Enhanced fire severity in modern Indian dwellings

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The present study focuses on assessment and probabilistic characterization of fire load, a key input to performance-based fire design, in office and dormitory buildings in India. A survey using combined inventory-weighing method was conducted and the results analysed with respect to several parameters such as room use, type of combustibles, etc. Probabilistic models based on the generalized extreme value and gamma probability density functions have been proposed for fire load energy density. It has been found that, on an average, the fire load present in modern buildings is about three times greater than what is reported by earlier studies and prescribed by building codes. Thus, the severity of potential fires that can occur in a compartment has increased considerably. Parametric fire curves have been developed and compared with standard fire curves to assess the increase in severity. The developed fire curves possess a greater growth rate and predict a greater temperature within the first one hour, when compared to the standard curves, showing that there is a greater fire risk.

Keywords: Design fire, enhanced fire risk, fire load energy density, fire load survey.

IN the last few decades, due to changes in socio-economic and cultural factors Indian lifestyle has seen a significant shift[1]. India has undergone rapid growth after liberalizing its foreign direct investment policies (that primarily started in the early 90s) leading to changed consumer demographics and increased per capita income. This has brought new office and residential cultures and luxuries. Modern office and residential buildings now use corrugated plastic roofs, partition walls, plastic doors, false ceiling panels, core panels for walls, interior finish materials, washing machines, refrigerators, air-conditioners, televisions, mobile electronic gadgets and computer hardware.

While such changes may indicate improved lifestyle, they also enhance the risks of fire due to changes in the composition of fuel load. The newer materials are often more inflammable and have greater calorific values than the earlier materials[2]. But the building codes do not account for these changes as most of them still utilize representative fuel loads derived from data collected in 1970s and 80s. Given the significant change in the type of materials used in modern buildings, use of data gathered by earlier surveys is questionable. The present study presents fire load estimates from surveys conducted in Ahmedabad, India in 2015 to further highlight this issue. Results indicate that design fire curves developed from collected data have a more severe growth phase when compared to the standard fire curves for the first one hour.

Fire loads are typically characterized using the fire load energy density (FLED) e_f, defined as

$$e_f = Q / A_f, \tag{1}$$

where A_f is usually the floor area of the compartment. Q is the total fire load of the compartment given by

$$Q = \sum_{i=1}^{n} (k_i m_i c_i), \tag{2}$$

where k_i is the proportion, and m_i, the mass of the combustible items assessed during a fire load survey. c_i is the net calorific value of the corresponding combustible item. Most of the fire load surveys for offices and residential buildings were conducted during the last three decades of the twentieth century[3–9]. Among these, the most extensive survey was carried out by Culver[4] for office buildings situated in 23 different geographical locations across the United States. A total of 2433 office rooms (total floor area 7246 m^2) were surveyed and categorized into different groups based on their usage and floor area. They reported average FLED values ranging from 130 MJ/m^2 to 4805 MJ/m^2 depending upon room usage. Narayanan[7] conducted a survey in five office buildings in New Zealand (total floor area 3999 m^2) and the reported mean FLED values varied from 426 MJ/m^2 to 947 MJ/m^2. Zalok[10] performed survey on five office buildings in Canada considering a total of 103 rooms (total floor area 935 m^2) and reported the highest and lowest mean FLED to be 852 MJ/m^2 and 530 MJ/m^2 respectively. Bush *et al.*[11] computed mean FLED for single family dwelling (SFD) homes (mean floor area of single home 159 m^2) across the United States to be ranging from 2337 MJ/m^2 to 2850 MJ/m^2. Recently, a fire load survey was conducted by Gao *et al.*[12] in China for students' dormitory that reported mean FLED to be 537 MJ/m^2 with a maximum value of 812 MJ/m^2. The only notable fire load survey for office and residential buildings in the Indian context was carried out by Kumar and Rao[5,9] in the early 90s. They considered 388 government offices (total floor area 11,720 m^2) and 35 residential buildings (total floor area 4257 m^2) and found the mean FLED to be 348 MJ/m^2 and 487 MJ/m^2 respectively. Fire load surveys[3–9,12,13] conducted in the past have shown that FLED in office and residential buildings vary greatly, even within similar geographical locations. Recent information

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Table 1. Comparison of FLED of office buildings with previous studies

Location	Year	Area surveyed (m^2)	Mean FLED (MJ/m^2)	Reference
London, UK	1970	2418	330	3
Nationwide, US	1975	7246	130–4805	4
Kanpur, India	1993	11,720	348	5
Wellington, New Zealand	1995	3999	426–947	7
New Zealand Building Code	2001	–	800	16
Ottawa and Gatineau, Canada	2011	935	550–852	13
Ahmedabad, India	2015	938	1334	Present study

Table 2. Comparison of FLED of residential/dormitory buildings with previous studies

Location	Year	Area surveyed (m^2)	Mean FLED (MJ/m^2)	Reference
Washington, DC, US	1980	42,735	450	17
Auckland, New Zealand	1984	–	442	6
Tokyo, Japan	1989	12,091	667	8
Nationwide, US	1991	–	2337	11
Kanpur, India	1995	4257	487	9
Beijing, China	2013	–	537	12
Ahmedabad, India	2015	4528	1409	Present study

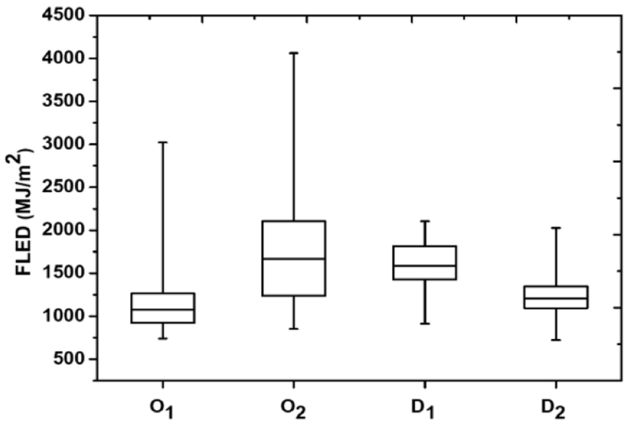

Figure 1. Influence of room use on FLED.

on fire loads in office and residential buildings is scarce in India and much of the available data often lacks detailed information about attributes such as floor area, composition of combustibles, opening sizes and fixed versus movable combustibles, which is essential in characterizing design fires. Given the significant change in the type of materials used in modern buildings, use of data gathered by earlier surveys is questionable.

A survey was carried out in Ahmedabad, India, which is a typical midsized metropolitan city with a population of about 7 million and is comparable to several Indian cities such as Bengaluru, Hyderabad and Pune as well as cities across the world (e.g. Chengdu and Zhengzhou in China)[14]. The survey was undertaken during January–April 2015 using the combined inventory and weighing methods in accordance with NFPA 557 (ref. 15). A total of 105 office rooms (total floor area 938 m^2) including faculty (O_1) and administrative (O_2) offices, and 202 students' dormitory units located in different buildings (D_1 and D_2 with total floor area 4528 m^2) were surveyed.

The lowest FLED in office and dormitory buildings was found to be 722 MJ/m^2 and 749 MJ/m^2 while the highest values were 4060 MJ/m^2 and 2104 MJ/m^2 respectively. It is important to note that IS 1642:1989 prescribes using design FLED of 25 kg/m^2 wood equivalent for such occupancies. Considering the calorific value of wood to be 18 MJ/kg, this amounts to 450 MJ/m^2, a value lower than even the minimum observed values herein. The highlights of the present survey along with that of previous similar surveys are summarized in Tables 1 and 2.

Building usage is an important consideration in design of structures for fire safety[4,18]. The FLED and composition of combustible contents vary with the type of room. The dormitories comprised of double and triple occupancy rooms where FLED of triple occupancy rooms was found to be greater. The mean FLED of double occupancy rooms (average floor area 14.8 m^2) was found to be 1246 MJ/m^2 while for triple occupancy rooms (average floor area of 20.6 m^2) it was found to be 1673 MJ/m^2. The overall mean FLED for all dormitory rooms was 1409 MJ/m^2. In office rooms, the variation among faculty and administrative rooms was found to be quite significant. The mean FLED of faculty offices (average floor area 8.02 m^2) was 1137 MJ/m^2 while that of administrative offices (average floor area of 8.95 m^2) was 1764 MJ/m^2. The storage and stationary rooms (FLED of 4060 MJ/m^2) have a much greater content of combustibles compared to other office rooms due to the presence of a large amount of plastics and cellulosic materials. Figure 1 shows the distribution of FLED for different occupancies. It can be seen that the maximum FLED in administrative offices

Table 3. Average proportion of combustible materials in office and dormitory buildings

Type of building		Wood (%)	Paper (%)	Textile (%)	Plastic (%)	Leather and miscellaneous (%)
Office	O_1	24	45	7	18	6
	O_2	32	34	8	22	4
Dormitory	D_1	41	13	35	8	3
	D_2	52	14	26	6	2

Table 4. Average proportion of fixed and movable combustibles in office and dormitory buildings

Type of building		Wood (%)	Paper (%)
Office	O_1	18	82
	O_2	27	73
Dormitory	D_1	29	71
	D_2	33	67

(O_2) is significantly higher than other occupancies. Further, the variability of FLED of office rooms is greater than that of dormitory rooms.

The characteristics and behaviour of fire depends on the type and distribution of combustibles as different types of combustibles burn at different rates and their combustion products are also different[19]. Information about FLED, in general, must be supplemented with adequate classification of combustibles (e.g. wood, plastic, paper, textile, leather, etc.) for proper characterization of growth fire[20,21]. The major combustibles observed in the present study include cellulosic materials (wood and paper), textiles (clothes, curtains, cushions and woolen fabrics), plastics (electronic and mechanical appliances) and leather. Table 3 shows the average proportion of combustible materials in office and dormitory buildings. Cellulosic materials appear to have the greatest proportion (54–69%) among all combustibles. The composition of plastics (18–22%) was second in offices followed by textiles (7–8%) and leather (4–6%) while, textiles (26–35%) were the second major contributor in dormitory buildings followed by plastics (6–8%) and leather (2–3%). Culver[4] reported the proportion of cellulosic materials in office buildings to be as high as 98.7% among all combustibles. Survey by Zalok and Eduful[13] for office buildings, however, showed a significant decrease in the contribution of cellulosic material (70%) and a greater proportion of plastics (22%). Survey conducted by Issen[17] for SFD homes in the US found the contribution of cellulosic materials to be 78%. In the Indian context, Kumar and Rao[5] found the proportion of cellulosic materials contribution to be 98.6%. It is evident that the amount of cellulosic materials has significantly decreased in recent years and it can be inferred that this decrease is compensated by the increase in proportion of plastic materials. It is primarily due to the increased use of electronic storage of data as opposed to the use of paper files. The introduction of computers, printers, air-conditioners, etc. in most offices has increased plastic-based combustible contents.

Further, the proportion of movable combustibles was found to range from 71 to 82% and 67 to 73% for office and dormitory respectively. Table 4 summarizes the average proportion of fixed and movable combustibles for office and dormitory buildings. Surveys performed in 70s and 90s for office and residential buildings show that movable combustibles contribute ~83–90% to the total combustibles[4,5,9,17]. The change in proportion of fixed combustibles in offices can also be attributed to the increased use of compact electronic, electric and mechanical appliances (e.g. computer, computer accessories, air-conditioners, composite partitions, etc.).

The variation of the FLED observed for office and dormitory buildings has been modelled using the generalized extreme value (GEV) and the gamma distributions with parameter estimates given in Table 5. The fitted cumulative distribution functions are shown in Figure 2. Goodness of both the fits was ensured using the Kolmogorov-Smirnov and the Anderson-Darling tests at a 5% significance level. For office buildings, a positive value for the shape parameter of GEV distribution implies a heavy tailed Frechet distribution indicating non-negligible probabilities of high FLED values. For dormitory buildings, a high value for the shape parameter of gamma distribution indicates that the degree of spread of FLED values is closer to a normal distribution.

To quantify the increase in FLED when compared to the prescribed codal design value of 25 kg/m^2 wood equivalent, an exceedance probability P_{FLED} is defined as

$$P_{FLED} = P(FLED_{observed} > FLED_{design}), \tag{3}$$

P_{FLED} for office and dormitory buildings are estimated through a Monte Carlo simulation using the parametric probability models developed with a sample size of 1000. For office buildings, P_{FLED} was found to be 93.5% while for dormitory buildings, it was 100%. Such high levels of exceedence probability P_{FLED} strongly suggest that the existing FLED levels are greater than the prevailing design standards.

Parametric design fire curves provide a simplified basis to approximate post-flashover compartment fire behaviour. In this section, representative parametric design curves for a total of 105 office rooms and 202 dormitory rooms have been developed in accordance with Eurocode's parametric fire model[22]. These have been derived from the developed probabilistic models, using the 80th

Table 5. Parameters estimated for probability density functions of FLED

		Parameters		
Types of building	Probability density function (PDF)	Scale	Shape	Location
Office	Generalized extreme value (GEV)	272.4	0.3	1096.1
Dormitory	Gamma	72	20	N.A.

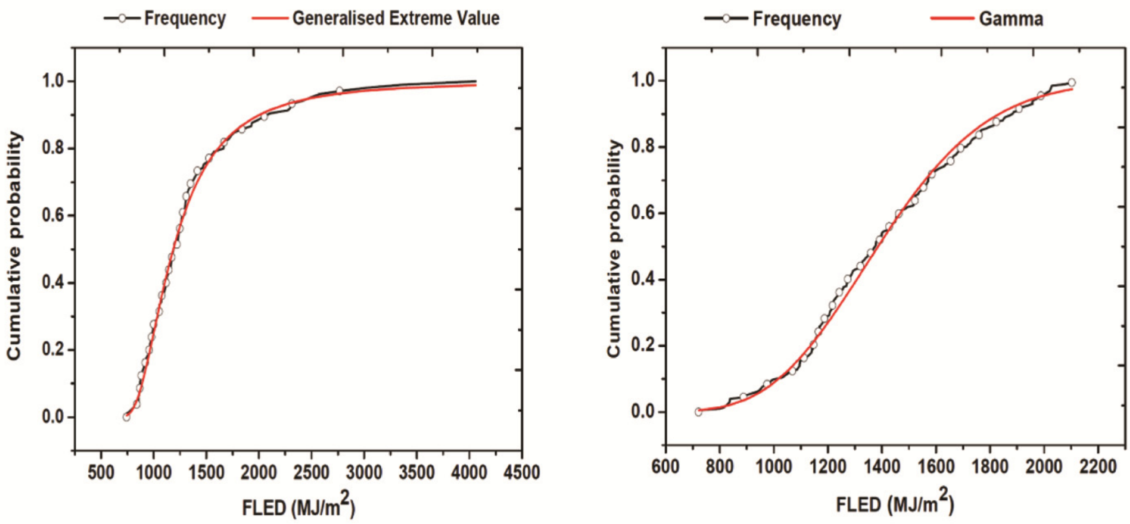

Figure 2. CDF for FLED of office and dormitory buildings.

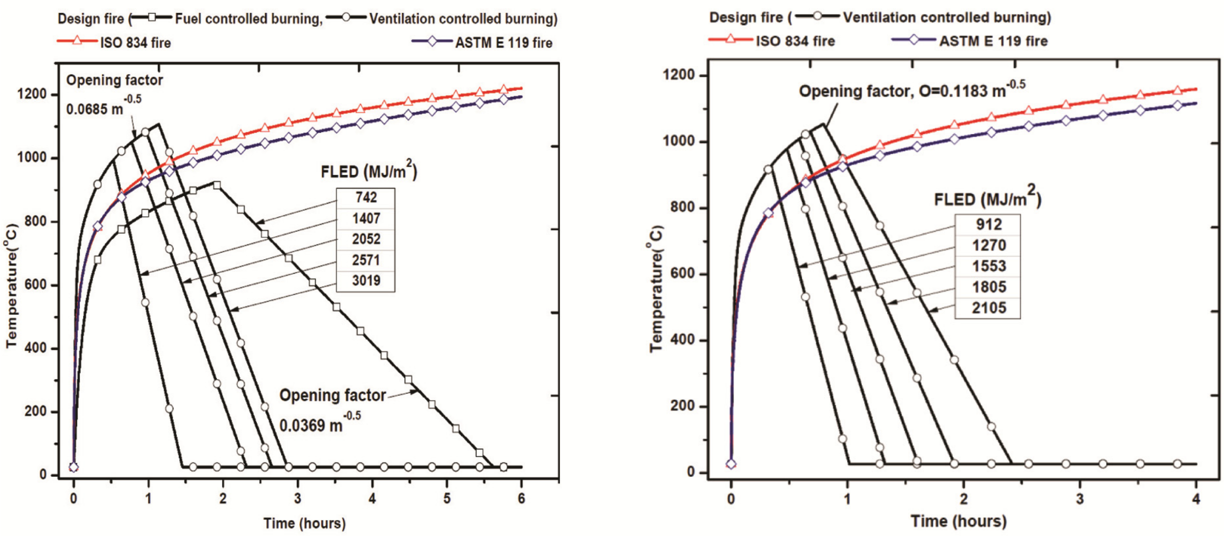

Figure 3. Design fire curve developed using Eurocode[22] for office (left) and dormitory (right) buildings.

percentile FLED values and are shown in Figure 3. It should be noted that ventilation conditions play an important role in the overall compartment fire behaviour and is considered in the development of the design fire curves through opening factor defined as

$$F = A_v \sqrt{H_v} / A_t, \tag{4}$$

where A_t and A_v are the total surface area and area of openings (e.g. windows) of the compartments and H_v represents the height of the building from ground level. A fire is ventilation controlled for low values of opening factor and fuel controlled otherwise.

In office rooms, maximum fire temperature was found to be 1107°C at 81 min for ventilation controlled burning,

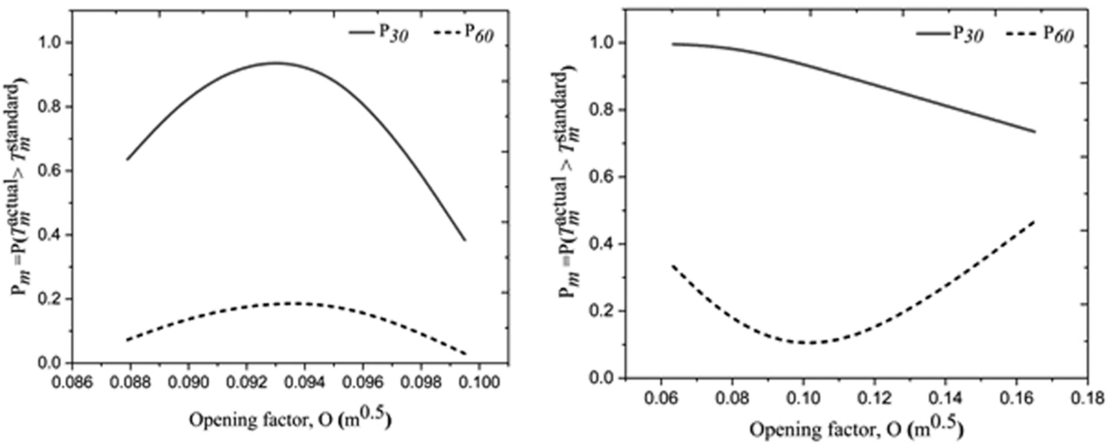

Figure 4. P_{30} and P_{60} versus opening factor for office (left) and dormitory (right) buildings.

while it was 922°C at 112 min for fuel controlled burning. The peak temperature in the dormitory unit was 1053°C at 47 min. The temperature-time plots for ventilation controlled burning for both office and dormitory buildings show a similar pattern. The standard ISO 834 and ASTM E 119 curves were also plotted against the developed parametric curves to highlight the severity of the developed curves. During the initial stage, the temperature predicted at by the parametric design curves agree well with the standard ISO 834 and ASTM E 119 fire curves. However, there are significant differences in the expected temperatures after few minutes of fire initiation.

Safety of building components during fires is described via fire rating – the time for which a structural component demonstrates satisfactory behaviour (e.g. temperature remains below a critical level) under a standard fire (ISO 834 or ASTM E119). Given the enhanced severity of expected compartment fires compared to standard fires, it is expected that the fire ratings derived from standard fire curves will lie on the unsafe side in a large number of scenarios. To quantify this, a probability of failure is defined as

$$P_m = P(T_m^{\text{actual}} > T_m^{\text{standard}}), \tag{5}$$

where m denotes time in minutes, T_m^{actual} is the actual fire temperature after m minutes and T_m^{standard} is the standard fire temperature after m minutes. Using Monte Carlo simulations with a sample size of 1000, P_{30} and P_{60} were estimated for office and dormitory buildings for various opening factors (Figure 4). This further highlights the enhanced severity of expected compartment fires for short durations (30 minute fires) and underlines the increased failure risk of structural members.

Typical values of FLED being used/prescribed by building codes were determined through surveys that were mostly conducted in the last century. This may not be suitable now as the distribution and type of combustibles have changed considerably in the past few decades. Thus, to characterize fire load present in modern buildings, a survey was conducted in office and students' dormitory buildings in Ahmedabad, India during January–April 2015.

Results indicate that modern buildings possess significantly greater fire load as compared to the values documented earlier. The average FLED of office and dormitory buildings was found to be around 1400 MJ/m^2 in the present study, which is about three times greater than the previous study conducted in India in the 1990s. In addition to assessing the total FLED, the present study critically examined the distribution of combustibles. The proportion of cellulosic materials was found to have decreased considerably, compared to previous studies. Interestingly, it was found that plastics, which have much higher calorific values than cellulose, have replaced the lost proportion of cellulosic materials. Probability distributions were also proposed to enable stochastic modelling of fire loads in office and dormitory buildings. To further quantify the increase in fire severity of modern dwellings, parametric design fire curves were developed as per Eurocode. It was observed that in the growth phase, the developed parametric fire curves were more severe compared to the standard fire curves (ISO 834 or ASTM E 119). The maximum fire temperature in the first one hour was also greater in the developed curves, compared to standard fires. This indicates that fire ratings derived from standard fires may be on the unsafe side in case a real fire breaks out in modern compartments. The increased risk was demonstrated through exceedance probabilities estimated through Monte Carlo simulations based on the developed probability models.

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Advances in sea surface layer temperature measurements with fast responding thermistor arrays on drifting buoys

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A precise and accurate ocean temperature measurement system is essential for better understanding and knowledge of the spatial and temporal variability of thermal stratification of the upper-ocean layers is fundamental. The National Institute of Ocean Technology, Chennai has indigenously developed a novel negative temperature coefficient (NTC) thermistor based sensor array with RS232 digital output for drifting buoy (Pradyu) (DB) wherein, it is mainly used in ocean observation applications. The DB is built with Indian satellite (INSAT) for real time data telemetry.

The NTC sensing element is used in developing the temperature sensor for the measurement of sea surface layer temperature. The Steinhart–Hart equation and coefficients are applied on each sampling to zero down the error components involved in temperature measurements which corresponds to the nonlinear functionality of the NTC element. In-house developed SST sensor and sensor array are calibrated and extensively tested in laboratory conditions. The results of the SST and sensor array laboratory calibrations and field validations are briefly presented here with significant data sets collected in the Bay of Bengal warm pool regions.

Keywords: Drifting buoy, NTC thermistor sensor, sensor array, Steinhart–Hart coefficients.

THE sea surface temperature (SST) measured with satellite remote sensing radiometers, ships[1], moored buoys and drifting buoys[2] has made a major contribution to climate research. Remote sensing of SST is limited by the presence of cloud and rain. The SST products are extensively used in ocean analysis and prediction systems to study the upper-ocean circulation and thermal structure. The SST is an important parameter in oceanographic and atmospheric study and in monitoring of biological habitations. Absolute values of SST are important to understand the nonlinear relationship between atmospheric convection and ocean–atmosphere coupling[3]. The physical parameters of ocean temperature and conductivity differ in

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