COMPARATIVE ANALYSIS OF MODELS CREATED OF DIFFERENT BUILDING MATERIALS IN ENCLOSURE FIRE SIMULATION

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ABSTRACT

The constant change in architectural landscape due to high-rise buildings, complex and confined spaces are making fire Fire calamities more diverse and difficult to predict. Over the past ten years, researchers and practitioners have benefited from the use of computer-based simulations (CFD) to assist with fire safety design. The Fire Dynamic Simulator (FDS), one of the most well-known CFD modeling tools for fire safety, predicts fire behavior and spread, partially in real-time. Both the plans and the tactics used to put out building fires rely on fire analysis, which is typically based on accurate fire simulations. Because of this, Building Information Modeling (BIM) makes it possible to create accurate, three-dimensional representations of structures that are detailed, realistic, and include information on the material's thermal properties. With the aim of preventing fire hazards in residential buildings, this study employs PyroSim, a CFD program, to numerically simulate a building model in order to investigate the impact of parameters that affect human evacuation due to fire and different building materials such as brick, hollow block, and Autoclaved Aerated Concrete (AAC). Fire simulation situations are divided into different fire zones by looking at factors like temperature, smoke density, and visibility in the smoke layer inside a building. The critical fire hazard judgment circumstances are used to determine the Available Safe Evacuation Time (ASET). Finally, in order to ensure the security of a building and its occupants during the design stage of construction, this analysis is assessed, and fire prevention countermeasures are defined based on the actual situation and the results of fire numerical simulation to reduce the likelihood of fires, casualties, and financial losses.

Keywords: *CFD, FDS, BIM, AAC, ASET.*

1. INTRODUCTION

Densely populated buildings with complex building geometry, high-density pedestrian flows, oxygen consumption, constrained movement space, and rising risk factors have resulted from Bangladesh's fast-paced economic development, the building industry's rapid growth, and the country's rapidly spreading urbanization. They increase the risk of fires of different intensities by acting as possible sources of ignition. As soon as a fire starts, there is a far higher chance that civilians will be hurt or lose property. The variety of materials used in construction has increased dramatically in tandem with city growth and architectural style changes.

Modern, lighter materials like sophisticated polymers and composites interact with more traditional materials like concrete. Masonry is typically used extensively as a primary building material in construction projects. Because of its strength and distinctive qualities, hollow blocks and AAC blocks are being utilized as conventional masonry components in addition to burned brick. These materials' response to fire is a complex phenomenon that calls for in-depth research and a detailed grasp of how these materials behave in fire situations.

The scope of experimental validation for studies connected to fire is limited by the complexity that comes with its violent nature. Unpredictably, fire-related incidents can happen relatively frequently and have a wide range of devastating consequences. In Bangladesh, structural fires are a common urban calamity. Bangladesh Fire Service and Civil Defense reports 24,102 fire occurrences in total in Bangladesh in 2022. At least 98 individuals lost their lives and 407 were injured in these accidents. Nationwide fire incidents caused damage to properties valued at around Tk 342 crore (Defense, 2023). The main reason why most evacuees die at a fire scene is that they have a poor sense of escape, encounter obstacles during evacuation as vigorous flames block the vision, lack of emergency fire escapes or lack sufficient time to escape.

Information technology advancements over the past few years have affected fire egress planning, management, and procedures. Scholars have observed that a safe evacuation is contingent upon the fire's features (such as intensity, growth, and smoke yield)(Zhang, Zhang, Xiong, Cui, & Lu, 2019), the building's qualities (such as materials and layout)(Wehbe & Shahrour, 2021), and the characteristics of the individuals involved (such as personality, mobility, and familiarity with the building)(Sun & Turkan, 2020). Since Bangladesh lacks sufficient experimental facilities for conducting fire investigations, simulating a fire is a very useful strategy for addressing fire-related problems and enabling the appropriate implementation of preventive measures. Smoke from a fire is thought to be more deadly than the fire itself in an accident. Fortunately, to reduce the deadly consequences of fire mishaps, smoke and flames may be easily recreated utilizing a variety of already available modeling tools. (Khandoker, Mou, Muntaha, & Rahman, 2018).

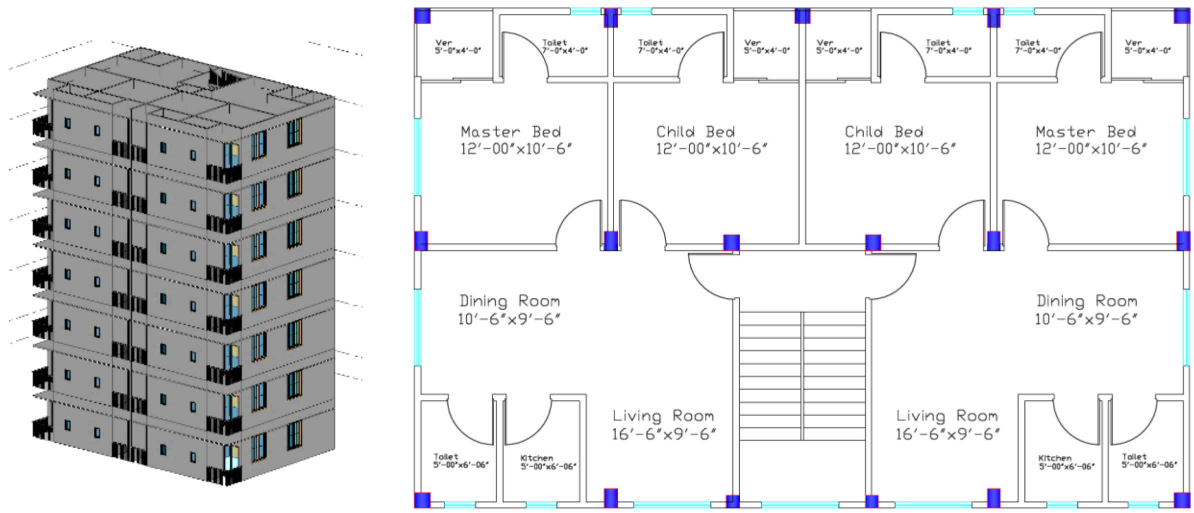
The combustion characteristics of fire, such as fire behaviors, gas temperature, and oxygen content, have a direct impact on the safety of people, machinery, and building compartments. This study aims to make a valuable contribution to this important field by comparing models made of various construction materials in the context of enclosure fire simulation. A popular computer numerical simulation tool for simulating real-world fire scenarios is the Fire Dynamics Simulator, which enables researchers to evaluate the performance of structures under controlled circumstances (Guo, Wang, Zhang, Yang, & Sun, 2020). The primary objective of this research is to systematically compare and contrast the behavior of diverse building materials when subjected to enclosure fire simulations. The outcomes of this study are anticipated to predict fire safety performance and to assist in fire evacuation planning. Such insights are imperative for architects, engineers, and policymakers to make informed decisions regarding material selection, building design, and fire safety protocols at buildings design phase, and contribute to the development of more resilient and fire-safe urban environments.

2. METHODOLOGY

The primary objective of this study is to examine and contrast the flame spread properties of various construction materials in enclosure fire simulations, with an emphasis on comprehending the possible health risks connected to certain materials. The basis and primary platform for information resources, integration, and visualization in this study is a BIM model. Furthermore, it employs FDS to replicate structure fires and modifies simulation parameters and fire source location based on various conditions. Both the duration and the outcomes of the simulation are saved in a case database.

2.1 The building

The building geometry used in the simulation was based on the floor plan and working drawings of an actual residential building in Bangladesh. Having reviewed the designs of a few other comparable structures, this one was chosen as a representative residential building. Two criteria were set in order to choose a building for the scenario study. First, the geometry or layout of the building had to be intricate enough to depict the worst-case situation. Second, there are said to be a respectable amount of people that visit or live in the building.
The structure with ten floors was the only one on a shortlist of possible structures that met all the requirements. The height of the building from the ground to the first story was roughly 3.5 meters, and the height of each storey after that was 3 meters, for a total height of 33 to 34 meters. There was a single main entrance to the structure, and each story held two units. The main staircase was attached to the main entrance. Furthermore, the building lacked an emergency exit. As-built blueprints were not available, thus in order to guarantee that the building was modelled as exactly as possible, pictures of the entire structure including staircases, apartments, and exits were obtained. In order to document building geometry measurements, several walk-through audits were also carried out.
The 3D model of the residential building, which has about 300 people living there overall and solely uses the ground floor as a garage, is depicted in figure 1(a). The average floor arrangement, which has a total floor area of 1540 m2, is depicted in detail in figure 1(b). This is the floor where the fire scenario was developed, and the source zone is attached to the living space. Research has been done on how smoke and heat affect various routes through homes and stairwells.



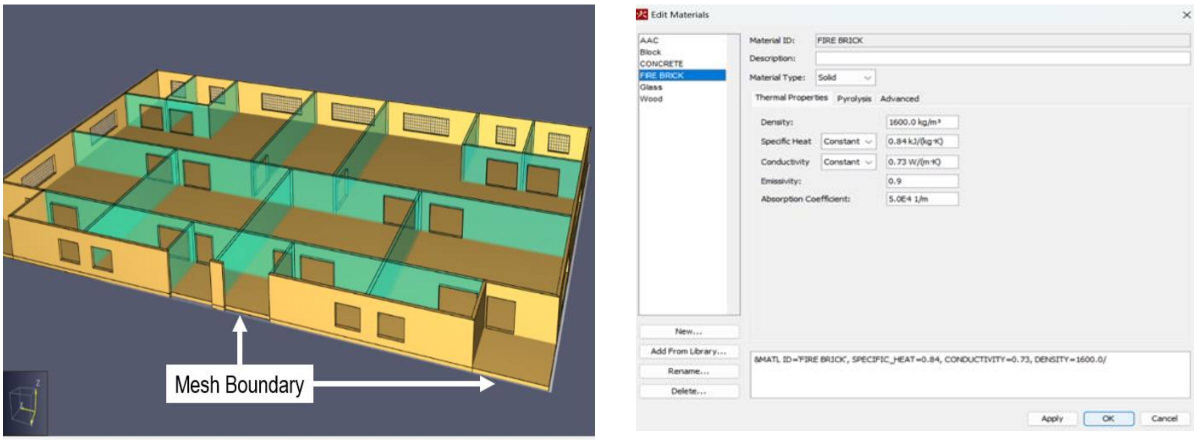
(a) (b)

Figure 1: (a) External view of the 3D building model showing different floors, phantom zones and mesh boundary of simulation; (b) Typical floor layout for a residential building

2.2 FDS and BIM integration

Autodesk Revit, the primary platform for information on building materials and simulation parameters, was used in this study to produce the BIM model. In order to carry out the structural fire simulation based on large eddy simulation, which has been used in several studies, PyroSim was chosen as a trustworthy FDS program (Wang, Xu, Chen, Nzige, & Chong, 2021). Accurate building geometry and material thermal characteristics data are fundamental and necessary for any fire simulation model. In order to shorten the rendering time, this study reuses the data from the BIM model. The integration of FDS and BIM is depicted in figure 2. The BIM model is first created in Autodesk Revit using the standard CAD data-exchange file format, DXF. It includes the model's geometric and graphical data. After that, PyroSim imports the DXF file and uses it to find the material data needed to build the model. Because of this, when building the BIM model, it is essential to enter the accurate material attributes.

There are two categories for object attributes in the BIM model. The first category includes the fundamental attributes, including quantities, geometric diagrams and property specification. The item's visualization properties, such as materials and line formation, make up the second category. Since the main application of this BIM model is structural fire simulation, variations in the materials will have an immediate impact on the simulation's outcomes; thus, the object attributes must be clearly specified for the structural fire simulation program. Building supplies and parts are automatically sorted and prepared for simulation in PyroSim. The next stage entails creating a fire reaction in the simulation environment and manually adjusting the thermal parameters of the materials shown in figure 2(b).



(a) (b)

Figure 2: (a) External view of the 3D building model in PyroSim showing floor and mesh boundary of simulation; (b) Fire source and burner.

The thermal properties of major building materials were obtained from ASTM E84 (ASTM)(shown in table 1). Furthermore, defined are the locations of apertures and functional areas like the burning zone. A material parameter database is offered by PyroSim. It can define the group's attributes in terms of a certain material type and match objects and materials. Since every material has unique thermal characteristics, the simulation is more accurate.

Table 1: Thermal properties of building materials

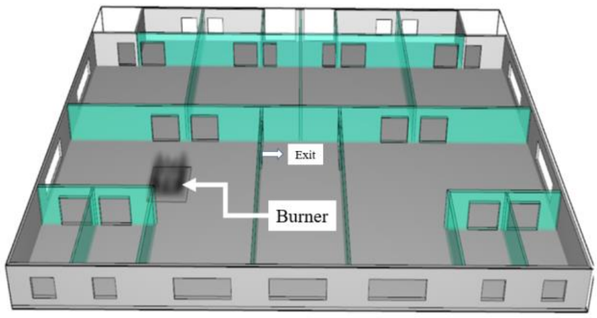
Materials	Density (Kg/ M3)	Specific Heat (Kj/ (Kg•K))	Conductivity (W/ (M•K))
Wood Panel	513	1.38	0.115
Concrete	1600	0.84	0.79
Glass	2700	0.88	0.8
Brick	1600	0.84	0.73
Hollow Block	1500	1.00	0.50
AAC	500	1.05	0.12

2.3 Fire source

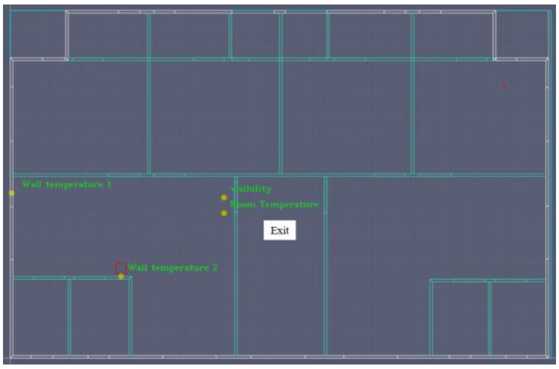
The fire's origin is another crucial detail in the FDS scenario. Stable and unstable fire sources are the two general types into which the design of the fire source is separated. An unstable fire source might have a variety of origins. As a result, as figure 3 (a) illustrates, the main fire source used in this study is steady. A stable fire source maintains a steady emissive energy while ignoring the effects of secondary causes and combustible materials on structure fire (Chen, Liu, & Wu, 2018). Electrical fire was chosen as the fuel for this study because it is a frequent and primary cause of fire occurrences (38.48%) and has a high Heat Release Rate per unit area (HRRPUA) of 585 kW/m2. The SFPE and other relevant recommendations are followed in the modeling of the fire scenarios and the fuel property characterisation (Hurley et al., 2015).

2.4 Device settings

In order to measure the various pyrolysis products in terms of heat, gas, and fluid, several devices have been positioned at the mean eye level for males and females to monitor density, temperature, and visibility through smoke at different portions of the geometry. A wall with a window opening has been installed at a height of 1.5 meters (Mahmud, Haque, & Rahman, 2019), and two gas devices have been placed to measure room temperature and visibility at the exit zone and two solid devices have been placed to measure wall temperature at the source zone, all while taking into consideration the anthropometry data for Bangladeshi men and women (illustrated in figure 3(b)). In order to be used in data visualization later on, this device gathers output values from the structure fire simulation and generates a data report.



(a)



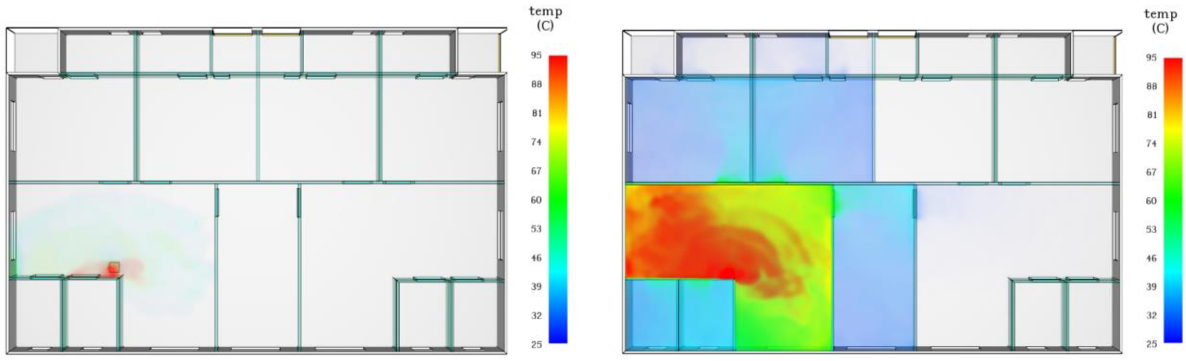
(b)

Figure 3: (a) Fire source; b) Device location.

In the event of a fire, the tenability limit indicates the circumstances under which residents can escape safely and survive. In order for a fire incident to be considered tenable, a number of characteristics (including temperature, CO concentration, and visibility through smoke) must be kept below a specific threshold. Since 100% water vapor saturated air cannot be inhaled at a lower temperature than 60°C, this temperature was chosen as the threshold for this study. The visibility threshold was determined to be 1.5 meters. The situation becomes unsustainable when visibility falls below this threshold. According to the standard values listed in the SFPE handbook10, these values have been determined as the tenability criterion.

3. RESULT AND DISCUSSION

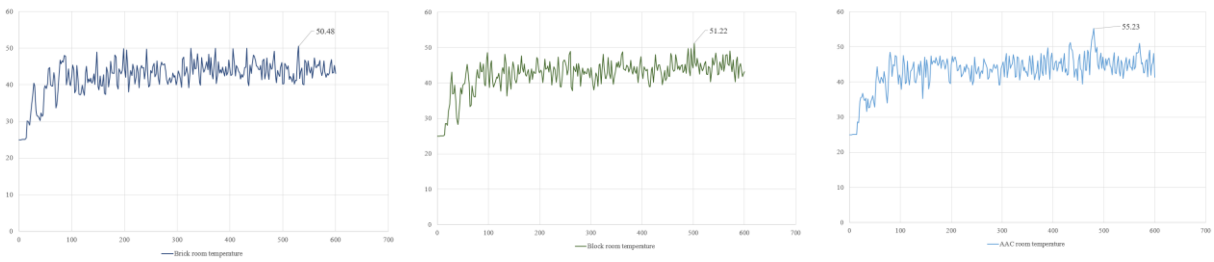
Reconstructing fire scenes, in particular, and working with fire scenarios in general have distinct restrictions. It is impossible to determine which of the numerous scenarios that could have occurred during the start and spread of the fire unless they are correctly identified and recorded as soon as possible after the fire incidence. The official report on the fire occurrence lacks many particular scientific facts because science-based fire scene documentation is uncommon in Bangladesh. As a result, the forensic investigation in this study was conducted using the scientific principles and fire dynamics expertise, as well as a thorough examination of various fire scenarios. The simulation of the fire involves burner (HRR: 585 kW/m^2) stacks of a total 1540 m^2 floor area with the consideration that all of the windows and doors of the fabric store are opened and the ambient temperature of the room was 25° C. The simulation time has been selected as 10 min or 600 seconds to investigate the fire impact on materials and tenability of the occupants. Figure 4(a) shows that the smoke, within 8s of start of the fire from the source zone, spreads through the living space in the typical floor.



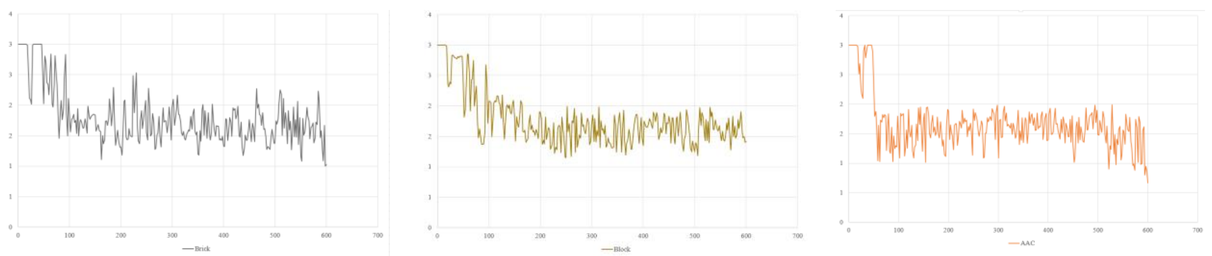
(a) (b)

Figure 4. Fire growth timeline in PyroSim.

The rapidly emerging heat and smoke, however, took much less time to spread through the whole building within 130-170 sec (shown in figure 4(b)). This is because of the fact that smoke is lighter than air and thus it finds the alternate way to spread to the floors through the open space. Critical situation does not reach at the same time for all the materials. In PyroSim, the time history plots generated by the statistic program indicate that: (1) For brick, within 600 seconds of analysis room temperature reaches at its peak 50.48°C at 530 sec (figure 5(a)) and the smoke layer reaches 1.5 m at 162 sec, which will cause a reduction in pedestrian movement speed(figure 5(d)).(2) For hollow block, room temperature reaches at its peak 51.22°C at 502 sec (figure 5(b)) and the smoke layer reaches 1.5 m at 220 sec (figure 5(e)) (3) For AAC block, room temperature reaches at its peak 55.23°C within 482 sec (figure 5(c)) and the smoke layer reaches 1.5 m at 58 sec(figure 5(f).

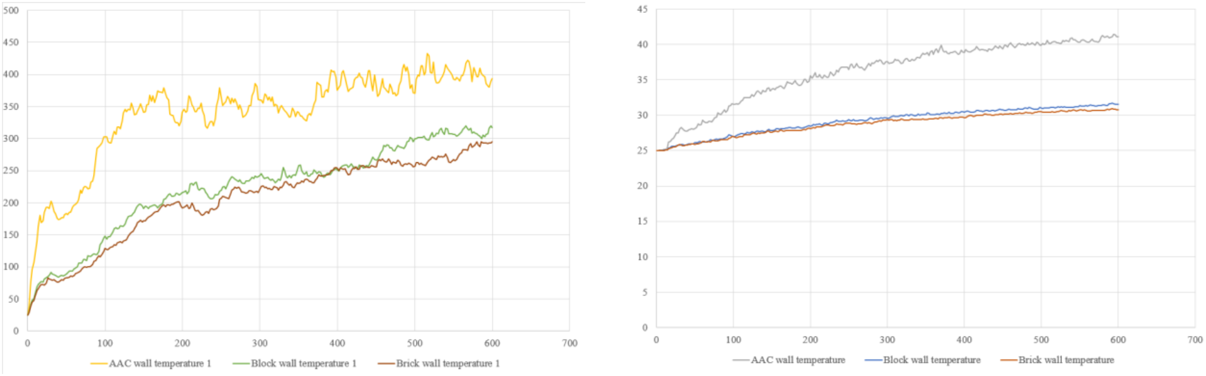


(a) (b) (c)



(d) (e) (f)

Figure 5. 2D time history plots of the fire simulation outputs in PyroSim.



(a) (b)

Fig. 7. 2D time history plots of the fire simulation outputs in PyroSim.

Figure 7 shows the temperature in both source zone and a wall with opening undergoes a rapid increase in temperature. At fire source zone AAC block wall shows maximum temperature increase while after 600 s it reaches at 393 ˚C (figure 7(a)). While brick and hollow block were close to each other 294 ˚C and 317 ˚C respectively. Similarly, for a wall with window opening wall temperature for AAC was on the top with 41 ˚ C while brick and hollow block were 30 ˚ C and 31.5 ˚ C respectively(figure 7(b)).
The fire simulation was done using standard values of the material attributes according to table 1, which can be in stark contrast to the real-life occurrence. Considering threshold values for safe evacuation, it is fair to say that building created with hollow blocks provides more available safe egress time (ASET) to its occupents. Since not all buildings have emergency exits, the fumes released by the combustible items within the building reduce visibility and make it more difficult for the residents to locate the fire escape or use the regular stairs to descend. They consequently become frightened and congregate in front of the stairs or decide to ascend to the building's summit. Enough time, proper escape route, and a reduction in smoke can prevent harm to property and human life.

4. CONCLUSIONS

The scenario of smoke propagation and fire growth in residential buildings was simulated. This study used a simulation-based methodology to recreate the fire scene and illustrate the sequence of events that resulted in the deaths of the occupants. Estimating the risk and tenability of a structure composed of various building materials was the goal in order to help engineers and designers make a logical choice about which material would be most cost-effective and safe for the project during the construction design phase. It also allowed for the modelling of an effective evacuation procedure. This kind of analysis aids in the development of more effective plans for fire safety instruction and design. In the conclusion, 3D BIM provides a visual representation of the outcomes of dangerous areas, as shown by the fire simulation, and efficient escape routes, as suggested by the evacuation plan. It was discovered that the fire-smoke travels quickly across residential areas and entirely obstructs the building's escape pathways. A model consisting of AAC blocks was developed to identify the most crucial criteria. Even though hollow blocks performed worse than bricks in the wall temperature test, it's important to note that each block's hollow centre contributes to its thermal insulation qualities.
The primary drawback of this study is that due to technology limitations, the findings of the fire simulations could not be displayed both in a FDS and in a real-world setting. In addition, the design of fire safety measures for structures can be considerably impacted by the wind and combustible materials, however this has not been covered in this assessments.

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