Reliability Analysis of Evacuation B Improved Response Surface Method

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Abstract. Due to lacking of explicit limit state equation in first order reliability method (FORM), solution is hard to obtain on building fire risk analysis; The direct Monte Carlo simulation will face huge computation. Therefore, a new analysis method based on improved response (IRS) is proposed, which constructed by uniform design (UD) and non-parametric regression (NR), and then, obtains the available safety egress time (ASET) and the required safety egress time (REST) probability distribution with Monte Carlo simulation. Through a practice of building fire risk analysis, the results show that UD picks up test inputs data together with alternative conditional expectation ACE regression for constructing response surface (RS) provide a small computation and good fitting effects method.

Introduction

The performance based fire safety design (PBFSD) is widely accepted in recent years. Generally, there are two parameters evaluated in PBFSD, i.e. available safety egress time (ASET) and required safety egress time (RSET)[1]. They can be calculated through specified fire dynamics analysis software, for example CFAST, and evacuation simulation software, for example EVACNET[2][3]. To account for the uncertainties of calculation parameters and evaluate the reliability of a fire safety design, the probability based reliability calculation is a traditional approach[4]. However, there are no explicit limit state functions provided by the software for a complex system which generally attaches the reliability analysis to computational Monte Carlo simulation (MCS).

To avoid above problem, many kinds of response surface (RS) based method were proposed [5][6][7]. The study introduces an improved RS method based on uniform design and non-parametric regression to analyze the reliability of occupant evacuation in a fire building considering the uncertainties of calculation parameters. The probability distributions of ASET and RSET are first calculated by RS based MCS, and then the reliability index of evacuation safety are calculated based on these probability distributions.

Calculation Process

It is required that ASET should be larger than RSET in a fire safety design [1][2].Thus the reliability problem of occupant evacuation can be written as,

$$P_f = P_{rob}(ASET - RSET < 0) \tag{1}$$

Where, P_f is failure probability. As mentioned above, ASET and RSET can be calculated through current available software, which generally provide no explicit limit state function. To overcome this problem, RS method can be introduced. An improved RS method proposed in this paper mainly include the following four steps:

1) Arrange the parameter groups for the construction of RS function. An uniform design method (UDM) is introduced to reduce the trial computation efforts.

2) Calculate the ASET and RSET for different parameter groups respectively through CFAST and EVACNET.

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3) Construct the RS function. An non-parametric regression technique, alternative conditional expectation (ACE), is introduced to get better data fitting between input parameters and output results.

4) Reliability analysis through RS based MCS.

Arrange Parameter Groups by UDM

The motivation of UDM proposed by Fang and Wang is to reduce the test work through proper arrangement of experimental datum [8]. As a special test carried out by computer simulation, construction RS can also adopt same idea to reduce the simulation work [9]. For a m parameter problem, X_1, X_2,…, X_m , the arrangement of parameter groups through UDM can be carried out as following steps:

1) Determine the calculation range $[X_{imin}, X_{imax}]$ $(i = 1,2,...,m)$, where X_{imin} , X_{imax} is the minimum and maximum of the ith parameter.

2) Divide each parameter range into n level.

$$X_{ij} = X_{i\min} + \frac{j-1}{n}(X_{i\max} - X_{i\min}) \tag{2}$$

Where X_{ij} denotes the jth ($j = 1,2,...,n$) level of the ith parameter.

3) Chose proper uniform design table (UDT) according to parameter number and level number. UDT is constructed by power generation method proposed by Fang [10] and there are series of UDTs prepared for use in Ref [8].

Determination of RSET and ASET

RSET is the required time begins with fire breaking out and ends with occupants evacuated to safety area. It is the sum of fire detection time t_{alarm} , the preparation time t_{pre} and travel time t_{move} [1]. In this paper, RSET of a fire building is calculated by the software EVACNET.

ASET is available time for safety egress. Generally, it begins with fire breaking out and ended by either one of the following conditions: (1) Thermal radiation fluxes > 0.25W/cm^2;(2) The temperature of upper hot smoke layer > 180℃; (3) The height of upper hot smoke layer to the floor <2.0 m[2]. These three states and together with corresponding ASET are analyzed by the software CFAST.

Non-Parametric Regression

After all RESTs and ASETs of corresponding input parameter groups are calculated through EVACNET and CFAST, a non-parametric regression method, ACE [11], is introduced to construct the RS function. The basic idea of ACE is to look for the nonlinear transform relations between inputs $x_1, x_2,...,x_m$ and response function $\varphi_1(x_1), \varphi_2(x_2)$,…, $\varphi_m(x_m)$ and $\theta(y)$, and make them meet following mapping relationship ,

$$\theta(y) = \varphi_1(x_1) + \varphi_2(x_2) + ... + \varphi_m(x_m) + \varepsilon \tag{3}$$

Where, ε is the fitting error. Thus the RS function will have the form:

$$y = \Theta[\varphi_1(x_1) + \varphi_2(x_2) + ... + \varphi_m(x_m)] + \varepsilon_2 \tag{4}$$

Where, $\Theta(.)$ is the inverse function of θ. ACE analysis of input and output parameters in this paper are carried out in the software S-Plus.

MCS basing on RS Function

After the RS functions for ASET and RSET are obtained, MCS can be carried out directly basing on RS functions. This avoids the time consuming work of CFAST and EVACNET and make huge mount of MCSs possible. In this paper, MCS can be carried out basing on an interpolation algorithm basing on RS function. $\varphi_i(X_i)$ can be got by interpolation, that is：

$$\varphi_i(x_i) = interp(X_i, \varphi_i(X_i), x_i), i = 1,2,3,..., m \tag{5}$$

$$\theta(y_i) = \sum_{i=1}^{m} \varphi_i(x_i) \tag{6}$$

$$y_i = interp(\theta(Y), Y, \theta(y_i)) \tag{7}$$

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Example

The case is a two floor office building. There are 3 stair cases and 2 security exits denoted by DS1, DS2, see Fig.1. No mechanical ventilation system and sprinkle system installed in this building. Ambient temperature and pressure is 20℃ and 101.3kPa respectively. Fire room size is $7.2m \times 3.6m$, close to DS1.

There are 10 uncertain parameters should be considered: combustion efficiency factor η_f, gas radiation factor γ_{qr}, fire growth factor α_g, net heat of combustion $H_{c,net}$, the characteristic heat release rate $\dot{Q}_f$, the fire load density q_f, the fire height H_{fuel}, pedestrians density ρ, walking speed v and the exit discharge coefficient f. For convenience, the probability distributions of these parameters are list in table 1 and for convenience they are also denoted by $X_1 \sim X_{10}$.

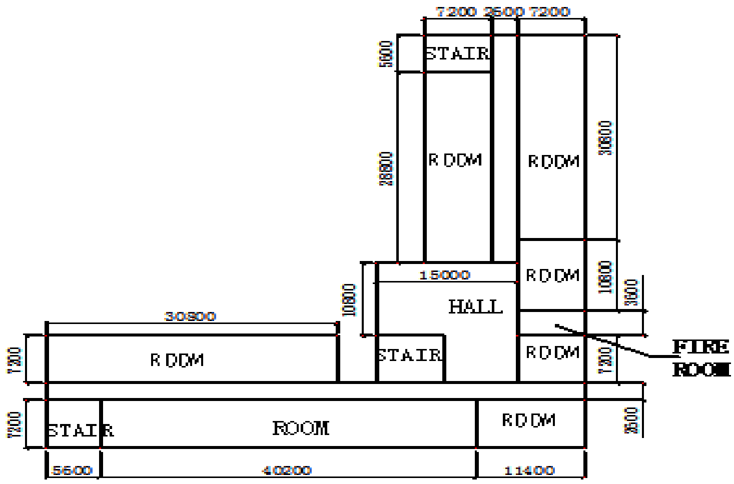

Fig.1 The layout of floor plan (mm)

Table 1 The uncertainty values range

Factor X_i		unit	Distributios	average	Standard deviation	minimum	maximum
X_1	η_f	--	Normal	0.8	0.08	0	1
X_2	γ_{qr}	--	Normal	0.3	0.03	0	1
X_3	α_g	KW/s^2	Normal	0.012	0.003	0	0.1
X_4	$H_{c,net}$	MJ/kg	Normal	17	1.7	14	20
X_5	$\dot{Q}_f$	kW	Normal	2060	206	0	--
X_6	q_f	MJ/m^2	Normal	860	86	0	--
X_7	H_{fuel}	m	Normal	0.3	0.06	0	2.7
$X8$	ρ	Man/m • s	Normal	0.98	0.23	0	1.37
$X9$	v	Man/m^2	Normal	0.26	0.08	0	0.4
$X10$	f	m/s	Normal	0.9	0.21	0	1.27

The reliability analysis is carried out step by step according to the process list in section 2.

1) Arrange parameter groups by UDM. The maximum and minimum of each parameter are list in table 1. There are totally 27 levels determined and based on which a UDT named U27* (27^{10}) is used to arrange the parameter groups, see table 2.

2) Determination of RSET and ASET. For each parameter groups, corresponding ASETs and RSETs are calculated respectively by CFAST and EVACNET. They are also list in table 2.

3) Non-parametric regression. The ten input parameters and corresponding output results (ASETs and RSETs) are analyzed by ACE provided by S-plus 8.0. The correlation coefficient is 0.971 for RSET and 0.966 for ASET. The result mapping functions $\varphi_i(x_i)$ and $\theta(y)$ are plot in Fig.2- Fig.12.

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4) MCS basing on RS Function. 100000 times of MCSs are carried out basing on the RS functions provide in step 3) through the interpolation algorithm described in section 2.4. The Probability distributions of ASET and RSET are plot in Fig.13.

Table 2 U27*(27^{10}) uniform design tables

factor \ groups	1	2	3	4	5	6	7	8	9	10	11	12	13	14
η_f	0.56	0.578	0.597	0.615	0.634	0.652	0.671	0.689	0.708	0.726	0.745	0.763	0.782	0.8
γ_{qr}	0.217	0.231	0.245	0.258	0.272	0.286	0.3	0.314	0.328	0.342	0.355	0.369	0.383	0.21
α_g	0.0051	0.0078	0.0106	0.0134	0.0162	0.0189	0.003	0.0058	0.0085	0.0113	0.0141	0.0168	0.0196	0.0037
$H_{c,net}$	15.554	16.815	18.077	15.081	16.342	17.604	14.608	15.869	17.131	18.392	15.396	16.658	17.919	14.923
$\dot{Q}_f$	2196.9	1663.8	2439.2	1906.1	2681.5	2148.4	1615.3	2390.7	1857.6	2633.0	2100	1566.9	2342.3	1809.2
q_f	809.23	845.77	882.31	918.85	955.38	794.62	831.15	867.69	904.23	940.77	780	816.54	853.08	889.62
H_{fuel}	0.1815	0.2277	0.1492	0.1954	0.2415	0.1631	0.2092	0.2554	0.1769	0.2231	0.1446	0.1908	0.2369	0.1585
ASET	250	266	184	216	217	195	305	262	236	224	214	210	202	272
ρ	1.163	0.955	0.748	1.34	1.133	0.926	0.718	1.311	1.103	0.896	0.689	1.281	1.074	0.867
V	0.252	0.389	0.241	0.379	0.231	0.368	0.22	0.358	0.21	0.347	0.199	0.337	0.188	0.326
f	1.241	1.212	1.182	1.153	1.124	1.095	1.065	1.036	1.007	0.978	0.948	0.919	0.89	0.861
RSET	160	200	181	180	155	190	182	176	170	195	171	165	161	191

factor \ groups	15	16	17	18	19	20	21	22	23	24	25	26	27	
η_f	0.818	0.837	0.855	0.874	0.892	0.911	0.929	0.948	0.966	0.985	1.003	1.022	1.040	
γ_{qr}	0.224	0.238	0.252	0.265	0.279	0.293	0.307	0.321	0.335	0.348	0.362	0.376	0.390	
α_g	0.006	0.009	0.012	0.015	0.018	0.020	0.004	0.007	0.010	0.013	0.015	0.018	0.021	
$H_{c,net}$	16.2	17.4	14.5	15.7	17.0	18.2	15.2	16.5	17.8	14.8	16.0	17.3	18.6	
$\dot{Q}_f$	2584.6	2051.5	1518.5	2293.8	1760.8	2536.2	2003.1	1470.0	2245.4	1712.3	2487.7	1954.6	2730.0	
q_f	926.2	962.7	801.9	838.5	875.0	911.5	948.1	787.3	823.8	860.4	896.9	933.5	970.0	
H_{fuel}	0.20	0.25	0.17	0.22	0.14	0.19	0.23	0.15	0.20	0.25	0.17	0.21	0.26	
ASET	241	231	218	208	200	190	278	245	230	222	212	206	204	
ρ	0.66	1.25	1.04	0.84	0.63	1.22	1.01	0.81	0.60	1.19	0.99	0.78	1.37	
V	0.18	0.32	0.17	0.30	0.16	0.29	0.15	0.28	0.14	0.27	0.13	0.26	0.40	
f	0.83	0.80	0.77	0.74	0.71	0.69	0.66	0.63	0.60	0.57	0.54	0.51	1.27	
RSET	166	172	162	196	167	173	177	197	178	183	168	192	175	

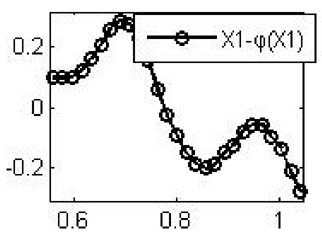

Fig. 2. $x1 - \varphi(x1)$

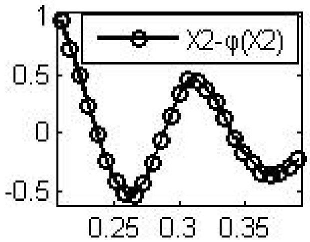

Fig. 3. $x2 - \varphi(x2)$

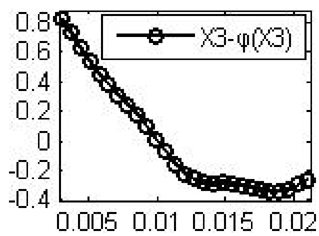

Fig. 4. $x3 - \varphi(x3)$

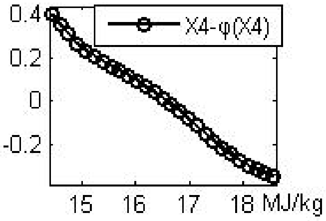

Fig. 5. *x4 - φ(x4)*

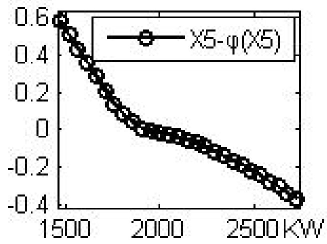

Fig. 6. *x5 - φ(x5)*

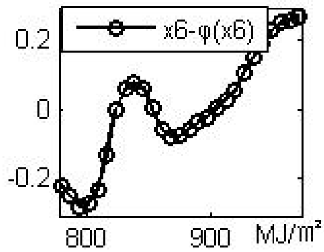

Fig. 7. *x6 - φ(x6)*

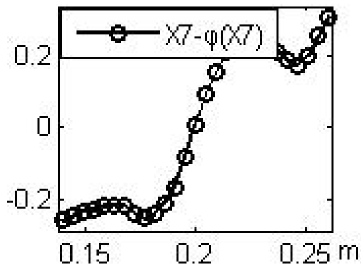

Fig. 8. *x7 - φ(x7)*

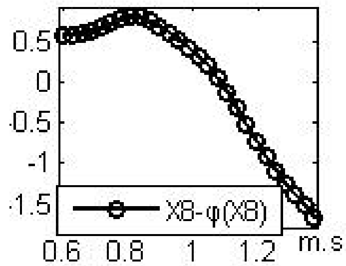

Fig. 9. *x8 - φ(x8)*

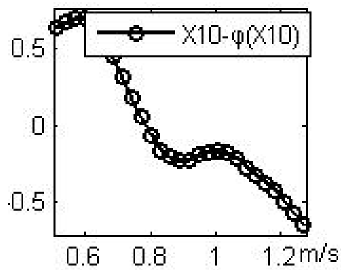

Fig. 10. *x9 - φ(x9)*

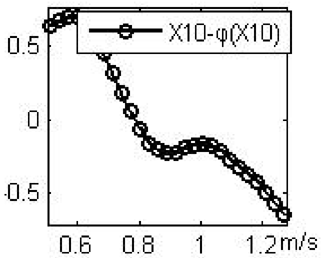

Fig. 11. *x10 - φ(x10)*

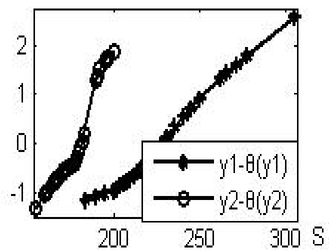

Fig. 12. *y - θ(y)*

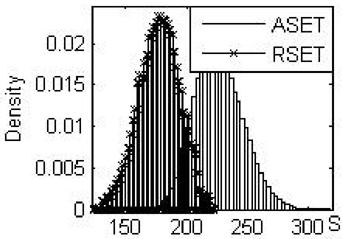

Fig. 13. The probability of RSET、ASET

According to safety evacuation guideline, if the available safety evacuation time is greater than the required safety evacuation time, the people in building can safely evacuated, that is ASET>RSET [1]. So the limit status equation is $Z = ASET - RSET$. When $Z > 0$, the people are safely evacuated, and when $Z < 0$, evacuation is incomplete. Based on the probability distribution of the 100,000 times Monte Carlo simulation seen in Fig. 13, the reliability index β is 2.0048.

Conclusion

Combining UDM and ACE regression, this paper proposed an improved RS method, based on which, the probability distributions of RSET, ASET and corresponding reliability index of occupant evacuation can be efficiently obtained. The conclusion can be drawn as below:

1) The introduction of UDM can significantly reduce the time of trial computation for the construction RS especially for those problem with many parameters.

2) It can get high fitting accuracy because of the adaptation of non-parametric ACE regression technique, at the same time, the MCS based on RS can avoid the large computational problem of direct MCS.

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References

[1] Weicheng FAN, Junhua Sun, Shouxiang Lu: Fire PRA Methodology [M]. Science Press, Beijing. (2004)

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[2] Peacock RD, Jones WW, Forney GP. CFAST — Consolidated model of fire growth and smoke transport (Version 5): User’s guide [S]. NIST Special Publication 1034. Gaithersburg: National Institute of Standards and Technology; 2005.
[3] A methodology for the determination of code equivalency with respect to the provision of means of escape. Fire Safety Journal, 1992
[4] Frantizich H. Uncertainty and risk analysis in fire safety engineering [M]. Lund University, Sweden, 1998(31):313-329..
[5] Magnusson S.E., Frantizich H., Harada K. Fire safety design based on calculation: uncertainty analysis and safety verification [J]. Fire safety Journal. 1996(27):305-334.
[6] Magnusson S.E., Frantizich H., Harada K. Fire safety design based on calculation: uncertainty analysis and safety verification [R]. Report 3078. Lund University, 1995.
[7] Guofan Zhao, Weiliang Jin, Jinxin Gong: Structural Reliability Theory. China Structure Industry Press, Beijing. (2000)
[8] Kaitai Fang: Uniform Design and Uniform Design Tables. Science Press, Beijing. (1994)
[9] Bin Li, Zhigang Song: Fire Science and Technology, Vol.17, No.5, (2009):43-48(in Chinese).
[10] Fang, K.T.and Wang, Y.(1994).Number-theoretic Methods in Statistics, Chapman and Hall.
[11] Hasofer A.M., Qu J. Response surface modelling of Monte carlo fire data [J]. Fire Safety Journal, 2002(37): 772-784.

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