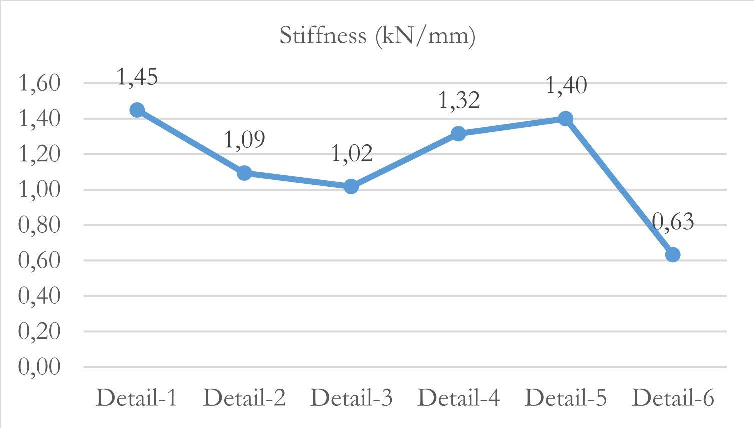


Fig. 12. Stiffness (kN/mm) graph of CLT wall details

After the experiments, it was concluded that Detail-6 had the highest displacement under all loads. Detail-6 was disconnected from the connection point shortly after the experiment started. Since the prepared profile broke off from the foundation, its displacement was high than the others. When 3.54 kN, 7.12 kN, and 10.71 kN loads were applied, there was 7 mm, 13.5 mm, and 17.5 mm displacement on the wall of Detail-6, respectively. The least displacement occurred in Detail-3 and Detail-4. When 3.54 kN, 7.12 kN, and 10.71 kN loads were applied, the displacements in Detail-3 and Detail-4 were similar and were 1.5 mm, 2.5 mm, and 4.5 mm, respectively. Detail-3, Detail-4, and Detail-5 showed similarity in displacements against these three applied loads (Fig. 10). Further, the max. applied load and displacement were in Detail-3, and the least displacement was in Detail-6. In Detail-3, the max. load is 101.66 kN, and the displacement is at the max. load is 99.94 mm. In Detail-6, max. load is 11.24kN, displacement at max. load is 17.77 mm (Fig. 11).

According to the results, as the load increases, the displacement ratio also increases. Based on these results, Detail-3, constructed using connection profiles (45 cm height), could bear more loads and its displacement was proportionally higher than other details. This means that the connection profiles with a height of 45 cm will show more resistance against the load in the event of an earthquake compared to other details. The selection of all connectors of the same type and longer than other details (especially Details 2, 4, and 5) in Detail 3 had a positive effect on the seismic behavior of the wall. In Detail-1, the resistance of the wall against the load has decreased due to the short angle brackets.

Rigidity, which is defined as the ability of the structure to remain stable under loads, is known as one of the important factors affecting the durability of structures [47]. In the experiment, the stiffness value was found by dividing the maximum load by the maximum displacement. In the results, the highest stiffness value is Detail-1 and the lowest Detail-6 connection. The stiffness value in Detail-1 is 1.45 kN/mm, and the stiffness value in Detail-6 is 0.63 kN/mm. As a result, it is seen that the stiffness value of Detail-1 is better than other details. In Detail-1, the deformation against the earthquake load is less than in the other details. When Detail-2-3 and Detail-4-5 were examined, they gave similar results in terms of rigidity since similar materials were used in their assembly. As the stiffness increases, the applied load must be higher for the deformation to be higher (Fig. 12).

In the results obtained from the study, although low horizontal deformation values seem to be a bad situation in terms of ductility, it also reveals that the structure is more successful in terms of rigidity. It is desired that the structures should be ductile in such a way as to reduce the loads during the earthquake but be rigid enough to carry loads [48].

5. Conclusion

The fact that wooden material is much lighter than steel and reinforced concrete reduces the horizontal load effect on the structure and the risk of collapse of buildings. CLT, which is an industrial new-generation wood material, is highly preferred in earthquake zones due to its lightweight, high carrying capacity, and flexible structure. When the literature is examined, it is seen that the elements used in the connections in the CLT walls are more damaged than the walls during the earthquake. In this context, deformations of the detail elements used in the connection of the CLT walls, produced from native tree species grown in the Eastern Black Sea Region of Turkey, against lateral seismic load were investigated. As a result, it is predicted that the obtained data will contribute to the estimation of the structural behavior and seismic properties of wooden structures.

As a result of the experiments, it was observed that the max. applied force and displacement occurred mostly in Detail-3. In this wall, connectors of the same type and longer (45 cm) were used compared to other walls. This configuration positively affected the seismic behavior of the wall. According to the stiffness results, the highest stiffness value is 1.45kN/mm in Detail-1, while the lowest is 0.63kN/mm in Detail-6. Although the wall in Detail-1 has a low horizontal deformation value, it has been more successful in terms of stiffness compared to other details.

In the test results, similar to the literature, it is seen that the main damage areas occur in the connections used in the walls [49, 50]. Since CLT is a rigid material by its nature, its displacement against horizontal loads depends more on the design of the connectors [51]. The most accurate design of the elements used in the foundation connection of the CLT walls will contribute to the maintenance of the structural system or the structural element's bearing capacity by showing flexing/deforming properties in the event of an earthquake.

The resistance of CLT walls to high deformations is particularly advantageous against lateral loads such as earthquakes and adds high ductility to the structure [52]. Because wood is an elastic material, it shows more shape changes rather than effects such as breaking against load. It is supported by experimental studies that the industrial material CLT, together with the correct connection details, will have more displacement and deformation in the face of an earthquake and this will prolong the collapse time in the event of an earthquake.

Although the issues of dissemination of wooden structures in the world are on the agenda, research on these issues is very limited in Türkiye. As a result of earthquake disasters that have occurred for years in Turkey and other earthquake-prone countries, hundreds of people have died, and many buildings have been destroyed and severely damaged. The fact that the rubble of reinforced concrete buildings is too much and heavy has also delayed reaching the people under the collapse. Therefore, it is very important to design wooden structures that are light, renewable, and resistant to earthquakes. In such countries, more industrial forests should be established, laws/standards related to wooden structure design should be issued and then earthquake-resistant wooden structure design should be given priority. It is thought that the increase in studies on CLT will contribute to the increase of CLT production, the widespread use of wooden structures, and the establishment of certain standards about wooden materials/structures.

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Author contributions

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Data availability statement

The data presented in this study are available upon request from the corresponding author.

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