Load Combinations for Buildings Exposed to Fires

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ABSTRACT

Load requirements in ANSI Standard A58.1.1982 appearing in the LRFD *Specification for Structural Steel Buildings* are selected, whenever possible, using probabilistic load combination analysis and structural reliability theory. The occurrence of a fire with the potential to cause severe structural damage is a rare event in comparison to events giving rise to design-basis load effects. Although probabilistic load modeling techniques reveal that a structure likely is loaded to only a fraction of its design load when a fire occurs, steel structural assemblies normally are fire tested while loaded to the full nominal design load. This paper presents an improved methodology for determining loads and load combinations for use in fire-resistant structural design. The basic methodology is illustrated by determining load combinations involving fire and live loads for limit states design and for use with the standard ASTM E119 fire test. A reduced nominal live load combined with the structural action due to fire apparently provides a load combination that is risk-consistent with other currently accepted load combinations. The method is consistent with the limit states design approaches under development or in use in Europe that recognize the influence of load on fire resistance of steel structures, and is compatible with the LRFD philosophy.

INTRODUCTION

Structures must be designed to withstand the effects of dead loads due to the weight of the structure and permanent attachments, live loads due to use and occupancy, and environmental loads arising from snow, wind, and earthquakes. The loading requirements in standards and codes[1] specify appropriate nominal loads and load combinations to be used in design. These nominal loads are determined, in part, by probabilistic considerations; thus, there is a small but finite probability that the nominal loads used in design will be exceeded in a given year.

The improvement of fire-resistant structural design for steel structures using probabilistic methods for analyzing event combinations has not been attempted and presents some novel features. The occurrence of a fire with the potential to damage a structure severely is a rare event in comparison with events giving rise to design-basis live load or other load effects.[4,6] Modern load survey data[10,23] and stochastic load modeling[5,11,15,21,25] have shown that the full nominal live load acts for only a very short period of time in office and residential occupancies. Accordingly, the structure likely is loaded to only a fraction of design load when a fire occurs. Nonetheless, steel beam assemblies normally are fire tested while loaded with the full nominal design live load.[2]

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Design methods currently under development or in use in Europe[3,6,26] recognize the influence of load on fire resistance of structures. However, there currently is no rational basis for determining what reduced live load might be appropriate for a fire test of a steel structure or what combination of loads might be appropriate for fire-resistant structural design. This paper presents such a basis for event combination analysis, with an application to the common case of fire combined with occupancy live load.

OCCUPANCY LIVE LOADS

Live loads on the floors of a building are defined as those loads produced by the use and occupancy of the building.[1] Roof live loads are produced either by workers, equipment, and materials during maintenance or by movable objects such as planters and people during the life of the structure.[1]

The codified design values for live loads have evolved over the last century from a combination of measured data and engineering judgement. Until about fifteen years ago, the results from live load surveys were used directly in a statistical analysis to characterize live loads for codification.[7] Conservatively high values from distributions fitted to observed histograms formed the basis for design loads, and the variations with floor area served to determine live load reduction. Within the last decade and a half, stochastic models of the live load process have been developed.[8,21,25] These physically meaningful process models reflect, in an approximate probabilistic manner, the actual load history to which a floor area will be subjected during a building's lifetime. As such, they lay the rational basis for developing load combinations, area-based live load reduction, and load duration formulae.[9,11,15]

Probabilistic load modeling treats the live load as consisting of two distinct parts: the sustained live load L_s and the extraordinary or transient live load L_e. It should be noted that the statistics presented subsequently, while typical for common floor areas, generally depend on the loaded area.[15]

Sustained Load

The live load normally present for the intended function of a given occupancy type is referred to as the sustained load.

This load, consisting of planned personnel, furniture, files, etc., varies somewhat with time, but the fluctuations are relatively minor, from a design standpoint, during the tenancy of a single occupant. Therefore, it has been found acceptable to model the sustained load as a constant until a change in occupancy occurs. The magnitude of the sustained load is what is measured in a live load survey and is actually a random variable, generally well described by a gamma probability distribution.[5]

With the assumption of a constant sustained load between occupancy changes, the realization of loading on a particular floor area over time will be as shown in Fig. 1a. The occurrence of an occupancy change is generally assumed to be a Poisson event,[25] and thus the duration of a single occupancy is a random variable following the exponential distribution. Therefore, the process shown in Fig. 1a is referred to as a Poisson pulse process. Studies have shown that for any particular type of use, the assumption of independence between successive sustained load magnitudes is appropriate.[8]

Sustained load statistics for several common occupancy types are given in Table 1. It should be noted that the statistics shown are actually for an "equivalent uniformly distributed load," or EUDL. This is an equivalent uniform load that produces the same load effect on a structural member as the actual loads. The values in Table 1 have been computed for column load effects.[11]

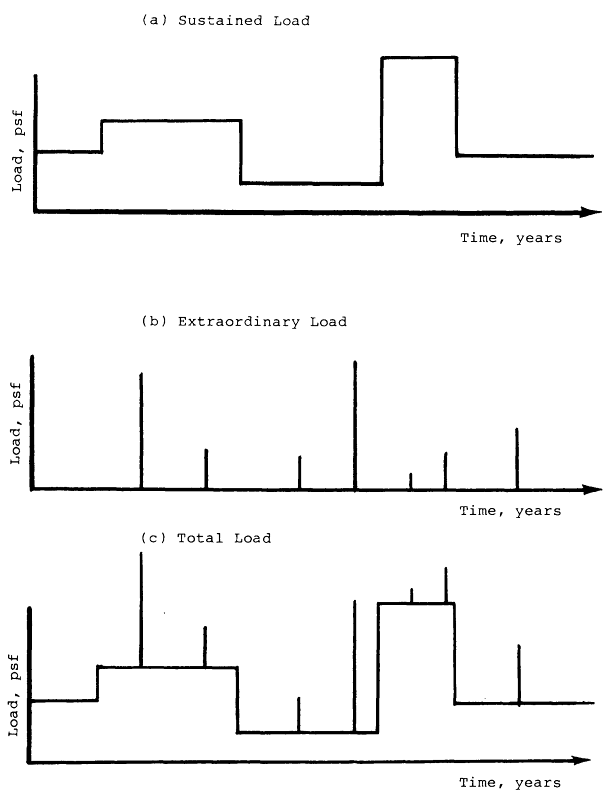

Fig. 1. Live load process model.

Extraordinary or Transient Load

In addition to the sustained load, a building is likely to be subjected to occasional extraordinary or transient loading events. These may arise from crowding in special or emergency circumstances, concentrations due to remodeling, etc.[15] These events tend to occur relatively infrequently, are of short duration, and cause significant load magnitudes. A typical set of realizations is shown in Fig. 1b. Comparing Figs. 1a and 1b, it is clear that the major difference in character is that the extraordinary load is zero during most of the structure's lifetime. Occurrences of the extraordinary load may be assumed to be independent (Poisson) events,[21,25,27] with mean rates of occurrence derived from interviews and engineering judgment. The magnitude of the extraordinary load is generally assumed to follow the gamma probability law.[21] The duration of each extraordinary event is assigned a nominal value for simplicity. Statistics for common occupancy types are available[5,11] and are summarized in Table 1. The extraordinary live load rarely, if ever, is measured in a load survey and must be determined from postulated event scenarios. The extraordinary load statistics in Table 1 are derived from a model of the extraordinary load conceived as groupings of people or furniture.[21]

For determination of the lifetime maximum design live load, the duration of individual extraordinary loads is not important. However, to consider formally the possibility of simultaneous occurrence of two rare events (e.g., fire and transient live load), the rate of occurrence and duration of each event is needed. In such a case it is advisable to use as realistic a model of the extraordinary load as possible. To account for the variety of events producing an extraordinary load and to relate the parameters to physically meaningful events, a model consisting of three separate load processes is used.[15] The results are summarized in Table 2. The remodeling load results from crowding furniture in one space from another. Its magnitude and mean rate of occurrence, therefore, are related to the particular occupancy type. Durations of the remodeling load are taken as two weeks. The special crowding load is derived from models of crowding;[5,11,21] durations for all occupancies are taken as six hours. Finally, an extraordinary load intended to model emergency crowding situations is considered. Mean rates of occurrence are set so that these events occur no more than a few times during the design lifetime, and the duration is taken to be 15 minutes.[15]

Total Occupancy Live Load

The total live load is the sum of the sustained and extraordinary live loads. Recent studies of live loads[5,11,15] have revealed that: (1) The presence of both sustained and extraordinary live load is necessary for the total live load to approach the nominal code value[1] and (2) The duration of the extraordinary (and thus the design-basis) live load is on the order of hours or days. The short duration of the near-

Table 1. Live Load Statistics								
		Sustained Load			Extraordinary Load			
Occupancy Type	Reference Area (ft^2)	Mean (psf)	Std. Dev. (psf)	Ave. Dur. (yrs)	Mean (psf)	Std. Dev. (psf)	Ave. Occur. (yrs)	Design Load (psf)
Office Buildings								
Offices	200	10.9	7.6	8	8.0	8.2	1	50
Residential								
Owned	200	6.0	3.4	10	6.0	6.6	1	40
Rented	200	6.0	3.4	2	6.0	6.6	1	40
Hotels								
Guest Rooms	200	4.5	1.5	5	6.0	5.8	20	40
Schools								
Classrooms	1000	12.0	3.0	1	6.9	3.4	1	40
Commercial								
First Floors	1000	17.9	5.6	2	10.4	5.1	4	100
Upper Floors	1000	12.0	10.6	2	6.9	3.4	4	75

Table 2. Multiple Extraordinary Live Load Model													
	Ref.	Remodeling				Special Crowding				Emergency Crowding			
Occupancy Type	Area ft^2	Mean psf	SD psf	Occ. 1/yr	Dur. wks	Mean psf	SD psf	Occ. 1/yr	Dur. hrs	Mean psf	SD psf	Occ. 1/yr	Dur. min
Office Buildings													
Offices	200	8.6	9.9	0.25	2	10.3	9.3	0.4	6	25.8	23.1	0.02	15
Residential													
Owner	200	4.9	4.4	0.1	2	7.7	7.5	1	6	25.8	23.1	0.005	15
Renter	200	0	0	0	0	7.7	7.5	1	6	25.8	23.1	0.005	15
Hotels													
Guest Rooms	200	2.8	2.5	0.5	2	7.7	6.6	10	6	25.8	23.1	0.1	15
Schools													
Classrooms	1000	10.3	5.0	0.5	2	6.9	3.4	1	6	17.4	8.5	0.1	15
Commercial													
First Floors	1000	16.2	7.9	0.2	2	10.4	5.1	4	6	17.4	8.5	0.1	15
Upper Floors	1000	8.7	4.1	0.2	2	6.9	3.4	4	6	17.4	8.5	0.1	15

design values of live load is a significant factor when the combination of live load with other transient events such as fire is considered.

STOCHASTIC MODELS OF FIRE OCCURRENCE AND DURATION

Fire is one of the primary causes of loss of life and property in buildings.[6,26] In the United States, acceptable performance during a fire is determined on the basis of a standard fire test rather than by analysis. The American Society for Testing and Materials (ASTM) Standard E119[2] is the most common standard used for the qualification of structural and nonstructural components. ASTM E119 identifies a "standard fire exposure" in the form of a time-temperature curve that must be used in a fire test of a component. This standard curve is illustrated in Fig. 2a. On the basis of such a test, a component or construction type is assigned a "fire rating," in hours. Building codes require different minimum ratings depending on building occupancy.

The above "design-by-test" procedure has been used for many years and generally results in conservative fire-resistant design requirements. Recent research has shown that the requirements may be excessively conservative or otherwise unrealistic in some cases.[19] The temperature in the ASTM E119 standard fire exposure curve increases monotonically during the entire rating period, implying an inexhaustible supply of fuel. In an actual fully developed fire, the supply of fuel is finite, and after it is exhausted the compartment temperature decreases.[20,26] A more realistic fire exposure is illustrated in Fig. 2b. Moreover, the ASTM E119 curve does not reflect the nature of the compartment bounding surfaces or ventilation, both of which are known to affect the temperature development significantly.[6]

Improvements in design procedures seem possible. Recent load surveys[10,22,26] have provided data on typical fire loads in various building occupancies. The fire load and compartment ventilation together determine the intensity and duration of the fire. These advances in characterization of fully developed fires have been accompanied by the development of computer programs that enable the performance of structures to be predicted analytically.[3,16,19] These analyses have been validated to the point where they can be considered in a probability-based limit states design framework as an alternative to the traditional method of designing by test.

The occurrence of damage-causing fire in a building is a rare event of relatively short duration. The ignition of a fire can be modeled as a Poisson event,[4,18] with probability of ignition for particular occupancies as given in Table 3.[6] The mean occurrence rate is approximately linearly related to floor area, i.e., $\lambda = pA_f$. Given that a fire occurs, the possibility of flashover (occurrence of a fully developed, structurally significant fire) depends on the fire load and the presence of fire detection and mitigation systems. In modern building systems, flashover occurs only in a relatively small number of fires. Flashover probabilities are listed in the last column of Table 3.[6]

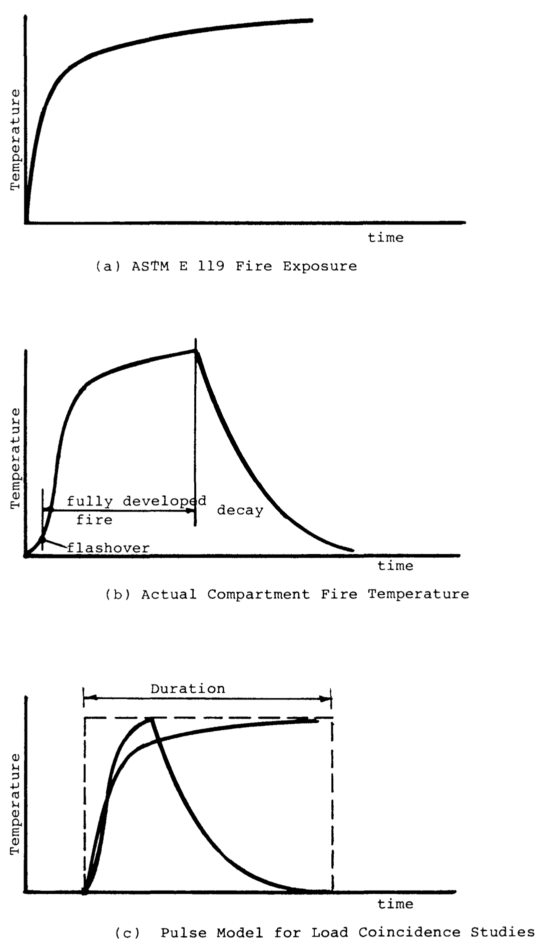

Fig. 2. Fire time-temperature curves.

Table 3. Fire Occurrence Statistics

Occupancy Type	Annual P[fire] per sq. meter ($\times 10^{-6}$)	P[flashover|fire]
Office	1–5	$>10^{-2} - 10^{-3}$ [1]
Dwelling	0.05–1	10^{-1} [2]
Hotel	0.5	2×10^{-2} [3]
School	0.5	2×10^{-2} [3]
Commercial	1.0	2×10^{-2} [3]

1. Assumes office will have alarm system and trained fire personnel in residence; the figure could be reduced to $>10^{-4}$ if sprinkler system is in operation.
2. Assumes public fire company as only response.
3. Assumes sprinkler system.

In order to combine fire effects with live loads in structural design, it is necessary to know the duration of the fire load for each structurally significant fire. Typical fire scenarios produce temperature-time curves such as that illustrated in Fig. 2b. These fire exposures can be enveloped conservatively by a rectangular pulse for purposes of event combination analysis, as shown in Fig. 2c. The duration of this pulse normally would equal the rating period for the ASTM E119 fire but could be taken as the actual fire duration if the fuel load and ventilation were taken into account explicitly.

EVENT COMBINATION ANALYSIS

Events giving rise to structural actions generally can be described by stochastic models such as those shown in Fig. 3.[13,14] When several time-varying actions are present, it is unlikely that each action reaches its maximum lifetime value at the same moment. Consequently, a structure may be designed for a combined action which is less than the sum of the individual lifetime maximum actions. Existing standards have recognized this for some time through the use of subjectively determined load combination factors with values less than unity.[1] Risk-consistent load combination factors can be selected using structural reliability theory and probabilistic load combination analysis methods.[13,14,27] The probability distributions of the maximum of the time-dependent stochastic loads and their combinations are used to develop improved load combination requirements for design.

Probability Distribution of Combined Event Intensity

Let

$$U(t) = X_1(t) + X_2(t) + \ldots + X_m(t) \tag{1}$$

$$U_{max} = \max_{0<t<T} U(t) \tag{2}$$

in which $X_i(t)$ = stochastic event (e.g., live load, earthquake, or fire). Exact solutions for the distribution of U_{max} generally are unavailable, and conservative approximations must be sought.[17,24,27]

The occurrences of the sustained live load, extraordinary live load, and fire events and associated loads are modeled by Poisson pulse processes, as illustrated in Figs. 1 and 2c. Each event in the combination is characterized by a pulse intensity distribution, F_{X_i}, a mean rate of occurrence, ν_i, and a mean duration, τ_i. If the pulse process is intermittent, the probability that it has a nonzero value at any time may be obtained from

$$p_i = \lim_{T \to \infty} E\left(\frac{1}{T}\sum_{i=1}^{N(T)} T_i\right) = \lim_{T \to \infty} (\nu_i T)E[T_i] = \nu_i \tau_i \quad (3)$$

in which $N(T)$ = number of load occurrences in time interval $(0,T)$ and $E[T_i] = \tau_i$ is the expected value of the duration of an individual pulse.

If two or more loads that are always nonzero are combined, the probability distribution of the combined load involving $X_1(t), X_2(t), \ldots$, at any point in time can be obtained by the convolution theorem of probability theory. For example, if $U = X_1 + X_2$, the cumulative probability distribution function, $F_U(x)$, of the sum is

$$F_U(x) = \int_0^\infty F_{X_1}(x - x_2) f_{X_2}(x_2) dx_2 \quad (4)$$

in which $F_{X_1}(x)$ is the cumulative distribution of X_1 and $f_{X_2}(x)$ is the density function for X_2.

Analyzing combinations of intermittent loads which may be zero for significant periods of time is more complex. The possibility must be considered that at any given time, only one of the loads acts or that two (or more) of the loads act simultaneously. Observing that the different possible combinations of intermittent loads are mutually exclusive and collectively exhaustive events, E_i, the probability that the maximum combined load, U_{max}, exceeds level x during time interval $(0,T)$ can be obtained as[24]

$$G_{U_{max}} = 1 - F_{U_{max}}(x) = P[U_{max} > x] \quad (5)$$

$$\approx 1 - \exp[-\Sigma \nu_i T(1 - F_{U_i}(x))] \quad (6)$$

in which ν_i = mean rate of occurrence of load event E_i and $F_{U_i}(x)$ = cumulative distribution function for the sum of loads in event E_i, evaluated from Eqn. 4.

The mean occurrence of events E_i can be evaluated utilizing available data on the mean rates of occurrence and durations of the individual loads. In the current application, this requires the analysis of two intermittent events: extraordinary live load and fire. Since the occurrence of the extreme load events is assumed to be modeled by Poisson processes, the probability of load 1 (or load 2) occurring in interval of time $(t, t + dt)$ is $\nu_1 dt$ (or $\nu_2 dt$), i.e.,

$$P[\text{load 1 occurs in } (t, t + dt)] = \nu_1 dt \quad (7)$$

To ensure that the load events are mutually exclusive, the possibility of a joint occurrence of loads 1 and 2 must be taken into account. The probability that load 1 occurs and load 2 does not occur during the interval in which X_1 acts is $\nu_1 dt(1 - \nu_2 \tau_1)$. A similar analysis must be done for load X_2 in combination with load X_1. The probability of a coincident load event occurring in $(t, t + dt)$ is $\nu_1 \nu_2 dt(\tau_1 + \tau_2)$. The mean rates of occurrence of the mutually exclusive load events are then:

$$\nu_{10} = \nu_1 - \nu_{12} \quad (8)$$

$$\nu_{02} = \nu_2 - \nu_{12} \quad (9)$$

$$\nu_{12} = \nu_1 \nu_2 (\tau_1 + \tau_2) \quad (10)$$

The mean durations of the mutually exclusive events are τ_1, τ_2 and, for the coincident event, $\tau_{12} = \tau_1 \tau_2 / (\tau_1 + \tau_2)$.

Assuming that the individual load events are rare, the probability of occurrence of the (mutually exclusive) events E_i in the time interval $(0,T)$ can be approximated by

$$P[E_{10}] = P[X_1 > 0, X_2 = 0] = \nu_{10} T \quad (11)$$

$$P[E_{02}] = P[X_1 = 0, X_2 > 0] = \nu_{02} T \quad (12)$$

$$P[E_{12}] = P[X_1 > 0, X_2 > 0] = \nu_{12} T \quad (13)$$

in which T = reference period of interest.

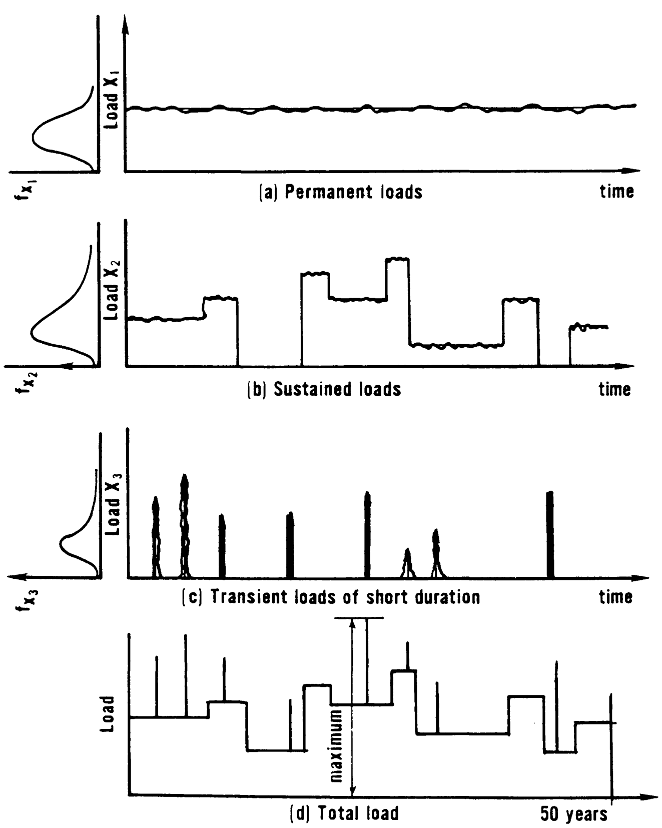

Fig. 3. Pulse process models of loads.

Load Process Statistics for Load Combination Analysis

The load event occurrence and coincidence probabilities are illustrated using the temporal characteristics of the live load

Table 4. Probabilities That Event Combinations Assume Nonzero Values

Event	Remodeling		Special Crowd		Emergency Crowd	
	ν	$\nu\tau$	ν	$\nu\tau$	ν	$\nu\tau$
$L_e>0, F_r>0$	9.6×10^{-9}	4.4×10^{-12}	4.6×10^{-10}	1.2×10^{-13}	9.7×10^{-12}	2.6×10^{-16}
$L_e>0, F_r=0$	0.25	9.6×10^{-3}	0.4	2.7×10^{-4}	0.02	5.7×10^{-7}
$L_e=0, F_r>0$	9.9×10^{-7}	4.6×10^{-10}	9.9×10^{-7}	4.6×10^{-10}	9.9×10^{-7}	4.6×10^{-10}
$L_e=0, F_r=0$	—	0.99	—	1.0	—	1.0

and fire occurrence processes summarized in Tables 1–3. Consider a general office occupancy in which the area of the structural bays is 1076 ft^2 (100 m^2). The mean and standard deviation in the sustained occupancy live load are about 11 psf and 5.48 psf (0.53 kPa and 0.26 kPa), respectively.[5,15] The sustained live load undergoes a significant change in magnitude every 8 years, on the average, due to a tenant change. Thus, $\nu_s = 0.125$ and $\tau_s = 8$ years.

Three sources of extraordinary live load are considered.[15] For those loads due to remodeling, $E[L_e] = 8.6$ psf, $SD[L_e] = 5.5$ psf (0.41 kPa and 0.26 kPa), $\nu_e = ¼$ yr and $\tau_e =$ 2 weeks. For those due to special crowding, $E[L_e] = 6.7$ psf, $SD[L_e] = 3.2$ psf (0.32 kPa and 0.15 kPa), $\nu_e = 0.4$/yr and $\tau_e = 6$ hr. Finally, for emergency crowding, $E[L_e] = 16.9$ psf, $SD[L_e] = 8.0$ psf (0.81 kPa and 0.38 kPa), $\nu_e = 0.02$/yr, and $\tau_e = 15$ min.

For fire occurrence in office occupancies, the mean rate of occurrence is $= (10^{-6}/\text{yr-m}^2)A_f$, in which A_f = occupied area.[6] For an area of 100 m^2, then, $\lambda = 10^{-4}$/yr. The probability of flashover, given ignition, is less than 0.01 in urban areas with municipal fire protection. Thus, the mean rate of occurrence of structurally significant fire, ν_f, is about 10^{-6}/yr for $A_f = 100$ m^2. The duration of such fires would depend on the fuel load but would be on the order of 4 hours or less.

The probability distribution of the maximum combined action due to fire and live load is given by Eqns. 5 and 6. There are four mutually exclusive and collectively exhaustive possibilities for combinations of the extraordinary live load and fire, described by the following events: ($L_e > 0$, $F_r > 0$); ($L_e > 0, F_r = 0$); ($L_e = 0, F_r > 0$); and ($L_e = 0$, $F_r = 0$). The mean occurrence rates and probabilities of nonzero events are listed in Table 4. The first line in Table 4 shows that the probability of a joint occurrence of a structurally significant fire with an extraordinary live load event is negligible.

RECOMMENDATIONS FOR FIRE RESISTANT STRUCTURAL DESIGN

Basic fire prevention measures are aimed at three levels: (1) to prevent the outbreak of fires through the elimination of hazardous practices, (2) to prevent fire growth (flashover) through early detection, and (3) to prevent structural collapse or loss of life through fire protection systems, compartmentalization, alternate exitways, and other passive measures.

The limit state probability of failure due to fire can be written as[4,6]

$$P(F) = P(F|FO,I)P(FO|I)P(I) \tag{14}$$

in which $P(I)$ = probability of ignition, $P(FO|I)$ = probability of flashover (development of a structurally significant fire), given that ignition occurs, and $P(F|FO,I)$ = limit state probability, given the occurrence of a structurally significant fire. This breakdown of the limit state probability is useful in order to focus attention on appropriate strategies for fire prevention, mitigation, and control. Reductions in failure probability and consequences of severe fires can be accomplished by reducing any one, or all, of the three probabilities in Eqn. 14. A similar approach was taken in developing design criteria to reduce the risk of progressive collapse in buildings.[12]

The ignition probability, $P(I)$, can be reduced by eliminating combustible materials from the building or by educating the building occupants on the need for caution with sources of flame and heat. The conditional probability of flashover, $P(FO|I)$, can be reduced through the use of warning systems such as smoke detectors, sprinklers and other fire-suppression systems within the building. Measures to reduce $P(I)$ and $P(FO|I)$ are mainly nonstructural in nature. The probability of failure given a structurally significant fire, $P(F|FO,I)$, depends primarily on the fire-resistant nature of the building construction, including fire proofing of structural or nonstructural components. Steps taken by the structural engineer to design fire resistance into the structure mainly affect the probability, $P(F|FO,I)$.

As noted previously, the ignition probability, $P(I)$, depends on the floor area of the building and is on the order of $10^{-6}A_f$/yr (with A_f in m^2). The flashover probability, $P(FO|I)$, is on the order of 10^{-2} for office or commercial buildings in urban areas of the United States. For areas on the order of 100 m^2, then, the limit state probability, $P(F)$, on an annual basis would be approximately 10^{-6} $P(F|FO,I)$.

To establish a frame of reference for these numbers, the limit state probabilities of steel or reinforced concrete flexural members designed to withstand gravity loads are on the order of 0.0005 to 0.005 on a 50-year basis, corresponding to reliability indices of approximately 2.5 to 3.3.[13,14] On an annual basis, then, these limit state probabilities are of the order 10^{-5}. However, the flexural limit state usually is benign and not life-threatening. Because of the severe consequences of a structural collapse during a fire and the large area of the building potentially affected, it is reasonable to require $P(F)$ to be less than 10^{-6}. If one were to set the target (conditional) limit state probability at $P(F|FO,I) = 0.1/\text{yr}$, the annual probability of structural failure from fire would be on the order of 10^{-7}, placing this risk in the low-magnitude background along with risks from extreme environmental events such as tornadoes and rare accidents such as electrocution.[28]

Criteria for fire-resistant structural design can be developed to be consistent with the above performance objective expressed in probabilistic terms. Pending the acquisition of additional data on material and structural behavior at elevated temperatures,[16,19] only the load combination aspect of the safety check involving dead and live loads is considered. The dead load is assumed to be described by a normal probability distribution, with a mean approximately equal to the nominal A58 load[1] and a coefficient of variation equal to 0.10.[14] Statistics of the live loads are summarized in Tables 1 and 2 and in the previous example. Using these data, the probability of exceeding any combination of design loads can be determined using Eqns. 5 and 6. Because of the negligibly small probabilities of a coincidence of extraordinary live load and fire (see Table 4), the loads acting at the time of the fire can be assumed to consist simply of dead plus sustained live load. The distribution of their sum can be obtained from the convolution of the dead and sustained live load distributions:

$$F_{U_{max}} = \int_0^\infty F_D(x-y) f_{L_s}(y)dy \tag{15}$$

Setting this cumulative distribution function equal to 0.9 (so that the probability is 0.10 or less that the combined dead load plus live load during the fire exceeds the design load), the resulting design load combination is

$$U_n = D_n + 0.5L_n + F \tag{16}$$

in which D_n and L_n are the dead and live loads from the ANSI Standard A58.1-1982 and F is the structural action due to fire. Additional justification for the companion action factor 0.5 is provided by the fact that the mean value of the maximum sustained live load to occur in 50 years also is about $0.5L_n$,[5,11] i.e., if the fire were to occur during the heaviest tenancy in a 50-year period, the likely companion live load at that time would be approximately $0.5L_n$. Severe fires are assumed to lead to ultimate limit states such as gross inelastic deformation or partial collapse. Thus, Eqn. 16 would be employed in an ultimate limit state (LRFD) safety check, in which the behavior of the structure at elevated temperatures would be taken into account. This combined load would also be appropriate for use in a fire test.

SUMMARY

Probabilistic load modeling techniques and modern load survey results can be used to develop appropriate load combinations for fire-resistant structural design and for structural component qualification testing. This study addressed the combination involving dead and occupancy live loads, the combination which would most likely be considered in fire-resistant limit states design.

Structurally significant fires are (statistically) rare events and occur with a probability on the order of 10^{-6} (or less) per year. The probability of a joint occurrence of a fire and an extraordinary live load is so small that the latter need not be considered in fire-resistant structural design. Thus, when considering what loads should be combined with fire effects in analysis or fire testing, a significant reduction in the load from its nominal design value is appropriate.

ACKNOWLEDGMENT

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