Disaster-Resilient Design And Water Demand Evaluation Of Residential Fire Sprinkler Systems

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Abstract
Residential buildings face significant fire hazards due to high occupancy and the presence of combustible materials. Automatic fire sprinkler systems offer a proactive and efficient solution for early fire suppression, significantly reducing life and property loss. This study presents a technical evaluation of water demand for residential sprinkler systems with a focus on disaster-resilient design. A three-story residential building was used as a case study, where fire load calculations were performed based on common household materials. Sprinkler head spacing, discharge flow, and operating pressure were analyzed using NFPA 13D guidelines. Hydraulic calculations, including friction loss and pressure drop, were conducted to ensure system performance. The study concluded that a minimum of 7000 liters of water is required to operate 43 sprinkler heads for 15 minutes, effectively covering a protected area of 474 m². The findings demonstrate that even in resource-constrained residential settings, a scientifically designed sprinkler system can be integrated without excessive water demand. This research supports the implementation of sprinkler systems as a vital component of fire-resilient infrastructure in residential buildings, especially in urban India.

Keywords: Disaster resilience, residential sprinkler system, fire load calculation, NFPA 13D, hydraulic design, water demand evaluation, pressure loss, automatic fire suppression, Indian residential safety, fire protection engineering.

1. Introduction

Residential buildings are particularly vulnerable to fire-related disasters due to high occupancy densities, combustible furnishings, and frequently inadequate fire protection measures. Fire incidents in such settings often escalate rapidly, leading to significant life loss, property damage, and emergency response burdens. Integrating disaster-resilient fire protection solutions such as automatic fire sprinkler systems offers a proactive and highly reliable method of minimizing such risks.

Automatic sprinkler systems are designed to detect heat and discharge water directly over the fire zone, suppressing the fire at an early stage and preventing it from spreading. These systems consist of an integrated piping network, with sprinkler heads containing thermal sensors, pressurized orifices, and water deflectors for effective coverage. Sprinkler types vary to meet different environmental demands, including wet pipe (most common in residential use), dry pipe, pre-action, and deluge systems.

Despite their proven performance in enhancing disaster resilience, the adoption of residential sprinkler systems remains limited in India due to misconceptions, water supply challenges, and regulatory gaps. This study focuses on evaluating the actual water demand for such systems in a typical multi-story residential building, considering fire load density, sprinkler spacing, hydraulic losses, and NFPA 13D compliance. The aim is to support resilient design practices and encourage the widespread use of automatic fire suppression systems as a key strategy for disaster risk reduction in residential infrastructure.

2. Materials and Methods

This study evaluates the water demand for residential fire sprinkler systems in multi-story buildings based on standard hydraulic design principles, fire load calculations, and NFPA 13D guidelines. A typical three-story residential building was selected as a case study to estimate water requirements and validate design feasibility under realistic conditions.

2.1 Building Description and Layout

The building considered for this study is a three-story residential structure with the following layout specifications:

- Building footprint: 60 ft × 30 ft= 1800. 00Sq.ft (≈167 m²)
- Total no. of floors: 3nos i.e Basement, Ground and First Floor.
- Total gross floor area: 167 m² ×3=501 m²

A portion of the building, specifically the garage located in the basement, does not have sprinklers installed. The garage area is:

- Dimensions: 16 ft × 18 ft
- Area: 288 sq. ft (27 m²)

Thus, the total area protected by the sprinkler system is:
Total protected area = 501 m²- 27 m²= 474 m²

2.2 Fire Load Calculation

Fire load is a critical parameter in determining the severity of fire and the subsequent water demand for effective fire suppression. It represents the total amount of heat energy (in kilojoules) that could be released per unit floor area when the combustible contents of a building are completely burned. To evaluate the fire severity, the fire load density was calculated using typical materials found in residential units. The formula used was:

$$\text{Fire Load } \left({}^{\text{kJ}}/_{\text{m}^2}\right) = \frac{\sum(\text{C}_\text{i} * \text{M}_\text{i})}{\text{A}}$$

Where, C_i is Calorific value of material (kJ/kg), M_i is Mass of material (kg) and A is Floor area (m²).
In this study, the fire load has been calculated for a typical residential building based on the presence of common household combustible materials such as wood, PVC, paper, and textiles.

Table 2.1: Combustible Materials and Their Properties

Sr. No	Material	Calorific Value (kJ/kg)	Mass (kg)
1	Wood	3441	755
2	PVC	9797	200
3	Paper	3226	50
4	Textile	1700	225

The total fire load (FL) is computed using the equation:

$$\text{Fire Load } \left({}^{\text{kJ}}/_{\text{m}^2}\right) = \frac{(\text{C}_1 * \text{M}_1) + (\text{C}_2 * \text{M}_2) + (\text{C}_3 * \text{M}_3) + (\text{C}_4 * \text{M}_4)}{\text{A}}$$

$$= \frac{(3441 * 755) + (9797 * 200) + (3226 * 50) + (1700 * 225)}{474 \text{ m}^2}$$

$$= \frac{(2597955) + (1959400) + (161300) + (382500)}{474 \text{ m}^2} = \frac{5101155}{474} \approx 10762$$

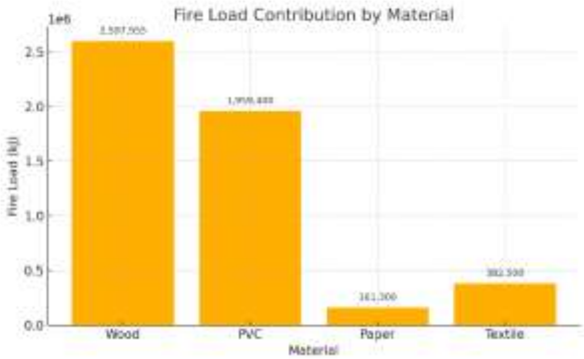

Figure 2.1 Fire Load Contribution by Material

Calculated fire load density for the protected area of the building is approximately 10,762 kJ/m², which indicates a moderate to high fire hazard as per NFPA and IS fire safety classification guidelines.

2.3 Sprinkler Head Spacing and Flow Calculation

a. Sprinkler Head Coverage and Flow Calculation

The net protected floor area $=A_{total} = 474\ m^2$

Assumed Maximum Coverage per Sprinkler Head$=A_{head} = 11\ m^2$/head

Sprinkler Head Requirement $N = \frac{A_{total}}{A_{head}}$

$= \frac{474}{11}$ =43 sprinkler heads (around)

b. Flow Rate Calculation per Head

D = Design density = 10.22L/min/m^2 (per head discharge)

Flow rate (Q) (L/min) $= A_{head} * D$

=11*10.22L/min/m^2

c. Pressure Requirement using K-Factor Equation

P = Required pressure (psi)`

K = factor of sprinkler head= 5.6(residential sprinkler)

$Q=K*\sqrt{P}$

$P=\left(\frac{Q}{K}\right)^2 = (1.825)^2$ =3.33psi

d. **Friction Loss Calculation (Hazen–Williams Equation)** for 1.25inch pipe diameter, C=100 (for cast iron):

$$P = \frac{4.52 * Q^{1.85}}{C^{1.85} * d^{4.87}}$$

Where, h_f is Friction loss per ft of pipe (psi/ft), Q is Flow rate (gpm), C = Hazen–William's roughness coefficient and d = Pipe internal diameter (inch)

$$P = \frac{4.52 * (2.641)^{1.85}}{100^{1.85} * (1.25)^{4.87}} \text{psi/ft}$$

$$P = 0.001833 \text{psi/ft}$$

For a short run (e.g. 50 ft), total loss = 0.00183×50=0.0915 psi

Net Pressure at Sprinkler Head= $P_{net} = P_{Total} - P_{Total}$

$= 3.33 - 0.0915 \approx 3.24$psi

2.4 Water Supply and Minimum Storage

The total volume of water required for a residential sprinkler system can be estimated using the following equation:

$V = Q_{total} X T$

Where, V is Total water volume required (liters), Q_{total} is Total discharge rate (L/min) and T = Minimum operating time (min)

According to NFPA 13D, the standard minimum duration for residential sprinkler operation is 10 minutes. However, in this study, a conservative approach of 15 minutes is considered to accommodate potential system delays and safety margins.

Q_{total} =43headsX10.22L/min=439.46L/min

$V = Q_{total} X T$

=439.46L/minX15min=6591.9 liters

Including safety margin, the final required water storage is: 7000liters (minimum)

3. Result

The evaluated residential building had a protected floor area of 474 m² with a calculated fire load density of 10,761 kJ/m², indicating a moderate to high fire risk. Based on NFPA 13D standards:

i. Sprinkler heads required = 43
ii. Coverage per head = 11.02 m²
iii. Design density =10.22 L/min/m²
iv. Discharge per head = 10.22 L/min
v. Operating pressure = 3.32 psi (after friction loss)
vi. Minimum operating time =15 minutes
vii. Total water demand =6591 liters
viii. Water demand including safety factor = 7000 liters

These results confirm that the sprinkler system can effectively operate within standard residential water supply parameters, ensuring early fire suppression and occupant safety.

4. Discussion

This technical study presents a detailed evaluation of water demand for residential fire sprinkler systems using a three-story building model. By aligning with NFPA 13D and Indian IS 15105 standards, the study highlights how sprinkler system effectiveness depends on proper calculations of fire load, flow rate, and pressure.

The research demonstrates that a fire load density of around 10,761 kJ/m² signals a moderate to high risk, necessitating a robust suppression approach. Hydraulic calculations confirmed that 43 sprinkler heads with a discharge rate of 10.22 L/min per head are adequate for the protected area. A total of 7000 liters of water over a 15-minute operation period ensures effective suppression and protection of life and property.

The integration of CAD tools for layout design and head spacing, along with pressure loss modeling, confirms that such systems are both feasible and effective in residential Indian settings. The study also reinforces the potential of sprinklers to reduce dependency on emergency fire services and improve response time in densely populated urban areas.

5. Conclusion

This research paper successfully quantified the water demand for sprinkler systems in residential buildings by applying standard fire engineering calculations and NFPA 13D guidelines.

With a calculated water requirement of approximately 7000 liters for a three-story structure, the study validates the practical integration of automatic sprinklers even in moderately resourced urban homes. By addressing layout, fire load, flow rate, and hydraulic losses, the study supports strategic implementation for enhanced fire resilience.

Ultimately, this work promotes the adoption of well-designed sprinkler systems as an efficient, proactive fire safety solution that can mitigate risk, save lives, and optimize water usage in the event of a fire.

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