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# Structure, energy and cost efficiency evaluation of three different lightweight construction systems used in low-rise residential buildings

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ABSTRACT

This article presents the analysis of the structure, energy and cost efficiency of three lightweight structural systems – wood light frames (WLF), lightweight steel frames (LGSF) and 3D sandwich (3DSP) panels – during their useful life. The structural systems focussed upon in this study are commonly used in Eastern Europe with specific reference to Turkey. The structural analysis and design was carried out using ETABS while EnergyPlus was used in the analysis of the energy consumption of the buildings.

The results of the structural analysis of the three alternative construction systems show that 3DSP has better structural behaviour in terms of resistance against lateral loads. The thermal performance evaluation of the walls and ceilings shows that the WLF and LGSF walls have better insulation values (12.5% lower *U*-value) while the roof construction of the 3DSP has much better insulation performance (70% lower *U*-value). Moreover, the building designed with 3DSP requires 11% less energy for total heating and cooling during one year. The information for the building industry in Turkey shows that the cost of construction for 3DSP construction is 34.6% lower than for WLF and 27.7% lower than LGSF.



## 1. Introduction

The depletion of natural resources due to the huge demand for energy and construction materials for the ever-increasing population and demand in the construction sector has caused irrevocable ecological imbalance. The environmental impact of human activities and the anxiety about decreasing energy resources warrants greater attention globally to ensure sustainable development. Thus, the living spaces in buildings where individuals spend most of their time need to be investigated in terms of thermal comfort and safety. A very large proportion of the energy used in the world, and the greenhouse gases that are released from the energy, are associated with the building sector [1]. Nearly 40% of the total US energy consumption in 2012 was consumed in residential and commercial buildings [1]. Housing, as one of the oldest building typologies, has always been one of the most important needs of human beings. The residential sector accounts for a large percentage of the total primary energy consumption, i.e. 21% in the US in 2013 [1]. In this respect, a high level of sensibility is required for developing appropriate principles of sustainable housing for the use of current and future generations [2].

Several solutions have been proposed by different companies and institutions to enhance the efficiency of residential construction [3–8]. In the past few decades, some methods of construction have been developed using standardized lightweight frames and materials [9–12]. Due to various economic, structural and environmental benefits, these kinds of construction techniques have rapidly changed the construction practices all around the world. The construction of these systems is clean, fast and easy. Moreover, they are lightweight and need less construction materials. These specific characteristics result in lower environmental loads and enhanced seismic resistance. Nowadays, platform framing is the most common method in constructing wooden houses. Also called "stick framing" or "stick construction", this kind of framing is the most popular method of light-frame construction in Canada and the United States [13]. Light gauge steel frame (LGSF) construction

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(also known as cold-formed steel structures or lightweight steel structures) is the non-combustible equivalent of WLF construction. The shapes and sizes of the sections are similar to what builders are accustomed to seeing in the dimensions of the timber used in lightweight timber framing [12]. In addition, other innovative structural systems, such as 3DSP and insulated concrete forms, have been developed using panels made with EPS insulating materials in order to fulfil the insulation requirements [10].

The concept of standardized light framed residential buildings is to build more buildings in a short period with fewer resources. In this respect, the structural analysis and the design of this type of structure is simplified in practical projects. The analysis is based on the design of the individual load-bearing members instead of the whole structural analysis. Although this method is simple, it is not accurate enough to assess the actual structural behaviour of the building. Researchers have investigated the structural behaviour of load-bearing walls constructed with lightweight systems [9–11,13–16]. However, no research work related to whole structure modelling and analysis of these structures has been found. In addition, there is no evidence concerning the calculation of the thermal behaviour of the walls or the energy efficiency of the buildings designed using the methods mentioned above.

The analysis and design of buildings using energy efficiency and thermal comfort is vital. Some previous works have focused on the energy efficiency of buildings with special consideration of residential buildings [3,5,17–22]. The energy usage of a building during its lifespan happens in two different phases. In the first phase, the great energy consumption that takes place during construction based on material usage and construction costs is considered; while the second phase focuses on the energy consumption during the operational stage when the building is in use. When analysing the energy costs, alternatively known as the environmental load of the building, it transpires that the greater part of the load results from the energy consumption during the lifespan of the building (assuming the lifespan of a building is 75 years) [23]. Researchers have investigated the energy usage of the buildings in each of the energy consumption phases. Some have investigated the energy requirements and environmental impacts of the building during the construction practice [19,23–28], while others explored the changes in building energy consumption during the operational phase considering different effective factors, such as building shape, building envelope [20,22,29–32]. However, the effects of the material and structure on the building energy consumption have not been investigated. Since lightweight residential systems are being widely used throughout the world, it is important to understand the actual behaviour of these structures after being constructed and during the operating years.

The main objective of this study is to evaluate three essential efficiency aspects – structural behaviour, energy consumption and construction cost – for residential buildings that use three different structural materials, namely, wood, steel and concrete; the materials and the systems focussed upon in this study are used in Eastern Europe with specific reference to Turkey. Since Turkey is located on one of the most active earthquake zones, the structural behaviour for seismic loads is of great importance in this region [33]. In addition, the energy costs constitute a significant portion of the total life costs in Turkey since the country is an importer of natural gas for its energy needs [34].

In order to investigate the structural behaviour and energy consumption, three types of the most prevalent prefabricated standardized structural systems, namely, wood light frame structures (WLF), light gauge steel frames (LGSF), and 3D sandwich panels (3DSP) were chosen. The mentioned structural systems are mostly used in the construction of low-rise residential buildings.

**Table 1**
Description of sample building.

| | |
|---|---|
| Building type | Family residential building |
| Area | First story: 124.86 m$^2$<br>Second story: 48.38 m$^2$ |
| Location | Istanbul, Turkey |
| Seismic zone according to "DBYBHY2007"[a] [28] | 1 |

[a] Turkey specification for buildings to be built in seismic zones.

## 2. Materials and methods

### 2.1. Sample building

A particular architectural plan of a home, as shown in Fig. 1, is used in the evaluation. This plan is a typical example of the type of single-family house being constructed in Turkey using lightweight structural systems. This paper applies three structural systems to one specific home plan, and then compares the results of the analysis.

Table 1 shows the definitions for the sample building. The ground and first floor plans of the sample building are shown in Fig. 1.

### 2.2. Materials

The properties of the materials used in the load-bearing structure in each construction system are given in Table 2. In Fig. 2, the details of the wall construction used in this study are illustrated. The wall, floor and roof materials are chosen according to the most prevalent methods; these materials are used in the construction of the three kinds of structural systems investigated in this research. The main structural members in the wall construction of the WLF system include vertical and horizontal framing members, as shown in Fig. 2(a). The vertical framing members, called studs, are generally made of 2″ × 4″ (50 mm × 100 mm) timbers placed in

**Table 2**
Properties of the materials used in load bearing structure of three construction systems [15,35].

| | | |
|---|---|---|
| **Material name: wood** | | |
| Species and commercial grade | | White oak – select structural[a] |
| Size classification | | 2″ and wider |
| Density (kg/m$^3$) | | 640 |
| Modulus of elasticity (Gpa) | $E$ | 7.55 |
| | $E_{min}$ | 2.74 |
| Bending (MPa) | | 8.4 |
| Tension parallel to grain (MPa) | | 4.9 |
| Shear parallel to grain (MPa) | | 1.54 |
| Strength (MPa) | Compression perpendicular to grain | 5.6 |
| | Compression parallel to grain | 7.7 |
| **Material name: steel** | | |
| Member thickness (mm) | 1, 1.5, 2 | |
| Density (kg/m$^3$) | 7800 | |
| Modulus of elasticity (Gpa) | 202.86 | |
| Poisson's ratio | 0.3 | |
| Shear modulus (GPa) | 77.8 | |
| Yield stress (MPa) | 240 | |
| **Material name: concrete** | | |
| Density (kg/m$^3$) | 2400 | |
| Modulus of elasticity (GPa) | 24.8 | |
| Poisson's ratio | 0.2 | |
| Compressive strength (MPa) | 25 | |

[a] The characteristics of the wood material are determined according to "2005 National Design Specification for Wood Construction" (NDS) [36].