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Analysis of roof live loads in industrial buildings

Adem Karasu[1], Kara D. Peterman[2], Sanjay R. Arwade[3]

Abstract

In design, structural engineers must have a clear understanding of live loads, both qualitatively and statistically. For decades, multiple studies have been published that relate live loads for floor loads in various occupancies such as offices and residences. However, survey data or probabilistic live load models for industrial building roofs are difficult to find. There are recommendations in major standards used in the modern world that give design live load values for roofs based on the accessibility of the rooftops. On the other hand, engineers may not understand the origin of these values. Comparison is made between current U.S standards for roof live loads and standards used in other parts of the world. To ensure that the most accurate live load assessment is implemented in the design, our understanding of live loads should be updated on a regular basis. Furthermore, in the United States, the current roof live load design value is 0.96 kN/m^2 (20 psf), which is much greater than the values recommended by European, Australian, and Chinese standards. As a result, determining the source of live load on industrial building roofs is essential. To cover the gap in the literature, this article gives survey methodology and probabilistic studies related to design live load value on roofs. The sensitivity of existing probabilistic models to mean, variance, and time duration was also investigated.

1. Introduction

The design of safe and efficient structures requires knowledge of loads likely to occur during their lifespan. For live loads, this can be complex, and reliant on building function and patterns of occupant use – both of which can change over building lifespan. Live load research has taken two paths since its conception: one that focuses on live load surveys, and another that focuses on live load modeling. Combined, these efforts have resulted in live loads for many common building types that can be characterized via a probabilistic distribution. Modern design codes leverage these distributions to specify live load minimums. However, this critical information is not equally known across building type and function. This study focuses on roof live loads for metal industrial buildings.

Metal industrial buildings are functional and cost-effective structures that are widely used around the globe. These systems are typically defined by built-up steel moment frames consisting structural columns and joist girder (JG) for the main lateral load resisting systems and open web steel joists (OWSJs) for secondary elements. While joist girders can be designed and manufactured as either simple framing members or as part of an ordinary steel moment frame, OWSJs are generally designed for simple span uniform loading. Photographic view of metal industrial buildings is given in Figure 1. Figure 2 illustrates a typical structural system of metal industrial buildings in plan view and elevation in the north-south direction.

Figure 1: Photographic view of metal industrial buildings
Taken from www.newmill.com

[1] Post-Doctoral Research Associate, Department of Civil & Environmental Engineering, University of Massachusetts Amherst, akarasu@umass.edu
[2] Associate Professor, Department of Civil & Environmental Engineering, University of Massachusetts Amherst, kdpeterman@umass.edu
[3] Professor, Department of Civil & Environmental Engineering, University of Massachusetts Amherst, arwade@umass.edu

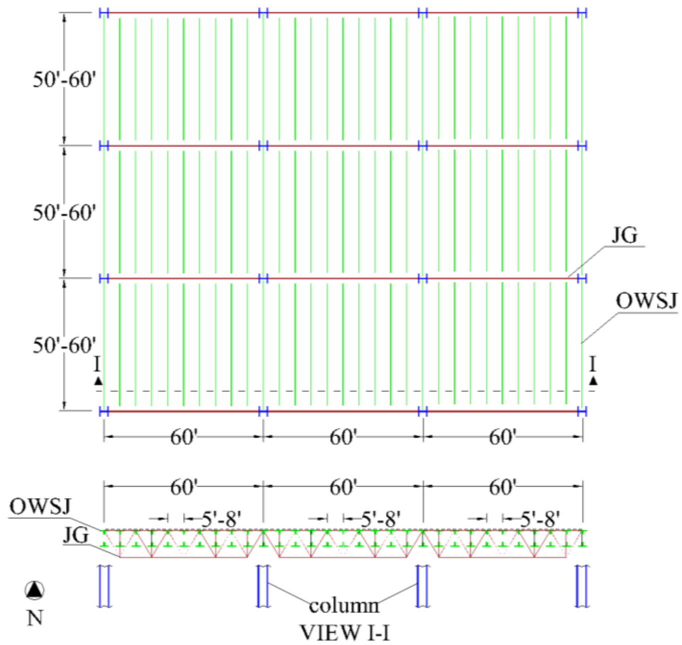

Figure 2: Plan and elevation view of typical metal industrial buildings

For these ubiquitous structures, which are frequently one-story buildings with long span roofs, roof live load is coarsely treated, without probabilistic characterization. This stems directly from a lack of data. Although considerable live load survey results exist for floor live loads in offices and residences [1–6] there is no data for roof live loads in metal industrial buildings. Compounding the lack of knowledge is the absent basis for current provisions. There are no references on the origin of the specified uniformly distributed or concentrated live load for roofs in major standards worldwide. Thus, the primary goal of this study is to examine the source of roof live load for metal industrial buildings. The paper begins with a discussion as to the origin of live loads for office buildings and the probabilistic basis for ASCE 7-22 [7]. Treatment of roof live loads are compared in national design specification around the world. Finally, survey methodology is discussed and preliminary results from the roof live load study conducted herein are presented.

2. Probabilistic Basis for Live Load Estimation

Structural loads are stochastic in nature and change throughout time and space. While the precise loads cannot be estimated with complete certainty, it is possible to model the live loads for design purposes in a probabilistic manner. Accordingly, the time-varying intensity and extent of live loads influencing the structure are examined probabilistically to determine the live load intensities specified in standards, and specifications. The probabilistic methodology provides a logical framework for incorporating the effect of randomness in the magnitude and placement of the individual loads such as sustained and transient load on the design load. Probabilistic models can also be used to predict lifetime maximum loads.

As a result, incorporation of roof live load data into the probabilistic model provides the means to develop realistic and consistent design roof live loads corresponding to a specified level of risk. This makes it possible to identify an equivalent uniformly distributed load (EUDL) that will have the same load effect on a structural member as actual random set of loads. Thus, it is another purpose of this research to develop a new probabilistic model to predict the design roof live load for metal industrial buildings, and to compare the estimated value of roof live load with the values specified in current standards around the world [8–11].

In this section, the stochastic model that is utilized to calibrate many current ASCE 7 live load values for point-in-time live loads on structures is described and a new stochastic model is developed to account for the spatial and temporal variation of live loads for flat and low-slope roofs. This model will be used to assess the existing 0.96 kN/m^2 (20 psf) design RLL based on the results from the RLL questionnaire and, if necessary, propose a new value.

2.1 Point-in-time LL model

Chalk and Corotis (1980) [12] developed a stochastic model for time-varying live loads (LL). This model was adopted and served as the basis for the current LL intensities codified in ASCE 7. A summary of the Chalk and Corotis model is provided in this section.

Equation 1 describes a time-varying, uniformly distributed LL as the sum of a sustained and a transient LL.

$$W(t) = W_s(t) + W_t(t), \quad t \in [0, T] \qquad (1)$$

where W(t) is the total LL, $W_s(t)$ is the sustained part of the LL, $W_t(t)$ is the transient part of the LL and T is the lifetime of the structure. Sustained LL, which acts on a structure for relatively longer periods than transient LL, is generated by moveable objects or appurtenances. These objects are likely to be in or on the structure for months or, more usually, years—for example, furniture in an office. Transient LL arises when people, moving items, or materials are present in or on a structure for a short period of time—typically not more than a few weeks and frequently not even an hour. Crowds of people at an office or meeting space, as well as equipment and supplies for repair and maintenance, are examples of transient LL.

The sustained LL process $W_s(t)$ is piecewise constant with the form

$$W_s(t) = W_{s,i} \quad t_{s,i} < t \leq t_{s,i+1}, \qquad (2)$$

in which $W_{s,i}$ are independent, identically distributed, Gamma random variables with mean value m_s and standard deviation σ_s and ($t_{s,0}$, …, $t_{s,n}$) is a set of time instants such that $t_{s,n-1} \leq T \leq t_{s,n}$. The time interval [0, $t_{s,n}$], therefore, completely covers the lifetime of the structure. The times ($t_{s,i}$) at which the sustained LL magnitude changes are random variables. Such that the times between changes in W_s are exponential random variables with mean value τ_s as given in Equation 3. This is a standard model (Poisson occurrence model) for randomly occurring events such as change of occupancy in a building.

$$t_{s,i} - t_{s,i-1} \sim exp\ (\tau_s\ ) \quad (3)$$

The transient LL process $W_t(t)$ consists of a series of loads superimposed on the sustained LL $W_s(t)$. They can therefore be modeled as instantaneous loads as given in Equation 4.

$$W_t(t) = W_{t,i}, \quad t = t_{t,i}, \quad (4)$$

in which $W_{t,i}$ variables are independent, identically distributed, Gamma random variables with mean m_t and standard deviation σ_t and ($t_{t,0}$, …, $t_{t,n}$) is a set of time instants such that

$$t_{t,i} - t_{t,i-1} \sim exp\ (1/\nu_e\ ) \quad (5)$$

with ν_e being the expected number of transient load events per time unit (typically a year). Similar to the changes in sustained loading, this is a standard model for the random occurrence of events such as transient loading events.

Figure 3 shows how to calculate the Total LL by superimposing a series of increasing and decreasing sustained LL step values with the instantaneous peaks of transient load occurrences.

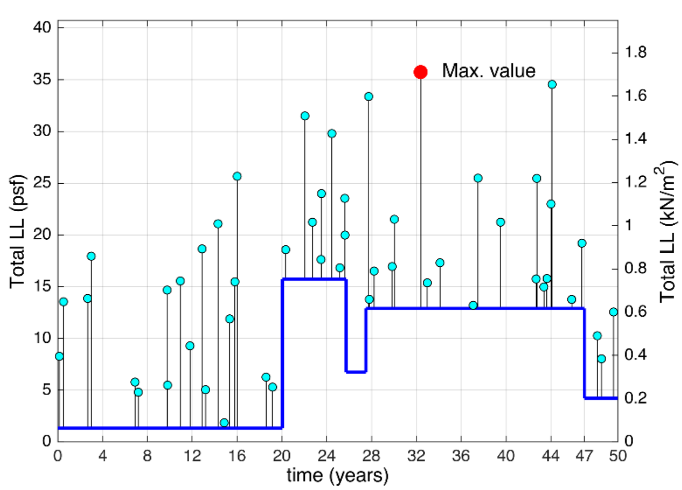

Figure 3: Superposition of sustained and transient loads

The illustrated example is for an office occupancy with parameters: m_s = 0.52 kN/m^2, σ_s = 0.28 kN/m^2, m_t = 0.38 kN/m^2, σ_t = 0.39 kN/m^2, τ_s= 8 years, ν_e= 1 per year, T = 50 years. The figure displays time in years to provide sufficient resolution for various transient load events. In the figure, the sustained LL $W_s(t)$ is shown by a solid blue line, the transient load events $W_t(t)$ are represented by vertical black lines, and the total LL W(t) value is shown by cyan circle markers. The red circular marker indicates the maximum lifetime LL for this particular load history.

The design LL is defined as

$$w_{design} = E[max_{t\in[0,T]}(W(t))] \quad (6)$$

where E[.] is an expectation that is typically calculated using a Monte Carlo simulation [13].

2.2 Spatial LL Model

Roof live loads, particularly transient live loads, vary spatially throughout the roof surface. In this study, a model that treats the transient LL as occurring over a rectangular portion of the roof is used to consider spatial LL variability. This model will eventually be utilized to determine the demand on structural elements. A typical roof framing plan is presented in Figure 2.

Figure 2 illustrates a flat roof composed of columns-supported joist girders and OWSJs that span between them. Typical spacings and dimensions are assumed such that the OWSJs are 6 ft (ranges from 5 ft to 8 ft) on-center and span 50 ft between joist girders. The joist girders are 60 ft in length. A roof with three bays in each direction is assumed since it is the simplest system of its kind that can include all potential bay types (center, edge, corner). The total dimensions of the roof system are 180 feet in the lateral position X, and 150 ft in the longitudinal position Y.

The LL region is rectangular and defined by four parameters. As shown in Figure 4, the location of the LL region is defined by the coordinates (X_{LL}, Y_{LL}) of a corner of the LL region while the size of the LL region is defined by the parameters $L_{LL,x}$ and $L_{LL,y}$.

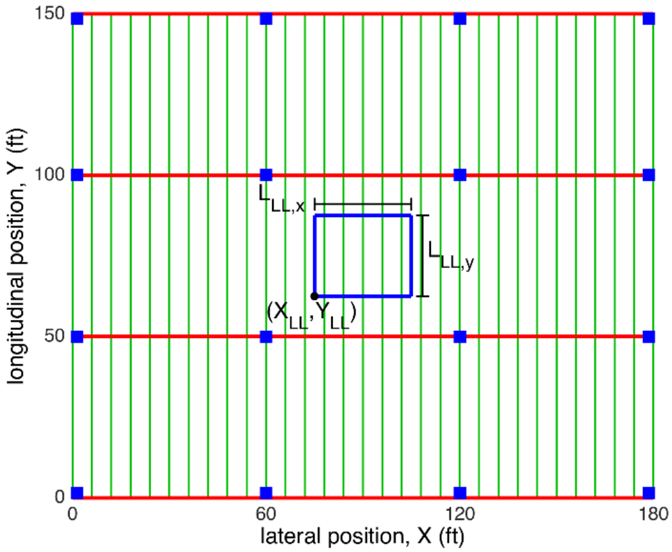

Figure 4: Spatial Live load modal for Metal Industrial Buildings

3. Treatment of Roof Live Loads Worldwide

Treatment of roof live loads in Europe (Eurocode 1 [8]), Australia and New Zealand (Australian/New Zealand Standard (AS/NZS) [9]), Canada (National Building Code of Canada (NBCC) [10]), and China (GB50009) [11] is summarized in this section and compared against the North American ASCE 7 [7] specification. While roofs in ASCE 7, Eurocode 1, AS/NZS, and GB50009 have unique classification, there is no such classification for roofs in NBCC. According to the roof projection area supported by structural elements, ASCE 7 and AS/NZS permit to adopt a reduced uniform roof live load; however, Eurocode 1, NBCC, and GB50009 do not allow this reduction. Roofs that can only be accessed for routine maintenance and repairs will be used to illustrate the standard/code treatments for metal industrial building roofs. Table 1 provides a summary of the findings from the comparison.

Table 1: Comparison of roof live loads in worldwide

Code/Standard	Uniformly distributed load kN/m^2	Concentrated Load kN
ASCE 7	0.96	-
Eurocode 1	0.0-1.0*	0.9-1.5*
AS/NZS	1.8/A+0.12≥0.25**	1.1-1.4*
NBCC	1.0	1.3
GB50009	0.5	-

* Range between minimum and maximum values is shown.
** A is a plan projection of the surface area.

3.1 ASCE 7 Specification

Roof live load is described in ASCE 7 Standard [7] as a load on a roof generated during maintenance by workers, equipment, and materials, as well as throughout the life of the structure by movable objects, such as planters or other similar small decorative appurtenances that are not related to occupancy. An occupancy-related live load is referred to as a live load rather than a roof live load. Based on its geometry and intended usage, roofs are categorized in detail in tables. The most appropriate category to use when describing roof of metal industrial buildings is "Ordinary flat, pitched, and curved roofs". 0.96 kN/m^2 (20 psf) is specified as a minimum uniform distributed design load for this category. In this category roofs are permitted to be designed for a reduced uniform roof live load as given in Equation 7.

$$L_r = L_0 R_1 R_2 \text{ where } 0.56 \leq L_r \leq 0.96 \quad (7)$$

Where L_r (kN/m^2) is the reduced roof live load per m^2 of horizontal projection supported by the member and L_0 unreduced design roof live load. The reduction factors R1 and R2 are determined by using the following equations respectively.

$$\mathrm{R1} = \begin{cases} 1.0 \text{ for } A_T \leq 18.58\text{ m}^2 \\ 1.2 - 0.011A_T \text{ for } 18.58\text{ m}^2 < A_T < 55.74\text{ m}^2 \\ 0.6 \text{ for } A_T \geq 55.74\text{ m}^2 \end{cases} \quad (8)$$

Where A_t is tributary area supported by the structural member.

$$\mathrm{R2} = \begin{cases} 1.0 \text{ for } F \leq 4 \\ 1.2 - 0.05F \text{ for } 4 < F < 12 \\ 0.6 \text{ for } F \geq 12 \end{cases} \quad (9)$$

Where, F is the rise in inches per foot for a pitched roof. All potential load patterns (full and partial loading) are considered in the design process when the uniform roof live loads are decreased to less than 0.96 kN/m^2, depending on which pattern has the most negative load effect.

3.2 Eurocode 1 - Part 1.1

According to Eurocode 1 [8], live loads are also known as imposed loads. Roofs are categorized according to their accessibility into three categories, H, I, and K. Generally, this project focuses on category H roofs: roofs that cannot be accessed for activities other than the routine maintenance and repair. For this category, uniform distributed live load q_k ranges from 0.00 kN/m^2 to 1.00 kN/m^2 (≅20 psf) and characteristic concentrated load value Q_k ranges from 0.9 kN to 1.5 kN. The standard notes that the minimum values do not consider "uncontrolled accumulations" of materials that may occur during typical maintenance. No guidance is provided as to the definition of "uncontrolled accumulation," or how the user should choose a design value from the prescribed range of imposed loads. For structural systems, q_k is used to assess global effects whereas Q_k is used to determine local impacts. Separate design check shall be performed for the uniform distributed load q_k and the concentrated load Q_k acting independently. Uniformly distributed load q_k acts in an area A that may be determined by the National Annex which may contain information on parameters used in the design of structures and other civil engineering projects that are left to national discretion under the Eurocode. The recommended value for A is 10 m^2. Eurocode 1 also suggests adopting lower uniform live load values, such as 0.4 kN/m^2 (≅ 8 psf). In addition, q_k may vary depending on the roof slope as defined by the National Annex. Finally, there are no load reduction factors for roofs in category H.

3.3 Australian/New Zealand Standard – Part 1

Similar to the methodology in Eurocode 1, roofs that are not accessible except for regular maintenance and minor repairs are classified as either R1 or R2. The R1 category corresponds to roof structures that can only be accessed from the ground, from neighboring windows, or from balconies. The R2 category corresponds to roofs that have structural elements supporting the cladding or roof cladding with protective mesh to support maintenance-related activities. Metal industrial buildings are classed as R2 roofs. In this category, uniformly distributed live load value is determined by the surface area of the roof supported by the member under examination as given in Equation 10 but not less than 0.25 kN/m^2 (≅5 psf). The 0.25 kN/m^2 limit is intended to address circumstances such as material stacking during maintenance. Furthermore, structural elements supporting more than 200 m^2 of roof area must be designed to resist 0.25 kN/m^2 on the 200 m^2 of the supported area that has the most detrimental impact.

$$1.8/A + 0.12 \geq 0.25\ \mathrm{kN/m^2} \qquad (10)$$

where A is a plan projection of the roof's surface area in square meters that is supported by the member under analysis. In addition to uniformly distributed loads concentrated loads are also defined and these loads must be considered independently throughout the design process.

3.4 National Building Code of Canada

The National Building Code of Canada [10] defines a prescriptive roof live load and does not allow for any reductions. The specified live load on a floor or roof depends on the intended use and occupancy and shall not be less than either the uniformly distributed load patterns (full and partial loading) or the concentrated loads, whichever produces the most critical effect. [10] specifies a minimum uniformly distributed live load value of 1.0 kN/m^2 (≅20 psf) and a minimum concentrated live load of 1.3 kN which are intended to cover maintenance loads.

3.5 GB50009 Load code for the design of building structures

The National Standard of the People's Republic of China [11] delineates roofs based on their function, specifically whether the roof is accessible by people, and whether there are any gardens or sports fields on the roof. For these instances, where the roof is regularly accessed, GB50009 specifies a uniform distributed live load. For roofs with no access, such as those on most metal industrial buildings, [11] specifies a minimum uniformly distributed live load value of 0.5 kN/m^2 (≅ 10 psf). This value is intended to address maintenance loads for these roofs. Additional data is also included in the table, including the load combination factor, frequency coefficient, and pseudo-permanent coefficient which are specified as 0.7, 0.5, and 0.0 for roofs without people access, respectively. Frequency and pseudo-permanent coefficients are used as live load factor in cases of accidental load combinations.

4. Survey Methodology

Live load surveys have historically taken the form of direct weighing and inventorying, formalized Delphi methods, and focused questionnaires. The wealth of previous work focuses on office building live loads. While these live loads themselves are not relevant to the roof live load study, the methodology used to determine these loads establishes a critical precedence. This section discusses each method, reviewing relevant literature and presenting the method adopted herein.

4.1 Direct weighing and the inventory method

Physical load inventories are determined by direct weighing of objects using special tools, unit weight, a manufacturer's list, or estimation based on past experiences. Instead of directly weighing an object, an inventory survey method gathers observable physical features such as item volume and building material that could be used to determine its weight. Mitchell and Woodgate [1] performed their early survey of UK office buildings via direct weighing. This study was extended for US office buildings by Culver [2]. Results of a survey of 23 office buildings were presented. The inventory survey methodology was used and the data collected for each object included: (1) item type (desk, table, etc.); (2) building material (wood, metal, etc.); and (3) measured dimensions (length, width, height). In the Culver work, no direct load weighing was carried out and the occupant's weight was not considered, in contrast to the work of Mitchell and Woodgate [1]. The weight of the objects was calculated by the surveyor using transfer functions or by utilizing both volumetric measurements and the standard furniture record. While [1] reduces the loaded areas to minimize computation time via notional bays, there was no attempt to construct the notional bays in [2]; instead, the loads in the rooms were computed. Compared to direct weighing, this inventory technique took less time and minimally disrupted regular business operations. The only disruption to the residents of the room caused by this methodology was opening drawers and other storage spaces to ascertain the weight of the contents. The National Bureau of Standards (NBS) Administration Building was chosen as the site for the inventory method evaluation. To ensure that the room contents were consistent across the two surveys, the direct weighing was performed just after the inventory survey. The results of the pilot survey of the NBS Administration Building showed that there was very little difference in weights obtained from direct weighing and inventory weighing.

Choi [3] outlines the live load survey of office buildings that the National Building Technology Centre conducted in Australia. In this survey, the weights of furniture and items were obtained by either direct weighing or the inventory method. Hydraulic load cells were used for direct weighing. Data sheets provided by the manufacturers were utilized to determine the net weight of commonly used standard furniture, including desks, chairs, and filing cabinets. The estimation of weight was required in situations like those where accessing a load item was difficult or where an occupant refused direct weighing. Weight estimation was carried out utilizing both volumetric measures and the standard furniture record. In certain cases, and with occupant permission, pictures were taken to record how the room contents were arranged. Surveys were also conducted to gather data on instances with unusual loads.

In order to analyze point-in-time load intensity in office buildings, eight office buildings in Kanpur, India, were surveyed in Kumar 2002 [4]. All gravity loads, including the loads imposed by the people, were measured in this study. The weights of the movable components were estimated by multiplying the densities by the measured volumes. Tables, chairs, safes, and other commonly used furniture items were measured, and the manufacturers data sheets were used to determine the item weight. The live load of a floor level was calculated by dividing the total weight of the movable objects present in the floor level by the corresponding floor area.

4.2 Delphi methods

Data gathering, fitting of physical and empirical models, and a high degree of engineering expertise have each been historically used for the determination of design loads. Corotis and Fox (1981) [14] leveraged the latter, termed the Delphi method. The Delphi Method involves asking a set of structured questions to established professionals, anonymously. To direct the survey, the expert respondents were provided with the current design code levels, and asked to assess whether current values were appropriate. Respondents do not know the identities of the other participants. After this phase, statistics are created and shared with respondents. For the second round of the Delphi, the respondents have the option of changing their response from the first round. After several rounds of questions and comments, the panel can finally reach a decision when findings converge. In [14] only two rounds of questions and answers were required for convergence. Results from this study informed the 1980 ANSI A58 Standard design live loads. As a direct result of the work, office and residential corridor live loads were reduced by 40-50%.

4.3 Focused questionnaires

In this project, a hybrid technique is used to estimate the total live load on the roofs of metal industrial buildings. The Delphi method successfully used in [14] relied on national experts in structural design providing their expert judgement as to the equivalent uniform live load. As roof live loads have received comparatively little study, and the basis for current design code recommendations unclear, the present study requires a different approach. What types of live loading are present on roofs? What are the magnitude of these loads, and over what area do they act? Are there sustained live loads? While engineering experts form a part of those surveyed, the most important respondents are those intimately aware of what occurs on their metal building roof: maintenance supervisors and building owners. A questionnaire focused on these fundamental questions was circulated among the metal building owner/operator community. A stochastic live load modal that includes both sustained and transient loads will be developed based on the results of the questionnaire.

5. Sensitivity Analysis

Sensitivity analysis quantifies the dependence of system outputs to system inputs. The sensitivities, forms of derivatives, are often computed numerically using finite difference approximations. Sensitivity analyses are implemented in this research to investigate the effect of LL parameters on the design LL (maximum lifetime LL). The stochastic model described in section 2 is used and the finite difference approximations have been carried out using Monte Carlo (MC) simulation in MATLAB [15].

In order to use MC simulation in the sensitivity analysis, a convergence study must first be performed to determine the appropriate number of samples to be used in the MC simulation. The results of such a convergence analysis are presented in Figure 5. The illustrated results are for an office occupancy with parameters: m_s = 0.52 kN/m^2, σ_s = 0.28 kN/m^2, m_t = 0.38 kN/m^2, σ_t = 0.39 kN/m^2, τ_s= 8 years, ν_e= 1 per year, T = 50 years. In the figure different colors represent the various number of simulations, with each point representing the mean of the maximum live load value (Total LL) determined from the specified number of simulations. As an example, the mean of the maximum live load value obtained from 25 analyses is represented by blue markers. In order to track the convergence of the mean results, this set of analyses is also run 15 times. While there is significant variation in the mean of the maximum live load for small simulation numbers, sufficient statistical convergence is obtained at approximately 500 simulations. Probability density function (PDF) of the total live load for each set of simulation numbers is shown in Figure 6.

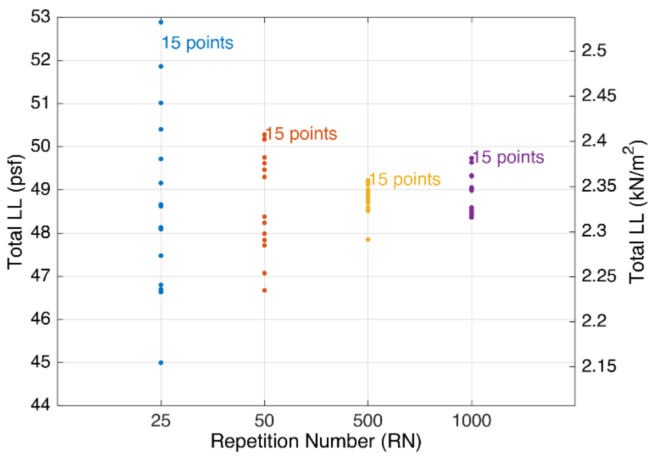

Figure 5: Convergence study result

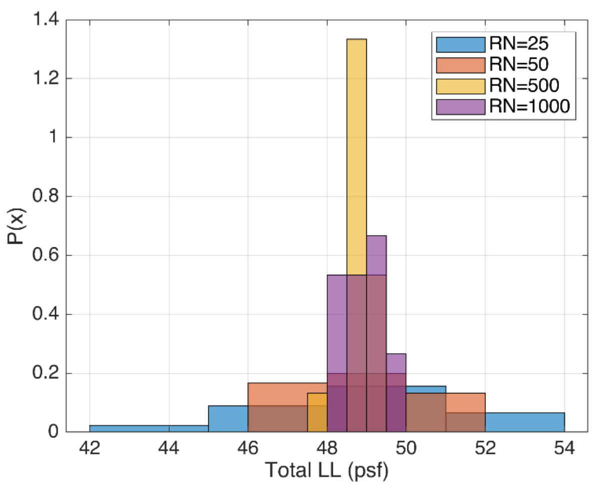

Figure 6: PDF of Total Live Load

For typical office buildings, total design LL depends on parameters including the mean and standard deviation of the sustained and transient LL, the duration of the sustained LL, the occurrence rate of the transient LL, and the design lifetime of the structure. Sensitivity studies have been conducted to examine the impact of these parameters on total design LL. With the other parameters held constant, the parameter for which the sensitivity is to be computed is increased and reduced by 20%. Table 2 shows the impact of each parameter on total LL. The difference in total LL divided by the change in parameter value yields the sensitivities listed in the table. The table shows that the total LL is highly sensitive to changes in the occurrence rate and standard deviation of transient loads. However, other parameters do not significantly affect total LL.

Additionally, an example is presented in Table 3 that represents a possible scenario relevant to metal industrial buildings. In this scenario, the sustained live load is set to a very small value close to 0 N/m^2, a situation that seems plausible for metal building roofs. The estimated total LL values for metal industrial buildings are shown in Table 3.

6. Conclusions

It is necessary to verify the design values provided in the national standards for metal industrial buildings due to the stochastic nature of roof live loading over the course of a structure's lifetime and uncertainty regarding the source of live loading. To achieve this, a probabilistic model that accounts for the temporal and spatial variability of roof live loads was investigated in detail. A series of load histories were simulated by assuming that the load changes occur as Poisson arrivals. Spatial variation of the LL was not considered in this study, though it is described as part of the stochastic LL model. The ASCE 7 treatment of roof live loads and other treatments used worldwide are described and compared. It has been noted that, based on the assumption that there is no public access to roof, national load standards generally specify prescriptive roof live load values for these types of structures. Equipment and maintenance loads are thought to be the primary sources of roof live loads for these types of structures.

Research has been conducted on several survey techniques for live load design that have historically been employed in LL assessment. The focused questionnaire methodology, which involves asking owners and operators of metal buildings fundamental questions about roof live loads, was used in this research to calculate roof live load characteristics, including standard deviation, occurrence rate, and mean value. Then the stochastic model was used to compute design LL and assess the sensitivity of the design LL to each LL parameter. It has been noted that the mean occurrence rate and standard deviation of transient load are found to be the parameters that to which the LL is most sensitive, while other parameters have little impact on total LL. Finally, the uniform roof live load value for metal industrial buildings was predicted using the stochastic model, without considering spatial variability.

7. Acknowledgments

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Table 2: Summary of the Sensitivity analyses

Baseline parameters	Case 1 -20%	Total LL psf (kN/m^2)	Baseline	Total LL psf (kN/m^2)	Case 2 +20%	Total LL psf (kN/m^2)	Sensitivity Indices
m_S psf (kN/m^2)	8.72 (0.42)	46.68 (2.24)	10.9 (0.52)	48.81 (2.34)	13.08 (0.63)	51.13 (2.45)	1.021 (psf/psf)
σ_s psf (kN/m^2)	4.72 (0.23)	48.38 (2.32)	5.9 (0.28)	48.81 (2.34)	7.08 (0.34)	49.72 (2.38)	0.568 (psf/psf)
τ_s (year)	6.4	49.34 (2.36)	8	48.81 (2.34)	9.6	48.89 (2.34)	-0.140(psf/year)
m_t psf (kN/m^2)	6.4 (0.31)	49.31 (2.36)	8 (0.38)	48.81 (2.34)	9.6 (0.46)	49.21 (2.36)	-0.031(psf/psf)
σ_t psf (kN/m^2)	6.56 (0.31)	42.59 (2.04)	8.2 (0.39)	48.81 (2.34)	9.84 (0.47)	56.36 (2.70)	4.198(psf/psf)
ν_e (per year)	0.8	47.23 (2.26)	1.0	48.81 (2.34)	1.2	50.43 (2.42)	8.000(psf.year)
T (year)	40	47.05 (2.25)	50	48.81 (2.34)	60	50.59 (2.42)	0.177(psf/year)

Table 3: Estimated total LL values for metal industrial buildings

m_S psf (kN/m^2)	σ_s psf (kN/m^2)	m_t psf (kN/m^2)	σ_t psf (kN/m^2)	τ_s (year)	ν_e (per year)	T (year)	Total LL psf (kN/m^2)
1 (0.048)	1 (0.048)	4 (0.192)	4 (0.192)	10	1	50	19.07 (0.913)
1 (0.048)	1 (0.048)	5 (0.239)	5 (0.239)	10	1	50	23.62 (1.131)
0.5 (0.024)	0.5 (0.024)	5 (0.239)	5 (0.239)	10	1	50	22.91 (1.097)
1 (0.048)	1 (0.048)	5 (0.239)	5 (0.239)	10	0.5	50	20.00 (0.958)
0 (0)	0 (0)	5 (0.239)	5 (0.239)	10	1	50	22.49 (1.077)
1 (0.048)	1 (0.048)	6 (0.287)	4 (0.192)	10	1	50	19.60 (0.938)
1 (0.048)	1 (0.048)	6 (0.287)	4 (0.192)	10	2	50	21.67 (1.038)

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