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Experimental and Numerical Simulation of Effects of High Temperature on RC Frame Infilled with Sandwich Panel

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Abstract

This study investigated the structural behavior of reinforced concrete (RC) frames infilled with masonry walls and polyurethane (PU) sandwich wall panels at elevated temperatures. This study aims to assess the influence of temperature on the stiffness and load-carrying capacity of infilled frames, optimize the thickness of the sandwich wall panel, and compare the performance of masonry and sandwich infill systems. Analytical investigations were conducted using finite element analysis software (ABAQUS) to simulate the behavior of the frames at elevated temperatures and consider various configurations of skin thickness for PU sandwich panels. Experimental tests were performed to validate the analytical results. The frames were subjected to transient temperature conditions and uniform unit loads to evaluate their response. Experimental tests were conducted on RC frames infilled with masonry and sandwich-wall panels at elevated temperatures. The frames were subjected to static loading, and their deformations and failure modes were observed. The analytical study revealed that an increase in the skin thickness of the sandwich panel improved its temperature resistance, stress-withstanding ability, and displacement. A skin thickness of 0.45 mm was determined to be the optimal choice considering stress levels and economic factors. The infilled frame with the sandwich wall panel exhibited a 19.22% higher initial stiffness than the masonry wall panel in the experimental tests. The ultimate load-carrying capacity decreased by 17.86% in the infilled sandwich wall panel frame compared to the masonry infill system. The study provides valuable insights into the behavior of RC frames infilled with masonry walls and sandwich wall panels under elevated temperatures. The optimized thickness of the PU sandwich panel was determined by balancing the thermal resistance and the structural performance. The infilled frames with sandwich wall panels exhibited enhanced stiffness but slightly reduced ultimate load-carrying capacity compared with the masonry infill. These findings contribute to the understanding of thermal effects on building structures and can aid in the design and construction of more resilient and efficient buildings in the future.

Keywords: Sandwich Panel; Finite Element Analysis; Transient Temperature; Optimization; Skin Thickness.

1. Introduction

Sandwich panels are innovative construction materials that are widely used in modern building designs owing to their excellent structural properties, thermal insulation, and versatility. These panels consist of a lightweight core material sandwiched between two rigid outer layers that are often made of metals, plastics, or composite materials. The core material is typically selected for its insulating properties, whereas the outer layers provide strength and protection. One of the critical factors influencing the performance of sandwich panels is their behavior under varying temperature conditions. Temperature fluctuations, particularly extreme heat or cold, can significantly affect the structural integrity and thermal efficiency of these panels. Understanding how sandwich panels respond to different temperature levels is essential for designing energy-efficient buildings, ensuring occupant comfort, and maintaining the structural stability of

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construction in various climates. In this context, this introduction explores the thermal behavior of sandwich panels under temperature variations, highlighting the key factors that influence their performance. It delves into the materials used in sandwich panels, the challenges posed by temperature changes, and measures taken to optimize their thermal resistance.

In addition, the introduction emphasizes the importance of studying sandwich panels under elevated temperatures to ensure their reliability and safety in real-world applications. The discussion touches upon various aspects, such as the types of core materials used, the effects of temperature on structural integrity, and strategies employed to enhance their resistance to thermal stress. By understanding the behavior of sandwich panels under temperature conditions, engineers and architects can make informed decisions, leading to the creation of sustainable and resilient buildings under diverse environmental conditions. These frames are made of concrete and steel reinforcements and are used in conjunction with other building components, such as columns, beams, and slabs. A sandwich panel is typically made up of one internal core with a low-density material that is covered by two exterior layers of high-potency material called 'wythes' or 'skin.' The combination of sandwich-wall panels and RC frames can result in a high-performance building system that offers excellent structural stability and energy efficiency. The heat capacity and designed temperature determine the size and type of the core [1]. In previous investigations, Expanded Polystyrene (EPS) was employed as a composite with a suitable thickness and smooth surface [2–5], wavy [6–8], or rectangular shape [9, 10]. The EPS was employed in individual sections [7, 11] or in small servings between both affect progress and shear connections [12–14]. Corrugated EPS cores have been found [14, 15] to improve the behavior of RCSP when compared with a smooth surface core [6].

Wythes are employed to provide load resistors, reinforced covers, anchoring to interconnections, and surface integrity [14, 15]. Its thickness is often below the core level. The majority of studies [6, 7] employed reinforced concrete to build wythes, while one study [2, 8] utilized foamed cementitious materials to build wythes. Wythes reinforcing is given by wire mesh with varying diameters and square separation [9, 10]. In several investigations, reinforcing bars were added to the bottom walls in addition to wires [3, 5]. Shear connections join wythes on multiple sides. Shear connectors maintain the wythes and cores in position while also transferring the in-plane stress between both wythes [1]. Carbonari et al. [6], Gara et al. [7], and Bajracharya et al. [8] employed continuous one-way and two different truss-style shear connectors, while Benayoune et al. [3, 13] and Mohamad et al. [2] utilized diagonal-type stress connectors. Daniel Ronald Joseph et al. [4, 5, 11] employed fracture ribs and one-way structure fracture connectors. GFRP shear connections in the shape of ribs have also been employed [10, 16].

In previous studies, several procedures were utilized to build the samples. The wythes in the majority of research were built by casting concrete [9, 10]. In a few experiments, the top wythe was built by pouring concrete, whereas the lower wythe was built by spraying concrete [7, 8]. Several researchers have employed RC [6, 8] or concrete strength beams [5] at the support ends of specimens. It is the best replacement for concrete, brick, and hollow block walls because of its low self-weight [17]. It should be emphasized that in civil and structural engineering, sandwich structure panels and slabs are rarely exposed to compressive forces, and in some situations, perimeter RC columns at floor/roof levels are used to combine the walls and floors.

Significant shear was mainly transmitted in the EPS core sandwich structures owing to the adhesion and resistance between the concrete and EPS surfaces. In the case of EPS cores with flat surfaces, the adhesive and resistance between both the inner and the general are liable for the transmission of approximately 60% of the maximum stress [16, 18]. Sand blasting, inundations, and deformation on EPS surfaces [19] can improve shear force data transmission. Kazem et al. [20] investigated the durability or long-term influence of the bond of masonry and EPS surfaces. The ultimate stress of the test panels was unaffected by the freeze-thaw processes. External exposure for a short length of time (a research period of six months) had no discernible impact on the final shear strength of EPS sandwich structures [20]. To prevent unnecessary deteriorating effects on the EPS, it is advised that the corners of the EPS are thoroughly shielded from the atmosphere [20].

De Luca et al. [21] investigated the strengthening of masonry-Infilled RC frames using sandwich composite panels improved the lateral behavior and stiffness of the confined masonry wall. Benayoune et al. [13] investigated the structural behavior of precast sandwich panels under flexure experimentally and numerically. Finite element modeling of the test specimens was used in the theoretical investigation. Structural capacity of sandwich panels composed of polyurethane foam interiors and fiberglass fiber-reinforced polyester (GFRP) skins. Panels with and without GFRP ribs joining the skin were examined. The goal of this study was to create new insulating covering panels for structures [22]. In this study, CoDyre et al. (2018) present an analytical and case study of structural components with sandwich panels. According to the findings, adding a stiffener enhanced the composite rigidity by nearly five times analytically and 1.9 times in terms [23]. The thermal behavior of polyurethane foam is influenced by several factors, including its density, thickness, and the temperature difference between the two sides of the foam. Under steady-state conditions, polyurethane foam has low thermal conductivity, which means that it can effectively resist heat transfer through the material [24].

The PU rigid foam changes its mechanical properties in this temperature range [25]. However, under transient temperature conditions, the thermal behavior of polyurethane foam can be more complex and requires careful investigation. The thermal behavior and structural performance of sandwich wall panels with steel frames under transient temperature conditions can be used to optimize their design for improved fire safety and reliability. Sandwich wall panels with steel wythes can maintain their structural integrity for longer periods of time under fire conditions, and the temperature distribution and thermal stresses induced in the panels under fire conditions are crucial for ensuring their safe and reliable use in buildings [26].

The thermal behavior of sandwich wall panels with RC frames is a critical factor for ensuring indoor comfort and energy efficiency. Understanding the thermal behavior of sandwich wall panels with RC frames under transient temperature conditions is essential for the design of energy-efficient buildings. The thermal behavior of sandwich wall panels with RC frames is influenced by various parameters, such as the thickness of the insulation layer, the thermal conductivity of the insulation material, and boundary conditions. The temperature distribution and heat flux through the panel are significantly affected by the transient temperature profile. It also shows that increasing the thickness of the insulation layer and reducing the thermal conductivity of the insulation material can significantly reduce heat transfer through the panel [27]. A higher load-carrying capacity with a low weight makes the sandwich suitable for infill in RC frames. The use of high-strength materials and thicker panel designs can improve the structural performance of sandwich-wall panels under blast loading [28]. In the study presented in this article, from the perspective of structural behavior, it is indispensable to consider thermal stresses.

Previous studies have been conducted on RC frames infilled with masonry, both with and without consideration of elevated temperatures. However, investigations regarding RC frames infilled with sandwich panels under elevated temperatures have not been conducted thus far. Also, the investigation of different skin thicknesses with the effect of elevated temperatures was carried out in this study with an optimization technique. A comparative study was performed using non-linear analysis on an RC frame infilled with both masonry and sandwich wall panels.

In this study, an investigation is attempted using the interaction between 1/4th scaled single-bay single-story RC frames [29] infilled with masonry walls and polyurethane (PU) sandwich wall panels. To evaluate the interactions, sandwich wall panels of various thicknesses were considered for the study. A heat flux was applied to understand the thermal behavior of the wall panel. Furthermore, it involves applying a unit load analytically to both RC frames infilled with masonry and sandwich wall panels. The goal of this step was to observe the stiffness of both types of frames and compare the results. Based on these results, researchers further optimized the thickness of the sandwich wall panel. The optimized panel thickness was then experimentally applied to RC frames and compared with conventional RC masonry frames.

2. Material and Methods

Figure 1 shows the flowchart of the research methodology through which the objectives of this study were achieved.

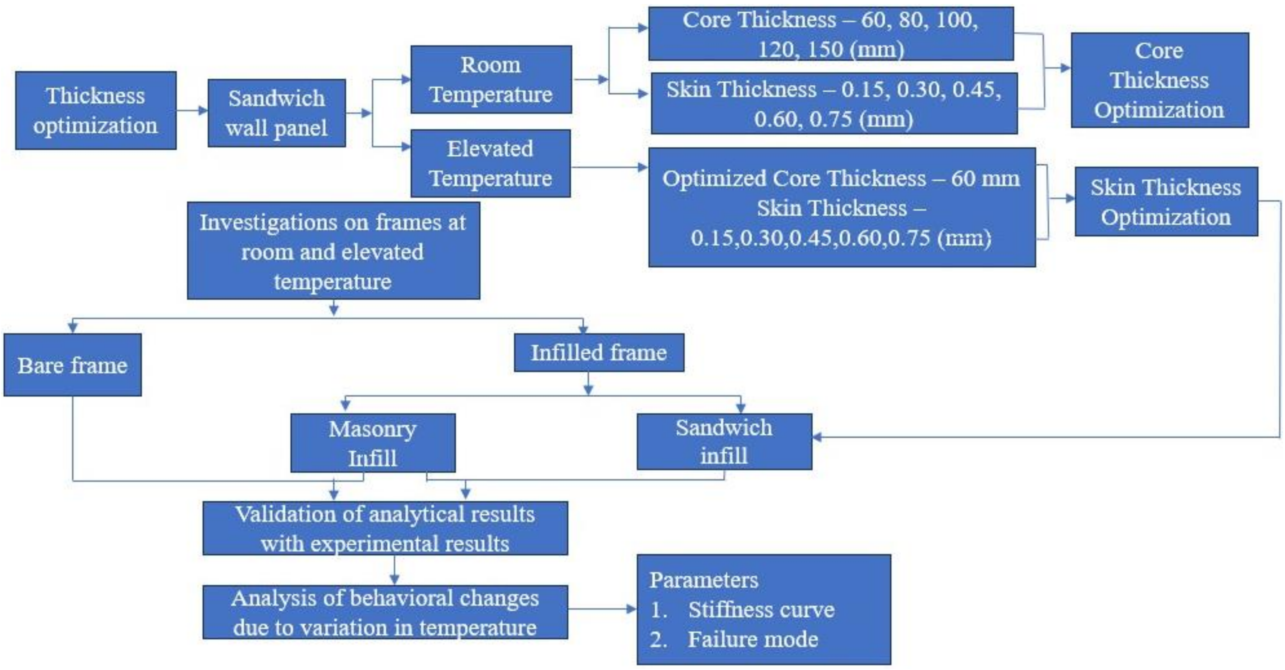


Figure 1. Flowchart for analytical and experimental work

2.1. Analytical Investigation

The analytical investigation was conducted using the FEA software (ABAQUS). The assembly and geometry of the masonry and PU sandwich panels filled with RC frames are shown in Figure *2*. Input values were provided for the material properties of concrete of grade M25 and steel of grade Fe415. Rectangular meshes were selected according to the linear shape of the column and beam, which were modeled using the quad 3D element type. In the finite element model, the concrete and reinforcement were connected using the embedded connection technique, whereas the concrete was connected to the mesh using tie connections. A Mesh Convergence Study was conducted to identify the element size for the analysis. Mesh sizes ranging from 20 to 140 mm^2 at an incremental rate of 20 mm^2 were subjected to test verification. The displacement was calculated for meshes of different sizes. The displacement values with respect to mesh size are shown in Figure 3. From the experiment, it was observed that beyond 50 mm^2, there was no significant deviation in displacement. Hence, an average mesh size of 70 mm^2 was selected for further analyses. To perform the analysis, a uniformly distributed load of 1 kN was applied under fixed support conditions at the bottom of the frame. The material properties were determined through experimental investigations, wherein the Young's modulus and Poisson's ratio of the cylinder were derived from a compressometer test as 25 N/mm^2 and 0.2, respectively. This analysis was divided into two stages: steady-state and transient-state analyses. During the steady-state analysis, a heat flux was applied and the corresponding temperature was observed. This stage helps identify the critical temperature at which the material fails. Based on the maximum temperature, a transient state analysis was performed with respect to time.

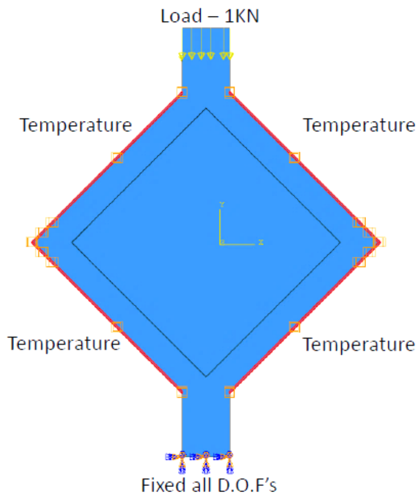


Figure 2. Reinforced concrete frame infilled with Sandwich panel

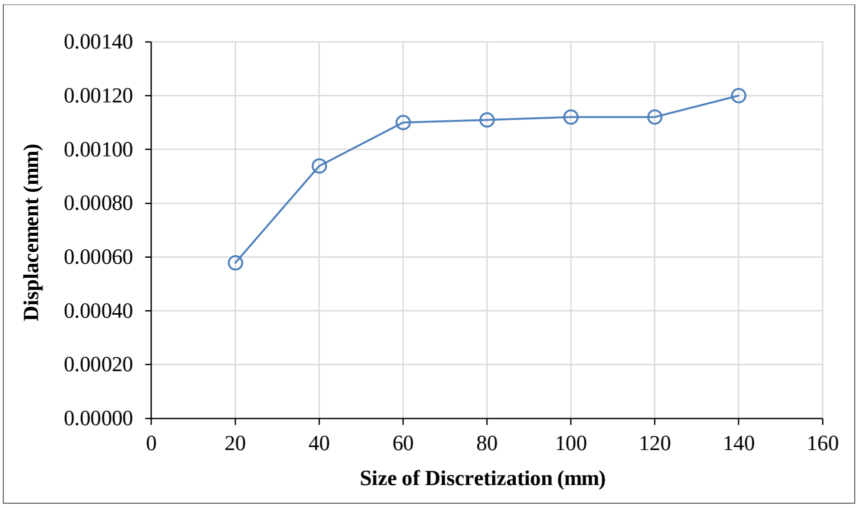
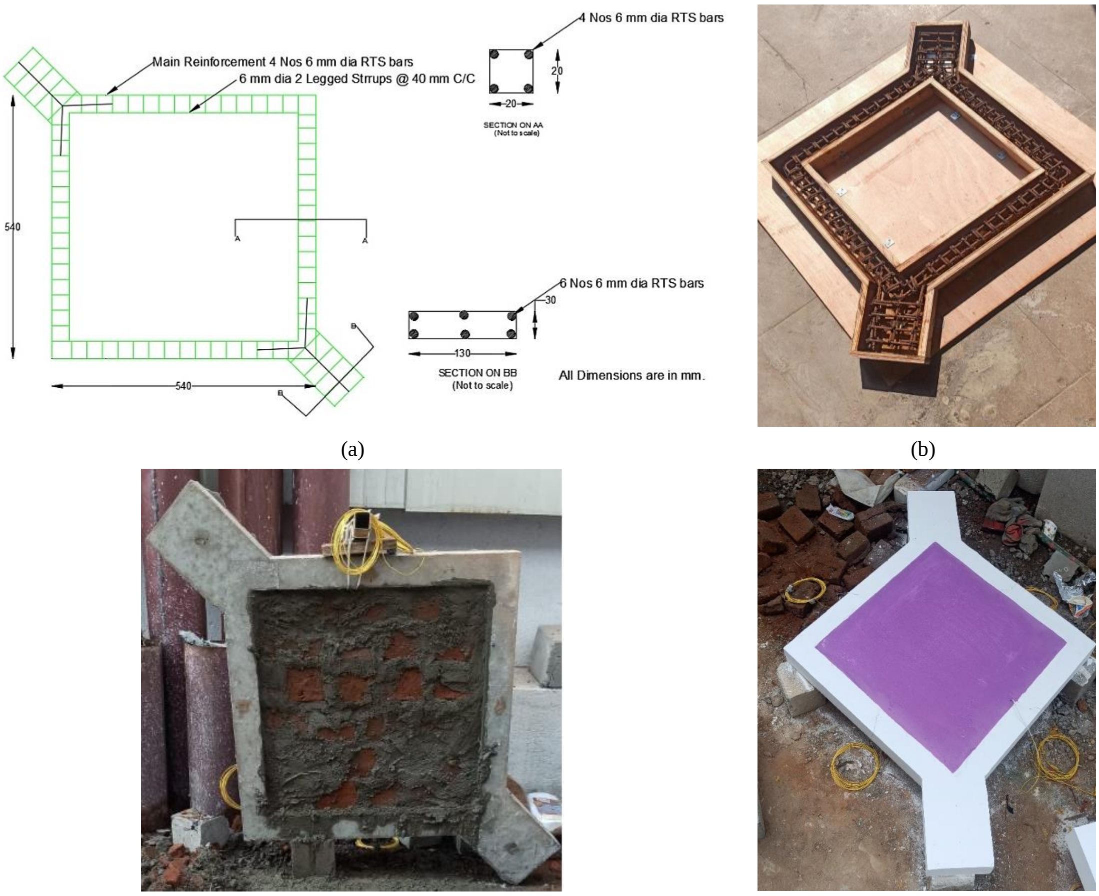


Figure 3. Mesh Convergence study

2.2. Experimental Arrangements

2.2.1. Frame and Panel Description

In this study, a square RC frame was used to determine the stiffness of the RC frame filled with masonry and sandwich wall panels, as shown in Figure 4. An RC column with dimensions of 50 × 50 mm with four longitudinal bars of 6 mm was used, and stirrups were placed at a spacing of 40 mm c/c with 6 mm diameter bars. RC beams were constructed with dimensions of 50 × 50 mm with four longitudinal bars of 6 mm, and shear reinforcement was placed at a spacing of 40 mm c/c with 6 mm diameter bars. The infill panel size for both the masonry and sandwich panels was 500 × 500 mm, and the thickness of the masonry and sandwich panels was 50 mm. Here, the sandwich panel core (PU) thickness was 48.5 mm and the skin thickness was 0.75 mm. The frame was subjected to an in-plane compressive unit load, and the stiffness of the frame was analyzed. The frames and panels were subjected to an elevated temperature. The influence of temperature was analyzed and compared with that of masonry-infilled RC frames.



(a) (b)

(c) (d)

Figure 4. Reinforcement Details and masonry work

2.2.2. Preload Arrangements

In the analytical investigations using the transient state, the temperature and loadings were simultaneously attained at a rate of 55 min. Owing to practical constraints in the experimental investigations, this concept of loading was simulated using the arrangement shown in Figure 5. It consists of two 10 mm plates with four rods of 20 mm diameter fixed using bolt connections. A load cell was placed over the specimen to simultaneously evaluate the intensity of loading upon the rotation of the bolts. A load of 3.73 tons was applied through the 180° rotation of the bolt. This was applied for p-reloading in the frame during the experiment.

The specimen with the aforementioned setup was placed in an oven at 225 °C for approximately 2 hours. The temperature measurements were carried out using a thermocouple fixed at five locations: two in the beams, two in the columns, and one in the panel. Upon the application of temperature, the specimen shifted to the loading frame, as shown in Figure 6. Displacement and strain were evaluated for their respective loadings.

(a) (b)

Figure 5. Preload arrangements and temperature setup of Infilled frame

(a) (b)

Figure 6. Testing setup for RC frame Infilled with masonry wall panel and sandwich wall panel

2.2.3. Brick Masonry Testing

Building stacks of five bricks bonded together with a 5 mm-thick layer of rich mortar with a height-to-thickness ratio of 3.45 were used to test the strength of the brick masonry. The bricks were rewetted and wrapped in wet burlap for 28 days for curing. The use of rich mortar with a 1:4 ratio improved the compressive strength of the masonry prism, resulting in an increase in its compressive strength. The testing revealed a compressive strength of 6.79 N/mm^2, indicating an overall increase in the strength of the masonry prism. This process is illustrated in Figure 7.

(a) (b) (c)

Figure 7. Brick masonry testing setup and specimens

The compressive strength of the masonry was tested using prism stacks composed of five bonded bricks with a length-to-thickness ratio of 3.45. Specimens were tested in various loading setups with a simply supported configuration to determine the flexural bond strength of the brick masonry. Brick's flexural strength has been determined to be 0.69 N/mm^2 (Figure 7-b).

To assess the shear bond strength of the mortar joints between the bricks, a triple brick specimen was used, as shown in Figure 7-c. The test setup revealed that the horizontal mobility of the top and bottom bricks was restricted, whereas the movement of the center brick was unrestricted. The force was increasingly applied via the compressive testing machine piston rod until the bond between both the brick and mortar joints partially collapsed, after which point the shear bond strength was estimated. As a result of the increased flexural bond strength, there was a significant increase in the shear strength, which was found to be 0.95 N/mm^2, as shown in Table 1.

Table 1. Strength of brick masonry

Type	Compressive Strength (N/mm^2) (Prism)	Flexural Bond Strength (N/mm^2)	Shear Bond Strength (N/mm^2)
Brick masonry	6.79	0.69	0.95

2.2.4. Polyurethane Foam Material

Polyurethane foam is a typical material used as a component of sandwich panels. This term encompasses an array of foams composed of polymers of cellulose molecules linked together through urethane linkages. It might be either elastic or rigid; however, it generally has a low density. Expanded polystyrene foam is commonly used in mattresses and fabrics, whereas rigid polyurethane foam is used as an insulation material and in vehicle panels. The small cell dimensions of open-cell foams and the small size distribution of particles make them perfect thermal insulators for applications ranging from paper cups to wall panels. They exhibit excellent energy absorption owing to their low compressive rigidity and substantial deformation ability. The material properties of polyurethane and steel are listed in Table 2.

Table 2. Material properties of steel and Polyurethane [27]

Properties	Unit	Polyurethane	Steel
Conductivity	W/mK	0.5	50
Density	Ton /mm^3	1.7x10^{-9}	7.8×10^{-9}
Specific heat	J/g ºC	1.57	0.466

3. Results and Discussion

The results and a discussion of the analytical investigation are presented below.

3.1. Analytical Investigation on Influence of Elevated Temperature on Masonry Infill RC Frame

Variations in temperature considerably affect the structural performance of the masonry and surrounding elements, such as the roof, beam, and column. The transient temperature induces thermal stress and damages the structure. In this investigation, masonry and sandwich wall panel-filled RC frames were analyzed. A unit load is applied and subjected to a transient temperature. A transient temperature was applied to the masonry-infilled RC component. The temperature was maintained at 23°C, which is considered the ambient temperature. Every five minutes, the stress variation with respect to the temperature was analyzed. Masonry Infilled RC frames are subjected to temperature exposure until the masonry components fail due to heat. Structural failure was observed at 380°C for both the masonry and sandwich wall panels, and it was considered to be the critical temperature, as depicted in Figure 8. The maximum principal stress observed at the critical temperature is shown in Figure 9. A unit load was applied, and the displacement of the component was determined, as shown in Figure 10.

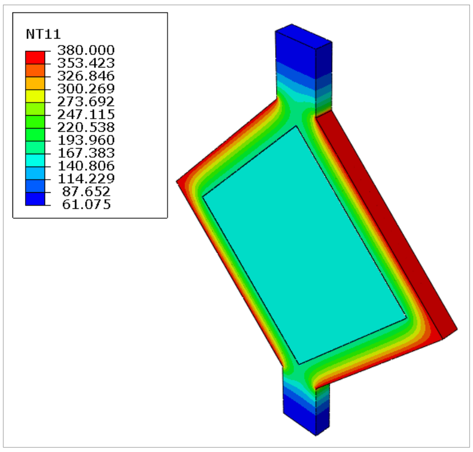


Figure 8. Maximum temperature in RC frame

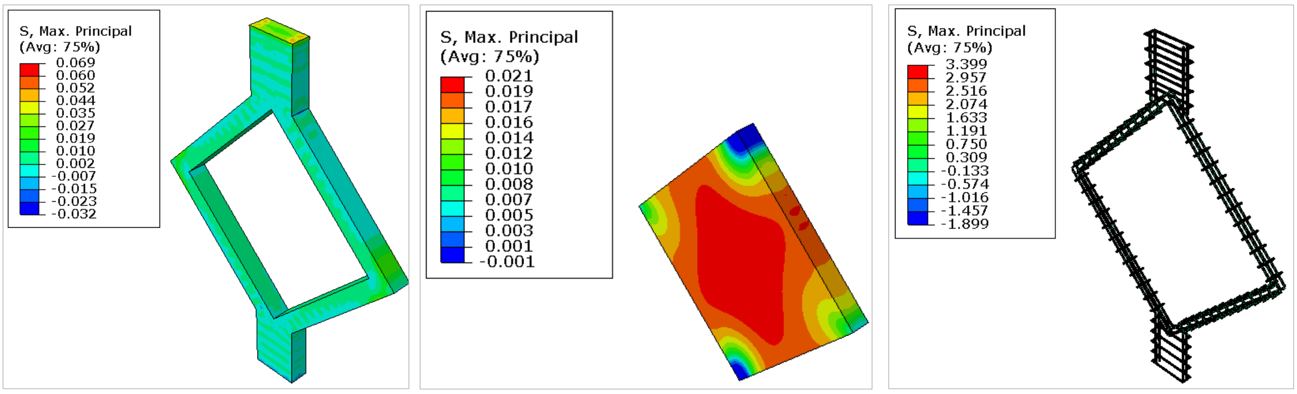


Figure 9. The maximum principal stress of the individual element at critical temperature

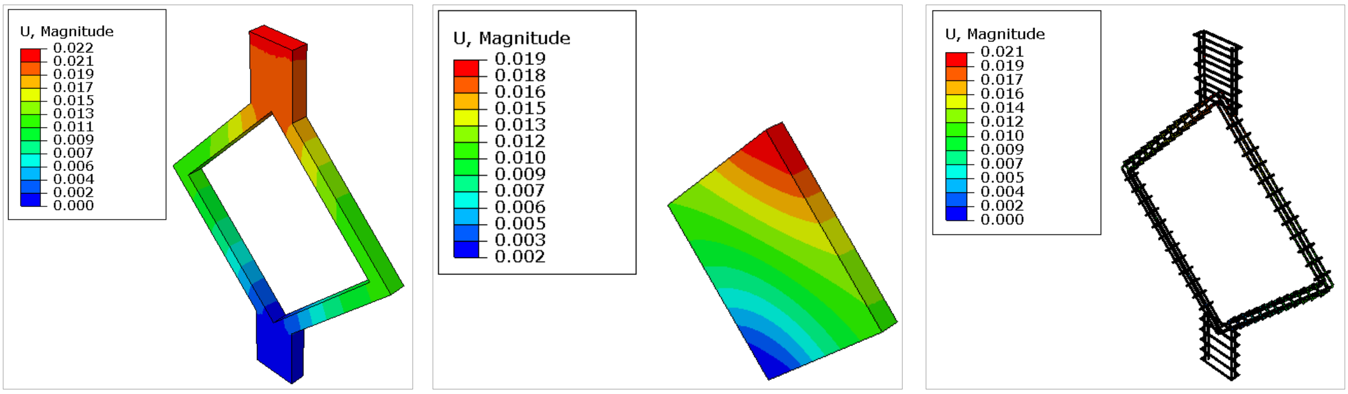


Figure 10. Displacement of the individual element at critical temperature

The maximum principal stress and displacement were 0.069 MPa and 0.022 mm, respectively, at the critical temperature for the unit load in the masonry-infilled RC frame. Similarly, the maximum principal stress and displacement were found to be 0.063 MPa and 0.019 mm, respectively, at the critical temperature for the unit load in the sandwich-filled RC frame. The stress and displacement in each element were calculated using the developed model to assess the influence of the temperature (see Figures 11 to 13 and Table 3).

Table 3. Stiffness comparison for RC frame infilled with masonry and sandwich wall panel

Description	Load (kN)	Displacement	Stiffness (kN/mm)
Infilled Masonry Frame	1	0.022	45.55
Sandwich wall panel frame	1	0.019	52.63

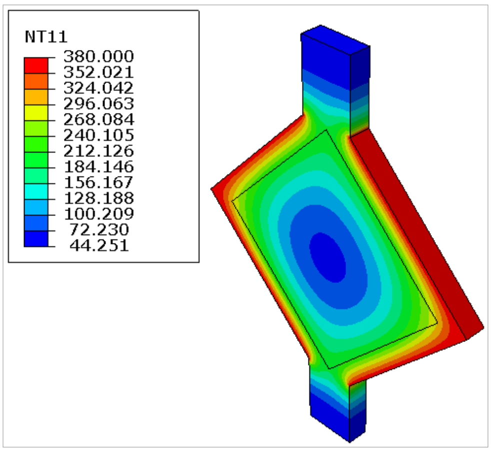


Figure 11. Temperature influence on the component

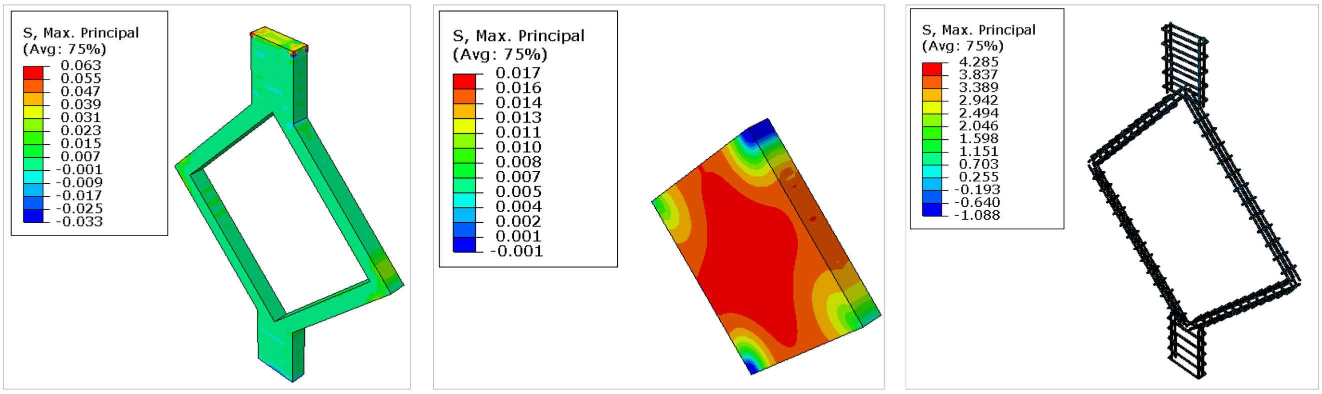


Figure 12. Maximum principal stress induced in each element

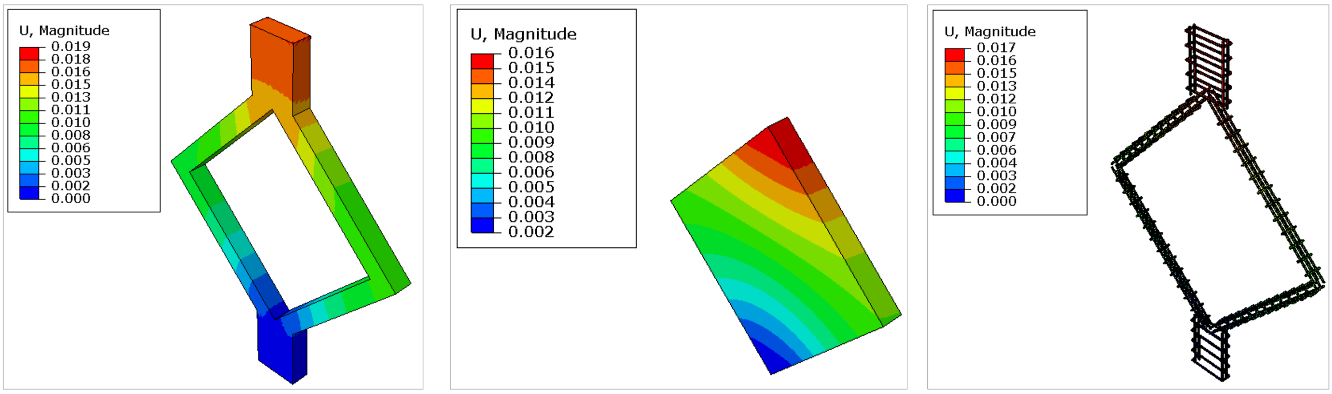


Figure 13. Displacement induced in each element

3.2. Analytical Investigation for Optimization of Sandwich Wall Panel

The analytical investigation was conducted using the FEA software (ABAQUS). The assembly and geometry of the PU sandwich panel are illustrated in Figure 14. This analysis was carried out for different configurations of varying skin thicknesses in 50-mm core composite elements. The skin thickness of 0.15 mm, 0.30 mm, 0.45 mm, 0.60 mm, and 0.75 mm has been used to find the optimal skin thickness for the panel. This analysis was divided into two stages: steady-state and transient-state analyses.

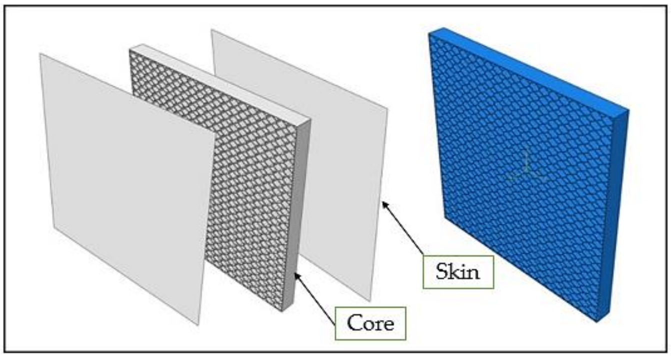


Figure 14. Geometry and assembly of the PU sandwich panel

For the analysis, a uniformly distributed load of 1 kN with fixed support conditions was applied to the infilled sandwich panels. During the steady-state analysis, a heat flux was applied, and the corresponding temperature was observed, as shown in Figure 15. This stage helps to identify the maximum temperature at which a material with a particular thickness is completely burned. Based on the maximum temperature, a transient state analysis was performed with respect to time. Various parameters, such as temperature distribution along the cross section, resistance time of the specimens, and maximum temperature resistance capacity, were monitored over time. A maximum duration of 55 minutes was used to attain the defined temperature for all the panels with varying thicknesses.

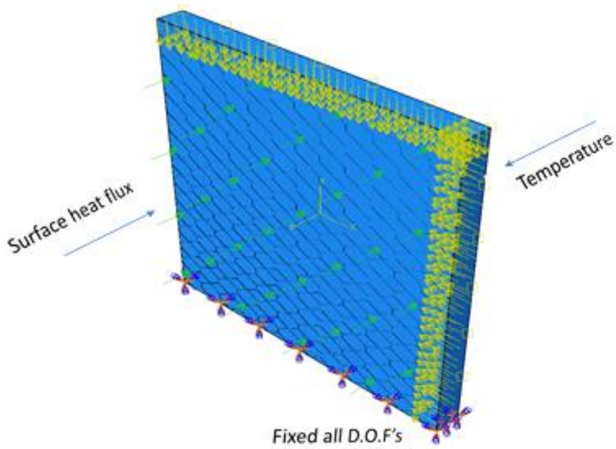
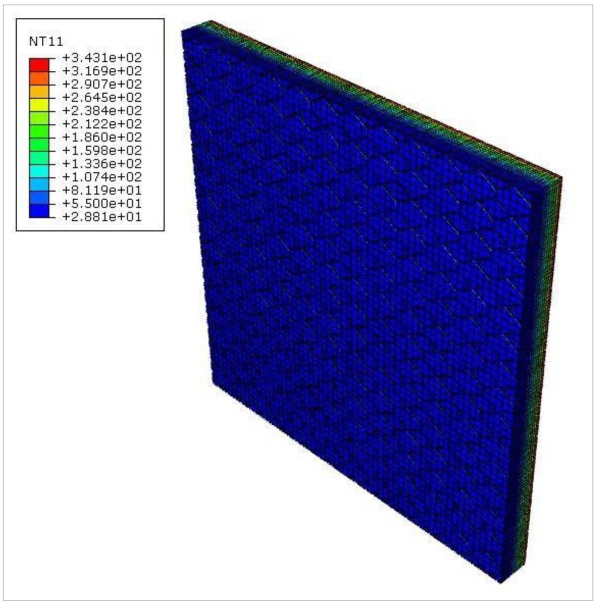


Figure 15. Heat flux and boundary conditions of typical sandwich panel

3.2.1. Influence of Elevated Temperature on Sandwich Panel with Various Skin Thickness

The analysis was conducted using a sandwich panel with different skin thicknesses. The heat flux was applied to one face of the panel, and the results were obtained on the core and the skin on the other face. The observations are evaluated in terms of temperature distribution, stress, and deflections at transient temperatures. Stress computations were performed using the developed model to assess the impact of temperature. The intensity of variation of temperature, stress, and displacement across the thickness and height of the panel is shown in Figures 16 to 20 for varying skin thicknesses of 0.15 to 0.75 mm, respectively. From Figure 16-a, it can be observed that the temperature on the outer face of the skin is lower than the core of the panel and is uniform across the size of the panel. Figure 16-b represents the intensity of stress variation on the panel for the applied heat flux. The outer face of the skin exhibits higher stress in the top region. Since the temperature is uniform across the skin, the reason for the higher stress is due to the load application, which is gradually decreasing towards the bottom of the panel. Figure 16-c represents the displacement on the panel for the heat flux applied at elevated temperatures. The displacement is more in the core area of the panel under the loading, and it is uniform in the skin area. The analytical results are found to be in similar form, with variation in the intensities for the panel with varying skin thicknesses of 0.30, 0.45, 0.60, and 0.75 mm, as shown in Figures 16 to 20, respectively. The results of the critical temperature, principal stress, and displacement for various skin thicknesses are listed in Table 4.



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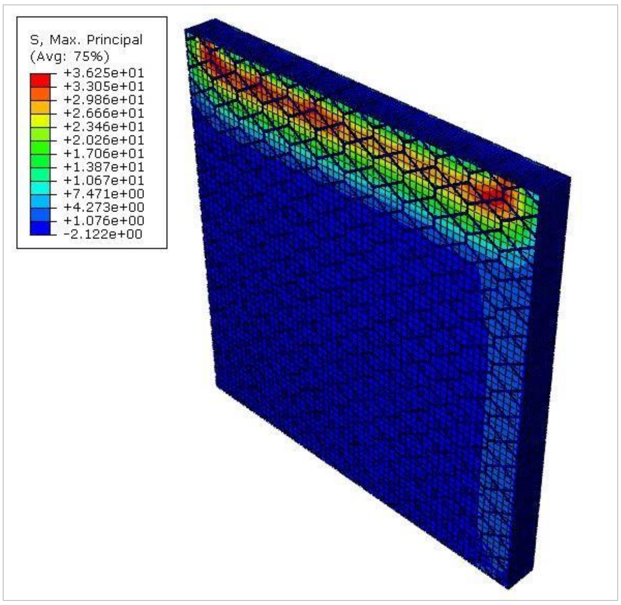

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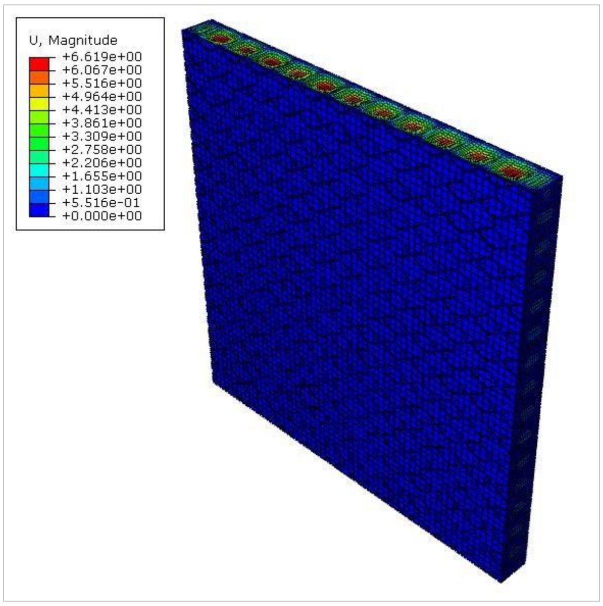
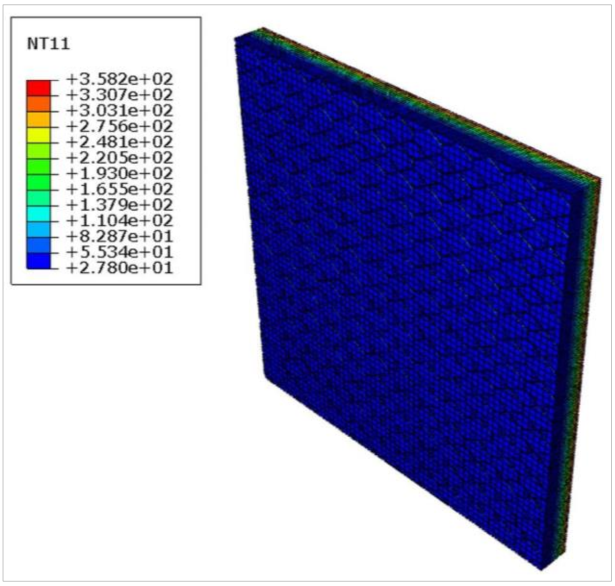


(c)

Figure 16. (a) Critical temperature of sandwich panel with 0.15 mm skin (b) Maximum Principal stress (c) Displacement



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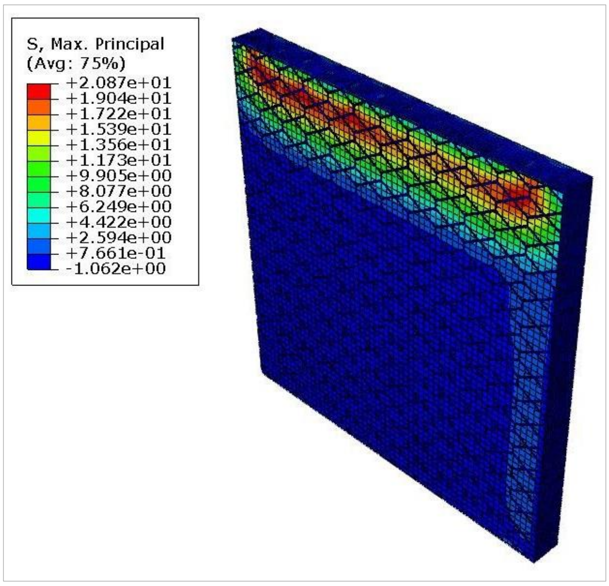

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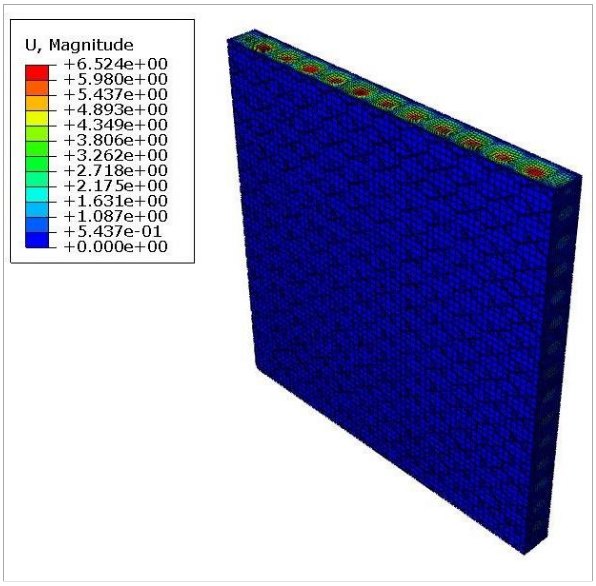
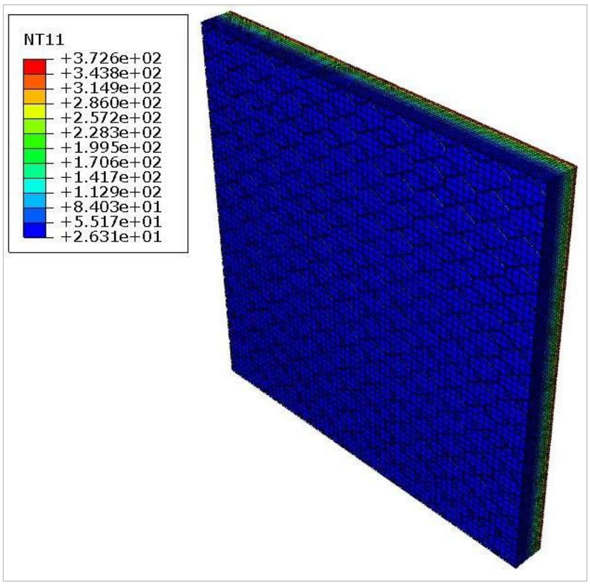


(c)

Figure 17. (a) Critical temperature of sandwich panel with 0.3 mm skin (b) Maximum Principal stress (c) Displacement



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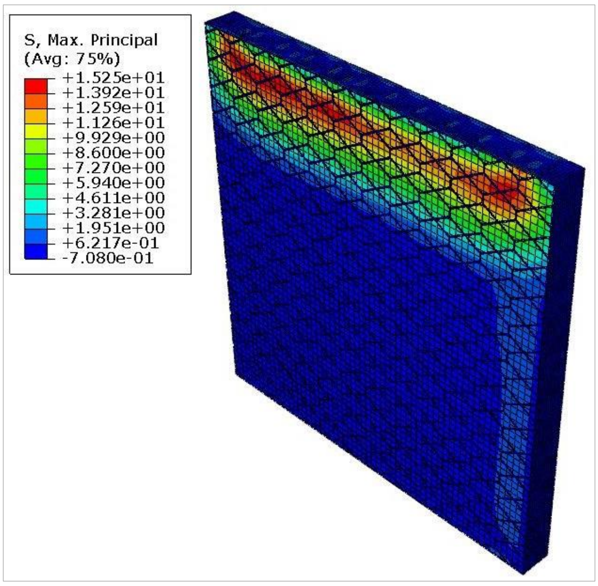

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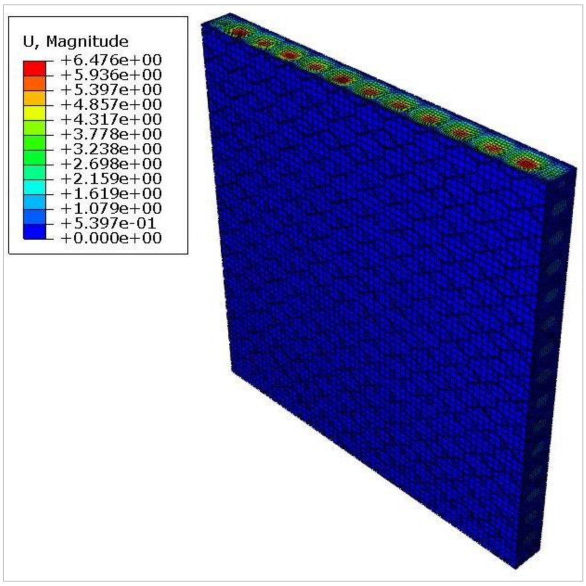
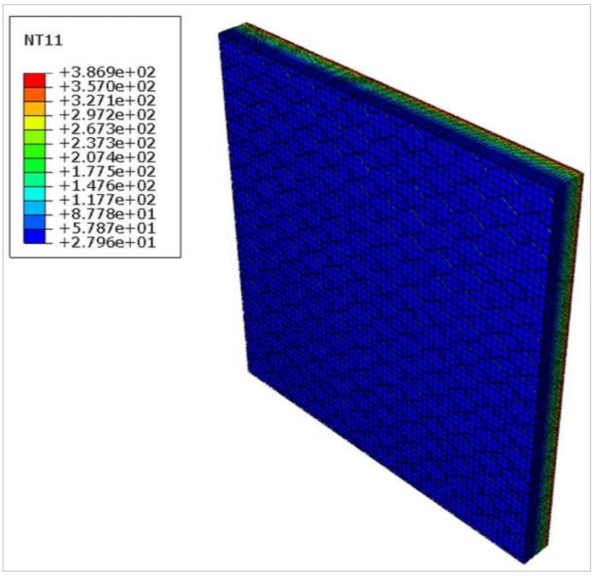


(c)

Figure 18. (a) Critical temperature of sandwich panel with 0.45 mm skin (b) Maximum Principal stress (c) Displacement



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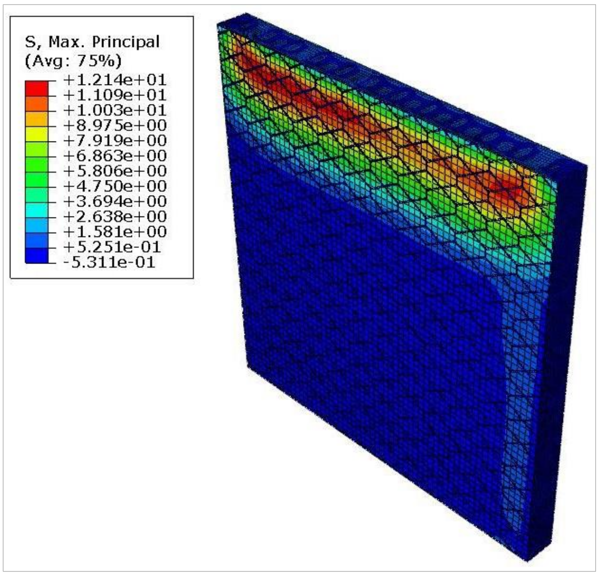
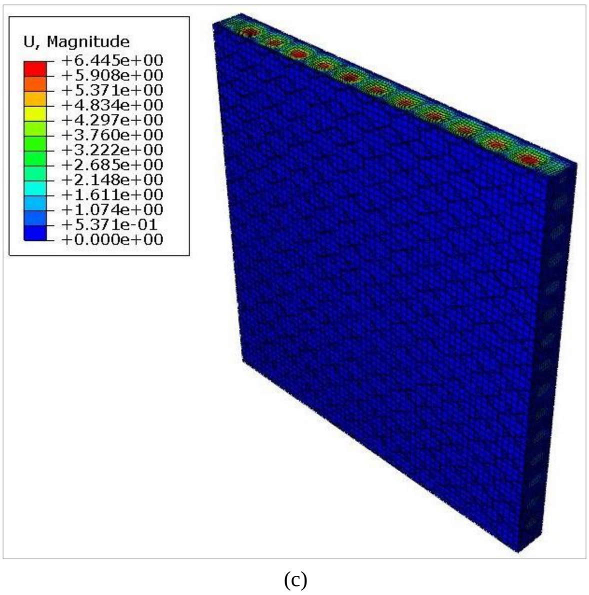
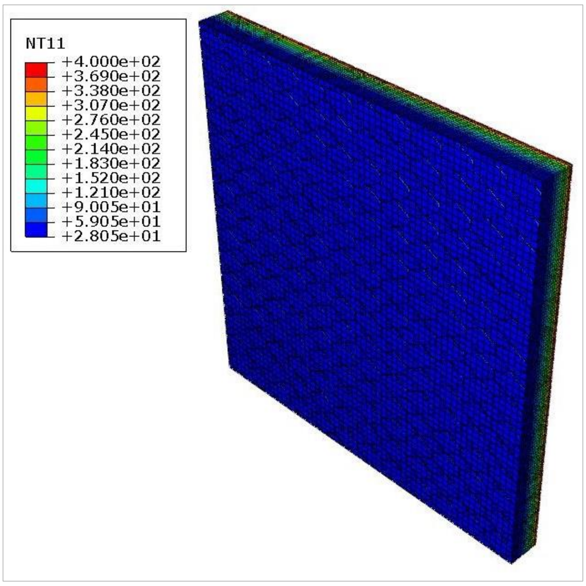


(b)

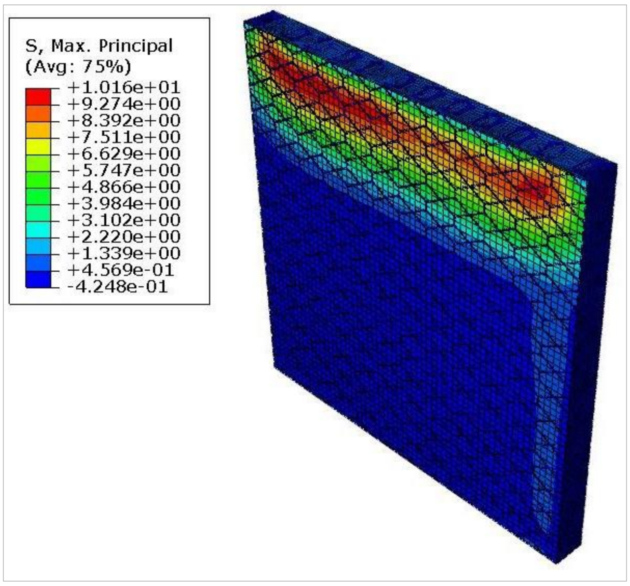


(c)

Figure 19. (a) Critical temperature of sandwich panel with 0.6 mm skin (b) Maximum Principal stress (c) Displacement



(a)



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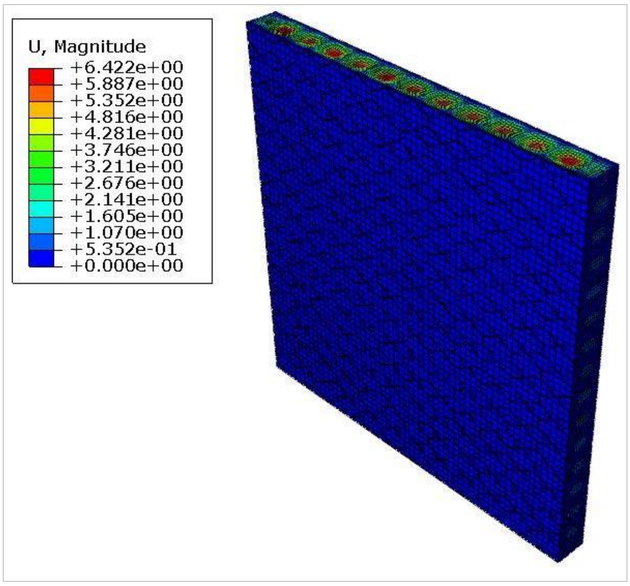


(c)

Figure 20. (a) Critical temperature of sandwich panel with 0.75 mm skin (b) Maximum Principal stress (c) Displacement

Table 4. Critical temperature, maximum principal stress and displacement for various skin thickness

Size of Skin Thickness (mm)	Critical Temperature (°C)	Max Principal Stress (MPa)	Displacement (mm)
0.15	343.1	36.25	6.62
0.30	358.2	20.87	6.52
0.45	372.6	15.25	6.47
0.60	386.9	12.14	6.44
0.75	400	10.16	6.42

Based on numerical modeling, the influence of temperature was assessed for different skin thicknesses of the PU sandwich panel. Figures 21 to 23 show the variations in temperature, stress, and displacement, respectively, with respect to time. An increasing trend is observed in the temperature, stress, and displacement of the sandwich panel with respect to time. It was observed that an increase in the plate thickness of the skin tends to increase the temperature resistance, stress-withstanding ability, and displacement of the sandwich panel.

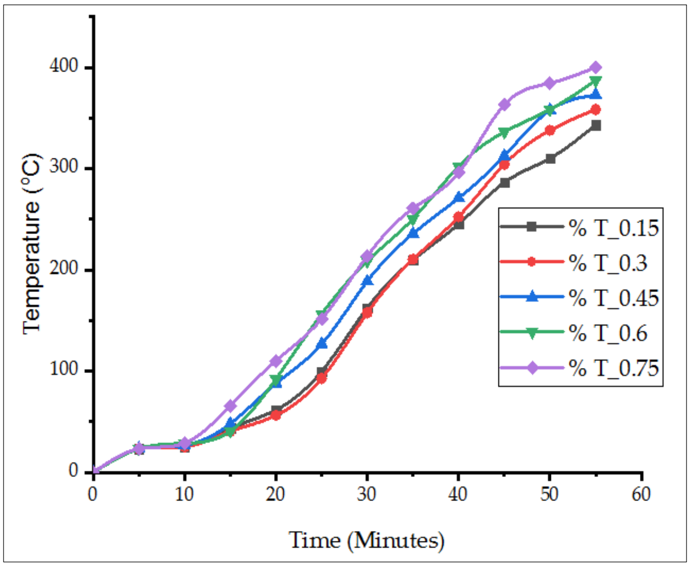


Figure 21. Time Vs Temperature variations with respect to skin thickness

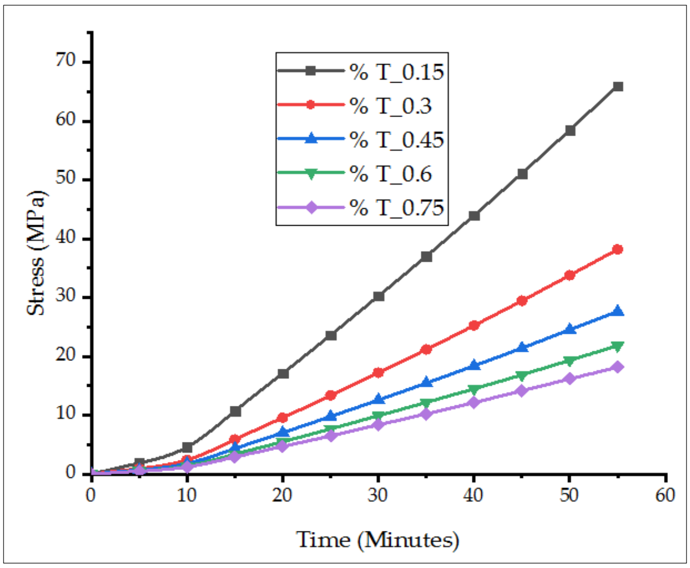


Figure 22. Time Vs Stress variations with respect to skin thickness

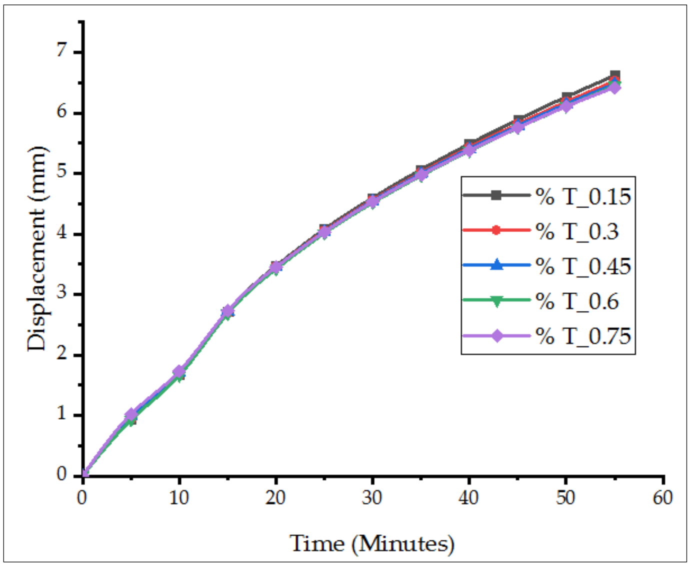
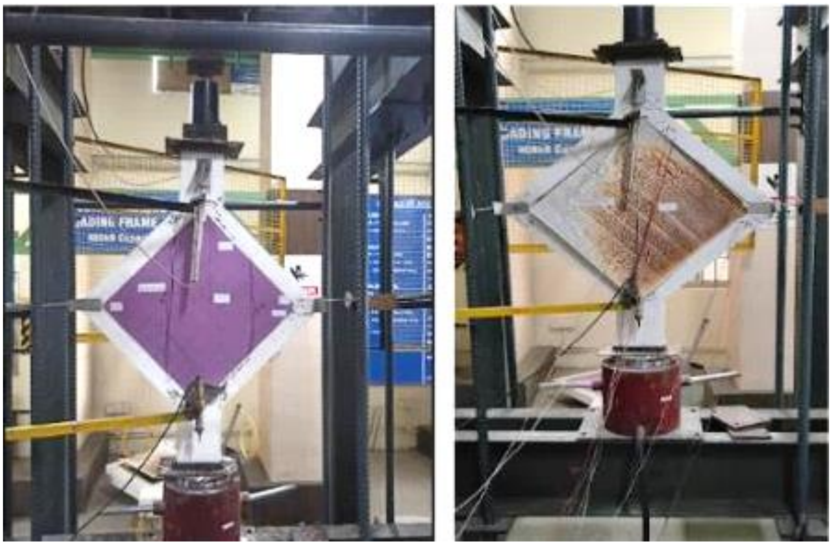


Figure 23. Time Vs Displacement variations with respect to skin thickness

The rate of heat flux was applied to the sandwich wall panel for up to 55 minutes until the maximum temperature was attained. The rate of increase in temperature with stress and deformation was recorded every 5 minutes for various skin thicknesses. As shown in Figure 21, the variation in temperature clearly shows that an increase in the skin thickness of the panel attains a higher temperature than the lower-thickness panels. However, the deformation during this increase in temperature was almost uniform throughout the duration, as shown in Figure 23. The variation in the stress in the panel provides a clear idea for optimizing the thickness of the sandwich wall panel. The increase in stress upon heating is greater for the lower thicknesses of 0.15 and 0.30 mm, whereas it is lower for the higher thicknesses of 0.45 to 0.75 mm. Therefore, to optimize the thickness of the panel member, the influence of stress levels was used, and a thickness of 0.45 mm was chosen owing to the smaller variation in stress level compared to the lower thicknesses depicted in Figure 22, and it is economically preferred over the higher thicknesses.

3.3. Experimental Investigation

The frame was arranged in a vertical position by erecting the loading frame and was adjusted such that the applied load passed axially. The LVDT were placed at the top, bottom, left, and right corner positions, where deformation needs to be evaluated. Loads were applied gradually at a rate of 1 kN, and the corresponding deformations at different points were recorded for every loading increment. As the impact gradually increased, careful inspection was performed to locate the fractures. The condition in which the frame continues to deflect beyond the ultimate loading point with no increase in load is defined as the failure stage. The loads corresponding to the initial crack, failure mode, and ultimate load were observed (Figures 24). An overview of the findings using the square frame model is presented as follows: (a) preliminary cracking load, (b) ultimate load, and (c) load vs. deflection charts and stiffness.



(a) (b)

Figure 24. Mode of failure for RC frame infilled with masonry and sandwich wall panel

3.3.1. Preliminary Cracking Load

During the load application, the initial crack on the surface of the frame was visually observed, and the corresponding displacement with the load was observed. Furthermore, the improvement of the cracks and the formation of new cracks were monitored until the experiment was completed. The initial cracking load and its displacement in the sandwich panel and infilled masonry frame are 9.03 kN, 2.60 mm, and 13.28 kN, 3.08 mm, respectively (Table 5).

Table 5. Comparison of experimental results

Sample	Before Cracking		Initial Cracking		Ultimate Load		Ultimate Load	
	Load (KN)	Displacement (mm)	Load (KN)	Displacement (mm)	Load (KN)	Displacement (mm)	Load (KN)	Displacement (mm)
IFSWPRCF*	0.90	0.016	9.03	2.6	26.39	8.55	-	-
IFMRCF**	0.95	0.020	13.28	3.08	32.13	7.09	34.16#	7.82#

* Infilled sandwich wall panel with reinforced concrete frame.

** Infilled masonry with reinforced concrete frame.

\# Muthukumar et al. (2016) [29].

3.3.2. Ultimate Load Carrying Capacity

The ultimate load and its displacement in the sandwich panel and infilled masonry frame are 26.39 kN, 8.55 mm, and 32.13 kN, 7.09 mm, respectively. The ultimate load was determined from the load vs. deflection curves as the maximum capacity that the specimen could withstand before displacement increased without any increase in the load value. The variation in the load against the displacement is plotted for both the sandwich panel and masonry-infilled frame, as shown in Figure 25. Because the crack patterns observed in both the experimental and analytical studies are comparable, the experimental examination revealed that the frame failed owing to a diagonal crack induced by tensile forces, as depicted in Figure 26.

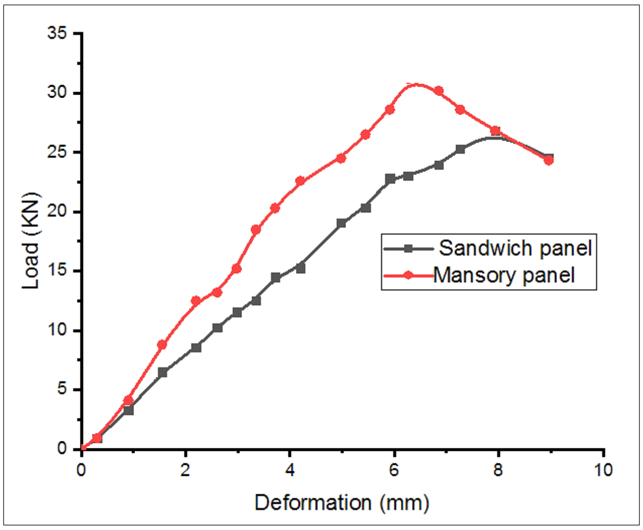


Figure 25. Load vs. Displacement for Sandwich and Masonry wall panel

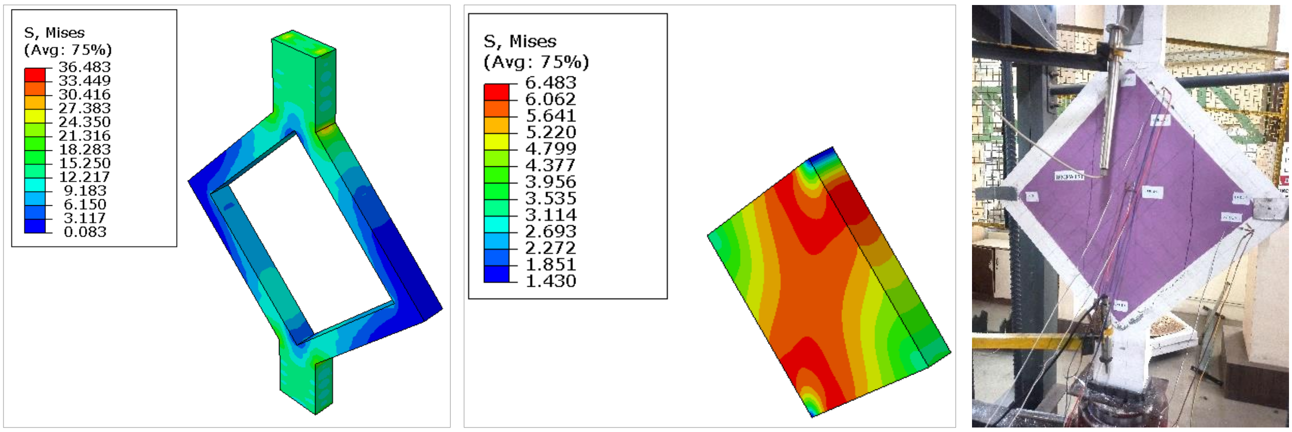


Figure 26. Mode of failure for RC frame infilled with masonry in analytical and experimental

Two parallel cracks were formed along the diagonal axis. The area between these cracks was identified as the strut width of the infill panel. The measured strut width was 362 mm. The corresponding frame was subjected to an analytical investigation, resulting in a similar failure mode. The highest recorded stress was 6.483 MPa within the diagonal zone, and the strut width was 331 mm. Both analytical and experimental investigations noted a minor 8.56% disparity in the strut width. This information allows the calculation of the relative stiffness of the frame based on the determined strut width (Table 6). As per Smith (1968), the relative stiffness is evaluated using the relation given in Equation 1, and it is found to be 4.522 kN/mm for the masonry frame.

$$\lambda h = h\sqrt[4]{\frac{E_{it}\sin 2\theta}{4E_c I_c h'}} \tag{1}$$

where λh is relative stiffness factor, λ is characteristic of infilled frame, E_i is modulus of elasticity of infill, E_c is modulus of elasticity of frame (material of column), h is height of storey, c/c of beams, h' is height of infill, t is thickness of infill, I_c is Second moment of area of column section, θ is slope of infill diagonal to horizontal angle of inclination of strut in radians.

Table 6. Stiffness for RC frame infilled with sandwich wall panel and masonry wall

Name of the specimen	Stiffness before Cracking		Ratio of Experimental / Analytical Values
	Analytical (kN/mm)	Experimental (kN/mm)	
IFSWPRCF*	52.63	56.25	1.07
IFMRCF**	45.55	47.18	1.04

* Infilled sandwich wall panel with reinforced concrete frame.

** Infilled masonry with reinforced concrete frame

4. Conclusions

The effect of high temperature on an RC frame infilled with a sandwich-wall panel was studied under static loading, and the major findings are summarized as follows:

- When a reinforced concrete frame infilled with a sandwich wall panel was compared to an infilled brick masonry frame, the displacement in the infilled sandwich wall panel frame was marginally reduced. Hence, the initial stiffness of the infilled sandwich wall panel increased by 15.5% compared to that of the masonry wall panel during the analytical simulation.
- The stress variation in the panel with a lower thickness was found to be higher but lower for the panel with a higher thickness of 0.45 mm. Hence, a thickness of 0.45 mm was chosen as the optimal thickness for the sandwich panel based on its influence on stress levels and economic considerations.
- The experimental investigation shows that the infilled frame with the sandwich wall panel at the elevated temperature has a 19.22% higher initial stiffness than that of the infilled frame with the masonry wall pane.
- The ultimate loads in reinforced concrete frames infilled with masonry wall panels and reinforced concrete frames infilled with sandwich wall panels were found to be 32.13 kN and 26.39 kN, respectively. This shows that the ultimate load decreased by 17.86% in the infilled sandwich wall panel frame compared to the infilled sandwich wall panel.
- During the experimental investigation, the sandwich panel frame failed in a ductile manner, in which the skin of the sandwich panel delamination was observed, followed by crushing failure at the corners of the frame, but in the masonry-infilled frame, brittle failure was observed.

4.1. Limitations

This study is limited to the connection between the RC frame and the sandwich panel, which relies solely on the bonding achieved through the use of a plaster of Paris without the utilization of any mechanical connections.

4.2. Future Scope

Future research can be improved by overcoming the study limitations of the interaction behavior of RC frames infilled with sandwich wall panels using mechanical connectors.

5. Declarations

5.1. Author Contributions

Conceptualization, S.S.A.R. and K.S.S.; methodology, S.S.A.R. and K.S.S.; formal analysis, S.S.A.R.; writing—original draft preparation, S.S.A.R. and K.S.S.; writing—review and editing, S.S.A.R. and K.S.S. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

6. References

[1] Seeber, K. E., Andrews, R. J., Baty, J. R., Campbell, P. S., Dobbs, J. E., Force, G., . . ., Wescott, H. E. (1997). State-of-the-Art of Precast/Prestressed Sandwich Wall Panels. PCI Journal, 42(2), 92-134.

[2] Mohamad, N., Khalil, A. I., Abdul Samad, A. A., & Goh, W. I. (2014). Structural behavior of precast lightweight foam concrete sandwich panel with double shear truss connectors under flexural load. ISRN Civil Engineering, 2014. doi:10.1155/2014/317941.

[3] Benayoune, A., Samad, A. A. A., Trikha, D. N., Ali, A. A. A., & Ellinna, S. H. M. (2008). Flexural behaviour of pre-cast concrete sandwich composite panel - Experimental and theoretical investigations. Construction and Building Materials, 22(4), 580–592. doi:10.1016/j.conbuildmat.2006.11.023.

[4] Daniel Ronald Joseph, J., Prabakar, J., & Alagusundaramoorthy, P. (2017). Precast concrete sandwich one-way slabs under flexural loading. Engineering Structures, 138, 447–457. doi:10.1016/j.engstruct.2017.02.033.

[5] Daniel Ronald Joseph, J., Prabakar, J., & Alagusundaramoorthy, P. (2018). Flexural behavior of precast concrete sandwich panels under different loading conditions such as punching and bending. Alexandria Engineering Journal, 57(1), 309–320. doi:10.1016/j.aej.2016.11.016.

[6] Carbonari, G., Cavalaro, S. H. P., Cansario, M. M., & Aguado, A. (2012). Flexural behaviour of light-weight sandwich panels composed by concrete and EPS. Construction and Building Materials, 35, 792–799. doi:10.1016/j.conbuildmat.2012.04.080.

[7] Gara, F., Ragni, L., Roia, D., & Dezi, L. (2012). Experimental behaviour and numerical analysis of floor sandwich panels. Engineering Structures, 36, 258–269. doi:10.1016/j.engstruct.2011.12.011.

[8] Bajracharya, R. M., Lokuge, W. P., Karunasena, W., Lau, K. T., & Mosallam, A. S. (2012). Structural evaluation of concrete expanded polystyrene sandwich panels for slab application. 22nd Australasian Conference on the Mechanics of Structures and Materials (ACMSM22), 11-14 December, 2012, Sydney, Australia.

[9] Hou, H., Ji, K., Wang, W., Qu, B., Fang, M., & Qiu, C. (2019). Flexural behavior of precast insulated sandwich wall panels: Full-scale tests and design implications. Engineering Structures, 180(December 2018), 750–761. doi:10.1016/j.engstruct.2018.11.068.

[10] Hou, H., Wang, W., Qu, B., & Dai, C. (2020). Testing of insulated sandwich panels with GFRP shear connectors. Engineering Structures, 209, 109954. doi:10.1016/j.engstruct.2019.109954.

[11] Daniel Ronald Joseph, J., Prabakar, J., & Alagusundaramoorthy, P. (2019). Experimental study on the flexural behavior of insulated concrete sandwich panels with wires as shear connectors. Alexandria Engineering Journal, 58(3), 901–908. doi:10.1016/j.aej.2019.08.005.

[12] Daniel Ronald Joseph, J., Prabakar, J., & Alagusundaramoorthy, P. (2019). Experimental studies on through-thickness shear behavior of EPS based precast concrete sandwich panels with truss shear connectors. Composites Part B: Engineering, 166, 446–456. doi:10.1016/j.compositesb.2019.02.030.

[13] Benayoune, A., Samad, A. A. A., Abang Ali, A. A., & Trikha, D. N. (2007). Response of pre-cast reinforced composite sandwich panels to axial loading. Construction and Building Materials, 21(3), 677–685. doi:10.1016/j.conbuildmat.2005.12.011.

[14] Tomlinson, D., & Fam, A. (2016). Combined Loading Behavior of Basalt FRP–Reinforced Precast Concrete Insulated Partially-Composite Walls. Journal of Composites for Construction, 20(3), 1–14. doi:10.1061/(asce)cc.1943-5614.0000611.

[15] Woltman, G., Noel, M., & Fam, A. (2017). Experimental and numerical investigations of thermal properties of insulated concrete sandwich panels with fiberglass shear connectors. Energy and Buildings, 145, 22–31. doi:10.1016/j.enbuild.2017.04.007.

[16] Tomlinson, D. G., Teixeira, N., & Fam, A. (2016). New Shear Connector Design for Insulated Concrete Sandwich Panels Using Basalt Fiber-Reinforced Polymer Bars. Journal of Composites for Construction, 20(4), 1–13. doi:10.1061/(asce)cc.1943-5614.0000662.

[17] Rajeshwaran, R., & Logeshwari, J. (2023). Experimental investigation on performance of sandwich wall infill in framed structure. Materials Today: Proceedings. doi:10.1016/j.matpr.2023.04.477.

[18] Ma, Q., Rejab, M. R. M., Abu Hassan, S., Hu, H., Azeem, M., & Yunus Nasution, A. (2023). Impact behaviour of spherical-roof contoured-core (SRCC) sandwich panel under the low-velocity impact (LVI): A numerical investigation. Materials Today: Proceedings. doi:10.1016/j.matpr.2023.03.339.

[19] Frankl, B. A., Lucier, G. W., Hassan, T. K., & Rizkalla, S. H. (2011). Behavior of precast, prestressed concrete sandwich wall panels reinforced with CFRP shear grid. PCI Journal, 56(2), 42–54. doi:10.15554/pcij.03012011.42.54.

[20] Kazem, H., Bunn, W. G., Seliem, H. M., Rizkalla, S. H., & Gleich, H. (2015). Durability and long term behavior of FRP/foam shear transfer mechanism for concrete sandwich panels. Construction and Building Materials, 98, 722–734. doi:10.1016/j.conbuildmat.2015.08.105.

[21] De Luca, F., Verderame, G. M., Gómez-Martínez, F., & Pérez-García, A. (2014). The structural role played by masonry infills on RC building performances after the 2011 Lorca, Spain, earthquake. Bulletin of Earthquake Engineering, 12(5), 1999–2026. doi:10.1007/s10518-013-9500-1.

[22] Dehghani, A., & Nateghi, E. F. (2010). Experimental results and conclusions obtained on the masonry-infilled concrete frames strengthened by CFRP. 14th European Conference on Earthquake Engineering, 30 August-3 September, 2010, Ohrid, Republic of Macedonia.

[23] CoDyre, L., Mak, K., & Fam, A. (2018). Flexural and axial behaviour of sandwich panels with bio-based flax fibre-reinforced polymer skins and various foam core densities. Journal of Sandwich Structures and Materials, 20(5), 595–616. doi:10.1177/1099636216667658.

[24] Zhang, H., Fang, W. Z., Li, Y. M., & Tao, W. Q. (2017). Experimental study of the thermal conductivity of polyurethane foams. Applied Thermal Engineering, 115, 528–538. doi:10.1016/j.applthermaleng.2016.12.057.

[25] Steineck, S., & Lange, J. (2023). Influence of Temperature on the Behavior of Sandwich Panels. Ce/Papers, 6(3–4), 16–21. doi:10.1002/cepa.2305.

[26] Nakaiwa, M., Huang, K., Endo, A., Ohmori, T., Akiya, T., & Takamatsu, T. (2003). Internally heat-integrated distillation columns: a review. Chemical Engineering Research and Design, 81(1), 162-177. doi:10.1205/026387603321158320.

[27] Wang, Y., Yang, J., & Chen, Z. (2020). Insulation performance analysis of novel higherature vacuum insulated panels with 2D and 2.5D braided structures. Materials Research Express, 7(1). doi:10.1088/2053-1591/ab6ad4.

[28] de Sousa, C., Barros, J. A. O., Ramôa Correia, J., & Valente, T. D. S. (2021). Development of sandwich panels for multi-functional strengthening of RC buildings: Characterization of constituent materials and shear interaction of panel assemblies. Construction and Building Materials, 267, 120849. doi:10.1016/j.conbuildmat.2020.120849.

[29] Muthukumar, S., Thirumurugan, V., & Satyanarayanan, K. S. (2016). The stiffness behaviour of infilled frames on the influence of different infill and interface materials under static loading. Disaster Advances, 9(5), 13–17.