Research Article

Experimental Investigation of Novel Reinforced Composite Panels Made of Cold-Rolled Galvanized Sheets Filled with Foamed Concrete and Fire-Resistance Polyurethane Foam

Fardad Aala, Yaghoub Gholipour, and Dana Samadi

School of Civil Engineering, University of Tehran, Tehran, Iran

Correspondence should be addressed to Fardad Aala; fardad.aala@rwth-aachen.de

Received 29 January 2022; Revised 12 June 2022; Accepted 26 August 2022; Published 19 September 2022

Academic Editor: Dora Foti

Copyright © 2022 Fardad Aala et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

While introducing the novel structural method, this paper compares the behavior of composite panels comprised of cold-rolled galvanized sheets infilled with the foamed concrete and the fire-resistance polyurethane foam. A series of axial and bending tests are carried out on the composite panels with mentioned fillers; also, the function of the wire mesh and surrounding cold-rolled galvanized sheets with different thicknesses and different fillers are investigated in an attempt to know the effects of mentioned sheets on the final strength. The results show that applying the fire-resistance polyurethane foam performs better in enhancing the bending and the axial strength of composite panels in comparison with the foamed concrete filler. By this combined system with foamed concrete as infilling material, the cold-rolled galvanized sheets, which endure low bending and axial tension, have been able to withstand bending and axial load around 1.92–4.08 N/mm² and 0.98–1.074 N/mm², respectively. In addition to the aforementioned composite system, those panels with fire-resistance polyurethane foam as infilling material, apart from the greater lightness, around 40% lighter, have been able to withstand more with approximately 50% and 10% higher bending and axial load, respectively.

1. Introduction

As countries are developing and housing is considered one of the crucial indicators of development, the issue of rapid, light, and methodical construction should be taken into account seriously. The application of cold-rolled galvanized sheets instead of conventional building materials has widely received a lot of attention for some advantages, such as rapid installation in short and medium-sized buildings; also, this method uses in times of a crisis as well as in high-quality construction. Above all, in developing housing construction, the lightness of buildings is one of the most important factors which has to be considered as there is no need to erect a building with heavy cranes. In addition, from the technical point of view, in conventional buildings, the dead load of walls and ceilings accounts for the majority of the building’s load in comparison with the live load. This would be highly problematic in the structure’s behavior in an earthquake and other national disasters. As a result, reducing the heaviness of the structure will decrease the internal bending and axial forces between the structure’s elements dramatically and will have a positive effect on structural behavior.

Due to the cold-rolled galvanized sheets’ weakness in the load sustainability, the gathering of steel sections in order to improve resistance is to no avail. With the advent of composite panels, the low structural capacity of these cold-rolled galvanized sheets could be eliminated by using infilling materials like concrete, lightweight concrete, foamed concrete, and fire-resistance polyurethane foam, to name but four. Hence, this study has reviewed several relevant related literature to underpin the work. Methodologically, it also touches on the application of bending and axial tests in investigating the performance of composite panels.

Wright and Gallocher studied the reaction of walling system consisting of a steel frame and concrete infill under the axial loads by four full-scale tests [1]. Later, Wright also studied the behavior of composite walls under both axial loads and bending moments [2]. The experiments revealed
that hooks as the shear connection could be used to prevent shearing failure, as well as the structural strength of the abovementioned system, which is related to the design of profiled steel sheeting [2].

Uy et al. investigated the combined axial and flexural strength of profiled composite walling systems [3]. The test and numerical modeling results were successfully calibrated by considering the impacts of local buckling [3].

Foamed concrete as one of the infilling materials provides some benefits such as fire protection, thermal insulation. Mydin and Wang proposed a new composite walling system, which consists of profiled steel sheeting with lightweight foamed concrete [4]. Then, they investigated the structural performance and applicability of mentioned composite system, in which the samples were two 6-sample groups with different ranges of external sheet thickness [4]. Flores-Johnson and Li also examined the behavior of fiber-reinforced foamed concrete surrounded by panels. The proposed infilled material was found to have better integration after failure [5].

Prabha et al. studied the impact of confinement on composite walling systems, including lightweight concrete under compressive loads [6]. It was demonstrated that the strength of the wall is related to the degree of confinement, considering the role of studs and sheet edge conditions [6].

Xu and Chen carried out their test on the mechanical behavior of composite walls under axial forces [7]. That research aimed to investigate the failure mechanism of walls with foamed concrete and without foamed concrete, followed by the investigation of the impact of the concrete density utilized in the samples. The results showed that the failure state of the nonfoamed composite wall was distortional buckling, where the final loading capacity of the walls packed with different concretes was 1.6–2.2 times as large as the capacity for the concrete-free case [7]. Hegyi also researched the design of cold-formed steel elements, which are infilled with polystyrene aggregate concrete, and then examined the buckling behavior of the aforementioned elements under compression [8].

In 2019, Ridha et al. conducted experiments as well as numerical simulation and formula prediction on the Sandwich panels made of light profile steel skins, including lightweight concrete under eccentric and concentric loads [9].

Recently, much attention has been given to the addition of new materials to foam concrete to improve the flexural and axial capacities of panels, as well as comparing their behavior with samples without additives.

Eltayeb et al. evaluated the possibility of improving the properties of foam concrete by adding rubber particles. His research shows that adding 8.5% rubber to concrete panels reduces axial capacity by 16.8%. This reduction rate is acceptable due to the additional properties of rubber, including high impact resistance, high damping ratio, ductility, and sound and heat insulation [10]. Also, Eltayeb et al. investigated the effect of rubber on foam panels under uniform and cyclic shear loads. This study shows that the optimal use of rubber by 8.5% improves the ductility and energy absorption of the panels by 19.5 and 13.6%, respectively [11].

Al-Shwaiter and Awang studied the performance of various types of foam concrete panels under axial loading, focusing on the effect of palm oil ash replacement. Based on the results of the test, it is shown that all samples, including reinforced, unreinforced, fiberglass-enclosed panels and steel plates, perform better when palm oil fuel ash is substituted [12].

With the increasing usage of novel materials in the construction industry, Polyurethane foam is applied as an alternative infilled material due to its lightness, strength, and durability. Due to its incendiary nature, we need to take measures to prevent fires in the building. This material has been generally used in composite systems in three forms.

First is lightweight concrete with polystyrene. Different grain sizes of polystyrene can be used in concrete in composite structural systems, resulting in different densities of the mixture [13].

Sari et al. [14–16] developed polyurethane-filled lightweight concrete formulation; they were able to achieve the lowest density and the optimal level of polystyrene content possible [13].

Apart from the aforementioned useability, it can be utilized as polyurethane polymer concrete (PPC) in composite structural systems. As a repair or finishing material, PPC can be used, and it consists of cement and aggregates bound with a polymer binder [13].

Second, Polyurethane can be used in masonry walls. Concrete reinforced structures with infills have been used more often since the 20th century [17], and fiber-reinforced mortars and thin joints have been studied in further detail [17]. Using laboratory tests on panel specimens, the mechanical characteristics of brick masonry and thin joints were compared [18, 19].

The shear strength of a masonry structure is one of the main parameters associated with earthquake resistance in seismic-prone areas [17]. This kind of joint can also be made up of polyurethane foam. As compared with traditional mortar, they are more deformable, ductile, and have a higher damping capacity [17].

Due to their workability, permeability, thermal insulation, and necessary mechanical properties, polyurethane-modified mortars have been introduced for use in construction applications [20–22].

Third, use of polyurethane in Sandwich panels. A number of studies have been conducted to investigate how foams might be used as filler in Sandwich panels [23, 24]. Different types of polyurethane foam have been used to realize the cores, and their mechanical characteristics have been evaluated [17].

Moreover, von der Heyden and Lange analyzed the buckling behavior of C-sections infilled with polyurethane foam [25]. It was concluded that the polyurethane foam could increase the load capacity of cold-formed steel members [25].

Polyurethane foam composites have also been studied using new materials to improve their properties. Polyurethane foam reinforced with natural fibers provides structural integrity, lightness, and higher energy absorption [26], as well as an environmentally friendly alternative [27].
According to Sagadevan and Rao, the use of polyurethane foam in shed columns and beams can help prevent damage and early buckling by increasing the axial, shear, and flexural capacities of samples [28].

Under a 4-point bending test, Cantillo-Lara et al. carried out laboratory experiments and numerical analyses of sandwich panels made with steel bodies and foamed concrete cores. The results indicate that samples with 1% natural fibers have higher load-bearing capacity and energy absorption than propylene fibers. In addition, his numerical analysis shows that the bonding between foam concrete and steel surfaces has an important influence on the performance of sandwich panels [29].

This study presents an effort to investigate the behavior of combined composite panels comprised of surrounding cold-rolled galvanized sheets, reinforced with two top-bottom wire meshes that are welded to the surrounding galvanized sheets; also, zigzag shape shear wires which are welded to the top-bottom wire meshes provide an integral skeleton infilling with foamed concrete or fire-resistance polyurethane foam to resolve the heaviness problem of composite panels, thereby producing light panels with high strength and suitable quality which worth sharing with the scholar community. Moreover, investigating this novel composite system in order to study further by utilizing different wire diameters as top and bottom meshes and zigzag-shaped shear wires; also, changing the thickness of surrounding cold-rolled galvanized sheets and making different skeletons for the precast panels, then fill them with two mentioned infilling materials. In the next step, this paper indicates the bending and axial test results of these panels in order to report their strength and compare their results. Compared with previous research studies, this paper is also motivated by the simultaneous examination of these composite panels with the same skeleton but different fillers, namely, foamed concrete and fire-resistance polyurethane foam. In addition, presenting a comparison between these two kinds of panels and trying to observe which one will have a better performance from the technical point of view, thereby investigating the structural performance of both types of panels under the axial and bending tests to compare their results.

As stated earlier, the majority of the conventional building’s load belongs to the dead load of the ceilings and walls. This can lead to the inappropriate behavior of structures in a crisis like an earthquake, flood, and other national disasters as the high dead load give rise to the increase in internal forces and moments of building’s elements as well as quick destruction of structures.

On the other hand, the high construction speed in the developing housing technology needs to be considered seriously, especially after a crisis, because temporary or permanent houses should be constructed as soon as possible. According to the literature, employing composite precast panels with lightweight fillers were taken into consideration as structural elements, specifically for bearing walls. This method resolves the high dead load of the buildings, thereby reducing the internal forces of structural elements. Also, due to the precast feature, high-quality examinations could be applied to the composite panels in the factory prior to the construction. This has positive effects on the quality of the buildings and high-speed erection.

As mentioned in the literature by Wright [1, 2], Uy et al. [3], Mydin and Wang [4], Prabha et al. [6], Xu and Chen [7], Hegyi [8], and Ridha et al. [9], these researchers investigated on various composite panels infilling with specific materials in order to propose different precast panels to take advantage of their features in the developing housing technology.

In modern construction, cold-rolled galvanized sheets are taken into account as this method benefits from the high construction speed and an easy set-up. However, this lightweight galvanized sheet has a problem buckling, especially in the axial loads of the bearing walls. Hence, this paper presents an effort to propose a novel lightweight precast panel to obviate the heaviness problem of composite panels as well as reduce the buckling feature of cold-rolled galvanized sheets. These panels could be made as modular construction elements to speed up the erection with high quality. Besides, the majority of previous research presented different composite methods, especially in bearing walls, and the panels were tested axially, but this paper tries to investigate the behavior of combined precast panels both in axial and bending tests because they could be used as structural elements in the ceilings and walls. This attitude had been employed less in the previous research. Also, in this research, all panels are made and tested as a full-scale model to be more accurate and practical for future research in modeling the whole building with various loads.

In this paper, these composite panels are comprised of cold-rolled galvanized sheets, reinforced with wire meshes, and filled with foamed concrete. Along with that, in recent years, using polyurethane foam as heat and noise insulators has been taken into account. This material could be utilized as a filler in composite panels [25].

Due to the lightness of this foam, this paper tries to use polyurethane foam as an alternative for foamed concrete to make the combined panel lighter. Indeed, fire-resistance polyurethane foam is used in this research in order to perform a better function in the fire. These new panels are made of a similar skeleton, but different infilling materials and a thorough comparison is made between foamed concrete panels and fire-resistance polyurethane panels to examine the effectiveness of fire-resistance polyurethane foam in combined precast panels.

### 2. Materials and Methods

In this research, for the experimental study, different composite panels have been made for the experiment. These combined composite panels have been synthesized by surrounding cold-rolled galvanized sheets, reinforced with two top-bottom wire meshes which are welded to the surrounding galvanized sheets; also, zigzag shape shear wires welded to the top-bottom wire meshes and provide an integral skeleton infilling with foamed concrete or fire-resistance polyurethane foam. The dimensions of these panels are 3 m (length), 0.5 m (width), and 10 cm (thickness) (Figure 1). As mentioned earlier, two series of wire mesh have been
considered in the top and the bottom, plus zigzag-shaped shear wires along the panel at specific intervals (the distance between wires is 10 cm). Note that all the top and the bottom meshes and the zigzag-shaped wires have been welded to each other as well as to cold-rolled galvanized sheets in order to form an integrated skeleton. Then, these panels are filled with foamed concrete or fire-resistance polyurethane foam. For this purpose, a mold is prepared for these panels to be filled with foamed concrete or fire-resistance polyurethane foam (Figure 2).

The foamed concrete is created by adding a foaming chemical (usually some form of hydrolyzed proteins) to the
mixture. The foaming chemical, while being mixed, generates air bubbles quickly and stabilizes them. The foamed concrete is made in centrifuge devices, such that air and chemical are mixed alongside cement and water with specific ratios, thereby forming foamed concrete. In preliminary experiments, a mixture of cement, sand, and polystyrene foam was used as a filler material for the panels. However, this mixture as a filler for panels could not keep the wire mesh, and no integrated system could be established. Thus, a new plan was used for making the foamed concrete, which was mixing cement with water plus foaming chemical with air blowing through a wind pump. It generates suitable foamed concrete, which is lightweight. Further, the structural strength in this concrete had greater power and created an integrated system. During the production, panels are controlled with technical instrumentation because this type of concrete is sensitive to three factors: (1) compressor pressure, (2) the content of the foaming chemical, (3) the mixing time; during some seconds of impairment in the function, the foamed concrete may not be created. The mixture design for the foamed concrete is shown in (Table 1). The pressure of the centrifuge device was 9-10 atmosphere. Note that in this method, a wind pump is also used, which blows air into the mixture, and finally, the desired foamed concrete is formed. Also, in the construction of the foamed concrete panels, the foamed concrete fills the mold homogeneously with special accuracy.

Polyurethane is a type of foam where a closed cellular structure based on polyurethane, the presence of the catalyst, and blower materials are created through a chemical reaction of a polyisocyanate with acidic hydrogen-containing compounds. This foam is one of the best insulators for Sandwich panels and is good noise and heat insulator. Polyurethane is prone to fire risk problems, so many countries do not put it to use as a construction material; however, in this research, fire-resistance polyurethane foam is applied to fill the composite panels. Now, in order to lighten and enhance the bending as well as axial strength of

Figure 2: The mold for making the combined composite panels.
panels, instead of concrete, fire-resistance polyurethane foam is used, which is a polymer foam. The mix design of the foam utilized in the experiment is as follows: 1 kg of the polyurethane resin is mixed with a 1.4 kg polyurethane hardener which functions as a catalyst. These two materials are mixed homogeneously by using an electric stirrer, then poured into the mold, and after 10–15 sec, this mixture hardens and adheres to the skeleton to form an integrated panel. The weight of the panels filled with fire-resistance polyurethane foam is around 40 kg, while this amount is around 70 kg for foamed concrete panels. Consequently, the weight in the fire-resistance polyurethane panels is roughly half of foamed concrete panels, and this contributes to the lightness of the building and better structural behavior in an earthquake and other national disasters. Eight foamed concrete panels are made for the bending test and four for the axial test. The types of mentioned panels, which vary in cold-rolled galvanized sheets’ thickness and wires’ diameter, are presented (Table 2). Having introduced the foamed concrete panels, now composite panels filled with fire-resistance polyurethane foam are discussed. Note that these panels are similar to the foamed concrete panels in terms of the internal structure, with the difference in the infilling material. The number of fire-resistance polyurethane foam panels is four, two of them for the bending test and the rest for the axial test. It should be considered that the notations are given in Figure 3.

The skeleton detail of fire-resistance polyurethane foam panels is similar to the type C-0.9-3 of foamed concrete panels (Table 2). 2.1. Compression Test on Cubic Foamed Concrete and Fire-resistance Polyurethane Samples. For the compression test of cubic samples, the California Bearing Ratio (CBR) device is used (Figure 4) because these cubic samples have low compression strength. Nine cubic samples are tested (5 cubic samples for foamed concrete and four cubic samples for fire-resistance polyurethane foam). The dimension specification, weight, special weight, and compression strength are shown in Tables 3 and 4.

2.2. Bending Test Set-Up. A four-point bending set-up is applied for the bending test. A particular interface is used between the hydraulic Jack and the panels to exert the force uniformly along the panel width. This connector consists of two loaders welded to a box frame, and this frame is attached to the load cell and the hydraulic Jack. The distance between the two loaders is 97 cm, and the distance between supports is 290 cm. Thus, the force is exerted in the middle 1/3 of the panels (Figure 5). Also, three strain gauges which are called Linear-Variable-Differential Transformers (LVDT) are installed to measure the displacement in three different parts of the panel; one below the middle part of the panel above which the hydraulic Jack is situated and two other Linear-Variable-Differential-Transformers (LVDT) are under the bars which exert the load uniformly (Figure 5).

In the bending test, the loading is applied gradually until the panel dissociates and the level of load absorption by the panels diminishes. This is performed for eight composite panels filled with foamed concrete and two composite panels filled with fire-resistance polyurethane foam. In the end, after the completion of the test, all data was extracted by the data logger (Figure 6).

2.3. Axial Test Set-Up. After the bending test, the axial test is performed. Now, four remaining foamed concrete panels and two fire-resistance polyurethane panels undergo the axial test. A particular set-up is designed for this test. Two reaction frames are used on both sides, where the hydraulic Jack is connected to one of the reaction frames. The panel is situated on two supports, and for the placing of the panel, two solid bars are used, which are lubricated so that the panel can move freely on these supports. Also, for the interface between the hydraulic Jack and the panel, a special connector is used between them, consisting of channel sections and boxes in order to exert the axial load to the panels symmetrically (Figure 7).

3. The Experimental Results of Foamed Concrete Panels in the Bending and the Axial Tests

The tension-displacement diagram for eight composite panels filled with foamed concrete in the bending test is shown in Figure 8. The maximum and the minimum bending force belong to C-0.9-4(2) with 4.08 N/mm² and C-0.5-3(1) with 1.92 N/mm², respectively. Also, C-0.9-4 and C-0.5-3 samples, according to Figure 9, in the axial test, endured the maximum and the minimum axial forces with 1.074 N/mm² and 0.784 N/mm² orderly. The bending and axial results are reported in Tables 5 and 6, respectively.

3.1. The Experimental Results of Fire-Resistance Polyurethane Foam Panels in the Bending and the Axial Tests and the Comparison between the Results of Fire-Resistance

<table>
<thead>
<tr>
<th>Table 1: The mixture design of the foamed concrete.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total volume (m³) 1 m³</td>
</tr>
<tr>
<td>Cement content (kg) 270 kg/m³</td>
</tr>
<tr>
<td>Water content (kg) 162 kg/m³</td>
</tr>
<tr>
<td>The bubbling chemical volume (kg) 1.2 kg/m³</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2: The notation of composite panels filled with foamed concrete.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>C-0.5-3</td>
</tr>
<tr>
<td>C-0.5-4</td>
</tr>
<tr>
<td>C-0.9-3</td>
</tr>
<tr>
<td>C-0.9-4</td>
</tr>
<tr>
<td>P-0.9-3</td>
</tr>
</tbody>
</table>
In this section, experimental results of the bending and the axial test between foamed concrete panels (C-0.9-3) and polyurethane panels (P-0.9-3) are compared. In these panels, general skeletons, comprised of cold-rolled galvanized sheet and the wire type, are the same, but the filler is either foamed concrete or fire-resistance polyurethane foam.

### Table 3: Special weight, dimension specification, and compression strength table (foamed concrete samples 10 cm * 10 cm * 10 cm).

<table>
<thead>
<tr>
<th>Panels’ number filled with foamed concrete</th>
<th>Length (cm)</th>
<th>width (cm)</th>
<th>height (cm)</th>
<th>Weight (kg)</th>
<th>Special weight (kg/m³)</th>
<th>fc (kg/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-0.5-3-(1)</td>
<td>10</td>
<td>0.32</td>
<td>320</td>
<td>37000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-0.5-3-(2)</td>
<td>10</td>
<td>0.35</td>
<td>350</td>
<td>28878</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-0.9-4-(1) &amp; C-0.9-4-(2)</td>
<td>10</td>
<td>0.36</td>
<td>360</td>
<td>32808</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-0.5-4-(1) &amp; C-0.5-4-(2)</td>
<td>10</td>
<td>0.47</td>
<td>470</td>
<td>37550</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-0.9-3-(1) &amp; C-0.9-3-(2)</td>
<td>10</td>
<td>0.48</td>
<td>480</td>
<td>36502</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Polyurethane Foam Panels with Foamed Concrete Panels

In this section, experimental results of the bending and the axial test between foamed concrete panels (C-0.9-3) and polyurethane panels (P-0.9-3) are compared. In these panels, general skeletons, comprised of cold-rolled galvanized sheet and the wire type, are the same, but the filler is either foamed concrete or fire-resistance polyurethane foam. In the following diagram, a comparison is made on...
Table 4: Special weight, dimension specification, and compression strength table (fire-resistance polyurethane foam samples 10 cm * 10 cm * 10 cm).

<table>
<thead>
<tr>
<th>Panels’ number filled with polyurethane foam</th>
<th>Length (cm) - width (cm) - height (cm)</th>
<th>Weight (kg)</th>
<th>Special weight (kg/m³)</th>
<th>fc (kg/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-0.9-3-(1)</td>
<td>10</td>
<td>0.0945</td>
<td>94.5</td>
<td>75000</td>
</tr>
<tr>
<td>P-0.9-3-(2)</td>
<td>10</td>
<td>0.0914</td>
<td>91.4</td>
<td>82000</td>
</tr>
<tr>
<td>P-0.9-3-(3)</td>
<td>10</td>
<td>0.0866</td>
<td>86.6</td>
<td>72000</td>
</tr>
<tr>
<td>P-0.9-3-(4)</td>
<td>10</td>
<td>0.0892</td>
<td>89.2</td>
<td>80000</td>
</tr>
</tbody>
</table>

Figure 5: The four-point bending set-up.

Figure 6: (a) The bending test set-up; (b) the data logger; (c) the placement of LVDTs under the panel.
the bending experimental results between four samples, two of which are filled with foamed concrete (bending test C-0.9-3 type) while the two others are filled with the fire-resistance polyurethane foam (bending test P-0.9-3 type) (Table 7 and Figure 10). As stated earlier, the bending and axial samples filled with fire-resistance polyurethane are only one type, and its wire diameter and cold-rolled galvanized sheet thickness are similar to the C-0.9-3 type of foamed concrete. Thus, the results are compared with the C-0.9-3 panel (Table 8 and Figure 11).
According to the bending and the axial diagram for both foamed concrete and fire-resistance polyurethane foam panels, the cold-rolled galvanized thickness is far more effective in panels’ load-bearing capacity than the type of wires. Take C-0.5-4 and C-0.9-4 as an example. When the bending and the axial test results of C-0.5-4 and C-0.9-3 are analyzed, although C-0.5-4 consists of thicker wire, it is evident that C-0.9-3 panels provided significantly higher strength compared to C-0.5-4 as C-0.9-3 comprised of thicker cold-rolled galvanized sheet. This shows that the thickness of cold-rolled galvanized sheets contributes higher to the load-bearing capacity than the wires.

In addition, according to the bending and the axial results, the charts demonstrate a better function for fire-resistance polyurethane foam panels than foamed concrete panels. Based on comparative results, P-0.9-3 and C-0.9-3 have the same skeletons. The information suggests considerably higher bending strength f70 or fire-resistance polyurethane foam panels to over approximately 50% higher than that of foamed concrete panels (Figure 10). Along with that, as far as the axial chart is concerned, the overall trend shows that the fire-resistance polyurethane foam increased the axial strength to above 10% higher than foamed concrete (Figure 11). As a result, fire-resistance polyurethane foam panels have a significantly better effect on the bending and the axial strength than foamed concrete in the combined composite panels.

The results revealed that the application of the fire-resistance polyurethane foam as infilling material performs higher strength in comparison with the foamed concrete filler and enhances the bending and axial strength of the composite panels. Besides, the weight of the fire-resistance polyurethane foam panels is around 40 kg; therefore, these kinds of panels, in addition to higher strength, are much lighter (around half) than the foamed concrete panels with a weight of around 70 kg. Since the lightness of the building is one of the most important factors in constructing the building, applying the fire-resistance polyurethane foam as infilling material could resolve multiple problems of the composite panels. However, the findings are found to be

---

**Table 5:** The bending test results for 8 foamed concrete panels.

<table>
<thead>
<tr>
<th>Type</th>
<th>Maximum bending tension (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-0.5-3(2)</td>
<td>2.04</td>
</tr>
<tr>
<td>C-0.9-4(2)</td>
<td>4.08</td>
</tr>
<tr>
<td>C-0.9-3(1)</td>
<td>3.24</td>
</tr>
<tr>
<td>C-0.5-4(2)</td>
<td>2.4</td>
</tr>
<tr>
<td>C-0.9-3(2)</td>
<td>3.54</td>
</tr>
<tr>
<td>C-0.5-4(1)</td>
<td>2.28</td>
</tr>
<tr>
<td>C-0.5-3(1)</td>
<td>1.92</td>
</tr>
<tr>
<td>C-0.9-4(1)</td>
<td>3.84</td>
</tr>
</tbody>
</table>

**Table 6:** The axial test results for 4 foamed concrete panels.

<table>
<thead>
<tr>
<th>Type</th>
<th>Maximum axial tension (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-0.5-4</td>
<td>0.980</td>
</tr>
<tr>
<td>C-0.5-3</td>
<td>0.784</td>
</tr>
<tr>
<td>C-0.9-3</td>
<td>1.020</td>
</tr>
<tr>
<td>C-0.9-4</td>
<td>1.074</td>
</tr>
</tbody>
</table>

**Table 7:** The bending test results for two fire-resistance polyurethane foam panels.

<table>
<thead>
<tr>
<th>Type</th>
<th>Maximum bending tension (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-0.9-3(1)</td>
<td>5.1</td>
</tr>
<tr>
<td>P-0.9-3(2)</td>
<td>5.0</td>
</tr>
</tbody>
</table>

---

![Figure 9: The tension-displacement diagram in the axial test for 4 composite panels filled with foamed concrete.](image-url)
Figure 10: The comparison of the bending test results between fire-resistance polyurethane foam panels and C-0.9-3 type of foamed concrete panel.

Table 8: The axial test results for two fire-resistance polyurethane foam panels.

<table>
<thead>
<tr>
<th>Type</th>
<th>Maximum axial tension (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-0.9-3(2)</td>
<td>1.134</td>
</tr>
<tr>
<td>P-0.9-3(1)</td>
<td>1.0975</td>
</tr>
</tbody>
</table>

Figure 11: The comparison of the axial test results between fire-resistance polyurethane foam panels and C-0.9-3 type of foamed concrete panels.
stand-alone. They are expected to have been related to the outcome of the earlier studies that were reviewed to underpin the current study, but this paper presents a novel construction method to resolve the heaviness of the buildings and increase the construction speed. This will place the findings of the study in the proper and broader perspective. Moreover, this paper will further ascertain the improvement obtained by the use of the fire-resistance polyurethane foam and foamed concrete in cold-rolled galvanized sheets to resolve the heaviness problem of composite panels. Along with that, the buckling problem of the cold-rolled galvanized sheets under low forces will be delayed by the idea of making the combined composite panel (Figure 1) and infilling these combined panels with the foamed concrete or the fire-resistance polyurethane foam as this integrated behavior does not allow cold-rolled galvanized sheets to buckle under low forces, and the whole system can tolerate higher loads. Moreover, this precast panel technique will play a key role in developing the quality of the building’s structural elements before construction and increasing the construction speed.

4. Bending and Axial Test Observation and Discussion

Regular bending and axial behavior of these panels are prepared in this part of the research; thus, the bending test on the C-0.5-3 type panel and the axial test on the C-0.5-4
type panel filled with foamed concrete are shown as the sample behavior of other tests.

4.1. Bending Discussion

Step 1: in the initial stage (tension level 1.89 N/mm²), cracks appear on the top of the panel due to the compression tension (Figure 12)

Step 2: in the next step (tension level 1.95 N/mm²), these cracks progress rapidly, and the bending strength levels off steeply (Figure 13)

Step 3: finally, when the strength’s level diminishes (tension level 1.32 N/mm²) the cold-rolled galvanized sheets between loaders buckle, so the panel loses its capacity and begins to be deformed completely (Figure 14)

According to the test observation, these panels absorb their maximum load before progressive cracks, and after that, their load absorption levels off and experiences a steep downward trend. Moreover, the same experimental behavior is observed in other foamed concrete panels and fire-resistance polyurethane foam panels (Figure 15).

4.2. Axial Discussion

Step 1: in the initial stage (tension level 0.626 N/mm²), some longitudinal cracks appear between the foamed concrete and the cold-rolled galvanized sheets (Figure 16)

Step 2: in the next step (tension level 0.8104 N/mm²), the longitudinal cracks increase, and cold-rolled galvanized sheets are about to buckle (Figure 17)
Step 3: finally (tension level 0.9244 N/mm²), deep cracks appear and cold-rolled galvanized sheets buckle completely in the crack zones, and the upward trend levels off drastically (Figure 18).

According to the tension-displacement chart and observation, the panel absorbs the maximum load before deep cracks and loses the load capacity when cold-rolled galvanized sheets buckle (Figure 19).

5. Conclusion

Through performing experiments, it is observed that the bending and the axial capacity of the combined composite panels infilling with the foamed concrete are very suitable. With this combined system, the cold-rolled galvanized sheets, which endure low bending tension under normal conditions, have been able to stand around 1.92–4.08 N/mm² of bending load and around 0.98–1.074 N/mm² of axial loads through this combined composite system because the fillers and the reinforced skeleton present the integrated behavior which contributes to the cold-rolled galvanized sheets to buckle in the high-tension level and this gives rise to bear a higher load. This suggests that the application of the reinforced foamed concrete has caused the capacity of cold-rolled sheets to grow significantly in comparison with the state without the combined system infilling with foamed concrete; also, this composite behavior enhances the axial strength. In addition to the foamed concrete as the filler of the combined panels, another material called the fire-resistance polyurethane foam is also used as the infilling material of this reinforced skeleton. Its bending and axial experimental results are compared with those of the foamed concrete panels. The results indicate that, in addition to the greater lightness of the panels (roughly 40% lighter), these fire-resistance polyurethane panels show greater strength in the bending and the axial tests, where this value for the bending test is around 50% higher and 10% higher for the axial test in comparison with the foamed concrete infilling. Moreover, after unloading, these fire-resistance polyurethane panels return to their initial state to a large extent, suggesting the advantage of the fire-resistance polyurethane panels over the foamed concrete panels (along with the high strength).
All in all, these combined composite panels are useful for the ceiling and load-bearing walls for short and medium-sized buildings, and they can be erected in a short time as they are precast panels; also, these composite panels are suitable for temporary and permanent accommodation, especially in a crisis, such as earthquakes or floods as they have a suitable load absorption and could be constructed with high speed.

In addition, the results suggest that the application of the fire-resistance polyurethane foam as the infilling material performs a higher strength for both bending and axial tests in the combined composite panel compared to the foamed concrete infilling. As a result, this methodology could resolve the multiple problems of composite panels, such as the heaviness of the building, displacing heavy construction elements by huge cranes, and time-consuming construction.

As stated in the paper, the results will help construction industry stakeholders to pay attention to the usage of these light composite precast panels in short and medium-sized buildings, especially in a crisis, because such panels could easily be erected at high speed without special construction equipment. Also, short-rise residential or office buildings account for the majority of the construction industry, and these precast panels could be used as ceilings and bearing walls, thereby increasing the construction speed and quality. This is a positive attitude for the reason that using the conventional reinforced concrete skeleton, the bearing wall system, and the steel skeleton make mentioned buildings unnecessarily heavy, and this can lead to the rise in internal forces when a crisis happens, such as an earthquake. With regard to using such panels, the heaviness of the buildings could be reduced significantly; also, due to the modular feature of these panels, factories can put such panels to many constructional uses in the industry. For these reasons, applying this novel method could be highly effective for future construction.

Data Availability
Data are openly available in a public repository that issues datasets, so data are openly available without any restriction.

Conflicts of Interest
The authors declare that they have no conflicts of interest.

Acknowledgments
The authors thank the University of Tehran because they allowed work in the structure laboratory. The authors also thank “Safe Saze Moghadam” Company because this company materially supported the paper.

References


