Fire Performance of Steel Tubular Columns Filled with Normal Strength Concrete

WOJCIECH SZYMKUC, ADAM GLEMA
and MICHAL MALENDOWSKI

ABSTRACT

The main goal of this paper is to predict the fire resistance rating (FRR) of composite concrete filled tubular (CFT) columns without external fire protection. In order to do that, the response of axially and eccentrically loaded columns to mechanical load in fire conditions is investigated.

This study is based on data from 41 available full scale tests of columns filled with siliceous aggregate normal strength plain concrete, tested in the last 25 years by various researchers [1-6]. Analyses are carried out taken into account different parameters for which results are given, including different stress-strain relationships for concrete combined with two yield criterions, namely linear and hyperbolic Drucker-Prager. Different formulations of thermal expansion are investigated. Regarding properties influencing temperatures inside the cross-section, influence of formulations of specific heat of concrete and thermal gap conductance between steel tube and concrete core are investigated. Sensitivity study concerning mesh size as well as imperfections shape and magnitude is carried out. Recommendations regarding model application range are given based on evaluation of the results, which are plotted or showed against independent variables such as relative slenderness, utilization ratio or boundary conditions. Mean ratio of calculated fire resistance time to time of fire resistance measured during experimental test is presented. For the proposed model and for set of 41 tested specimens the ratio is around 1.0, with a standard deviation around 0.3 for all specimens, while standard deviation does not exceed 0.2 for pinned-fixed and fixed-fixed columns in most cases. Selected results are presented in detail.

INTRODUCTION

So far several attempts were made in order to improve the ability to predict fire resistance time of CFT columns. The aim of this paper is to verify the proposed model based on extensive literature data [1-6] and recognize the influence of several parameters and properties, which in some papers are based on a study of limited number of columns. Similar studies can be found e.g. in references [7-11].

Wojciech Szymkuc, Adam Glema, Michal Malendowski, Institute of Structural Engineering, Poznan University of Technology, ul. Piotrowo 5, 60-965 Poznań, POLAND

After analytical data was collected an automated approach using Python and Matlab scripts was developed. A general python script was created to communicate with Abaqus, generate input files and apply necessary changes. Matlab is used to read the data from the database and create a set of python scripts that could be used further.

EXPERIMENTAL DATA

Study presented in this paper is based on experimental data obtained from five different research programs [1-6], containing results of 41 concrete filled circular specimens under mechanical load in furnace fire test conditions.

Test program described in [1] consists of 13 specimens, 8 of them did not have fire protection. As this paper focuses on columns without fire protection and filled with normal strength concrete, only 4 specimens from this program are included. One of them was loaded axially, while the other three ware loaded eccentrically, with the ratio of load eccentricity to radius (e/r) of 0.3 or 0.6. It is notable, that member utilization was 77% (ratio of the load applied in the fire test to load-bearing capacity in ambient conditions). Kim et al. [2] tested 20 columns, half of them were circular, while the other half were square. Results of calculations regarding 7 specimens are presented here. Utilization ratio for these specimens varied from 0.40 to 0.60. Out of many tests presented in [3], results for 20 circular specimens filled with siliceous aggregate concrete are included. One of the most recent research program regarding fire behavior of slender CFT columns is described in [4, 5]. This program included 40 fire tests with different load ratios (0.2, 0.4 or 0.6), plain and reinforced concrete, normal, high strength as well as fiber-reinforced concrete. Results of 7 specimens loaded either axially or eccentrically are included in this paper. Test results of three circular columns are given by Wainman [6], all three are included in this paper. Detailed analytical data is presented in Table I.

RESULTS

Studies are carried out by arranging the models into sets with different parameters. List of analyzed parameters includes stress-strain relationships for concrete proposed in the Eurocode and Lie [12], combined with two yield criterions used for this study: linear and hyperbolic Drucker-Prager. Von Mises yield criterion is applied for steel, combined with stress-strain relationship described in the Eurocode. Two different approaches of assessing thermal expansion are investigated, Eurocode and constant value recommended by Hong [10]. Moisture content is assumed the same inside each set of specimens. Six sets of models regarding thermal properties are studied, including the influence of moisture content (3 and 6 %) and thermal gap conductance between steel tube and concrete core. Sensitivity study concerning influence of imperfections by using different amplification ratios (L/500, L/1000, L/2000) and combinations of global buckling shapes along with influence of mesh size is presented.

TABLE I. EXPERIMENTAL [1-6] AND CALCULATED DATA (SET Th.1)

	d (mm)	**t (mm)**	**l (mm)**	**BC**	**load (kN)**	**ecc. (mm)**	**f_c (MPa)**	**FRR test (min)**	**FRR calc (min)**	**FRR ratio**
Han et al. [1], f_y=293 MPa:										
C1-1	478	8	3770	P-P	4700	0	31	29	38	1.31
C1-2	478	8	3770	P-P	2200	71.7	31	32	17	0.53
C2-1	219	5	3770	P-P	450	32.85	31	17	15	0.88
C2-2	219	5	3770	P-P	300	65.7	31	18	19	1.06
Kim et al. [2], f_y=304-311 MPa:										
AL1-1	318.5	7	3500	P-P	940.8	0	24	80*	53	0.66
AL2	318.5	7	3500	P-P	774.2	0	24	150*	67	0.45
AH1	318.5	7	3500	P-P	1548.4	0	35	28	45	1.61
BL1-2	406.4	9	3500	P-P	1675.8	0	24	59	81	1.37
BL2	406.4	9	3500	P-P	1254.4	0	24	120*	122	1.02
BH1	406.4	9	3500	P-P	2508.8	0	35	47	60	1.28
BH2-2	406.4	9	3500	P-P	1675.8	0	35	108	130	1.20
Lie et al. [3], f_y=350 MPa:										
C02	141.3	6.55	3772	F-F	110	0	33	55	50	0.91
C04	141.3	6.55	3772	F-F	131	0	31	57	44	0.77
C05	168.3	4.78	3772	F-F	150	0	33	76	58	0.76
C06	168.3	4.78	3772	P-P	150	0	33	60	79	1.32
C08	168.3	4.78	3772	F-F	218	0	36	56	50	0.89
C09	168.3	6.35	3772	F-F	150	0	35	81	74	0.91
C11	219.1	4.78	3760	F-F	492	0	31	80	68	0.85
C13	219.1	4.78	3760	F-F	384	0	32	102	85	0.83
C15	219.1	8.18	3760	P-P	525	0	32	73	66	0.90
C16	219.1	8.18	3760	P-P	525	34	32	33	21	0.64
C17	219.1	8.18	3760	F-F	525	0	32	82	65	0.79
C20	273.1	5.56	3760	F-F	574	0	29	112	125	1.12
C21	273.1	5.56	3760	F-F	525	0	29	133	143	1.08
C22	273.1	5.56	3760	F-F	1000	0	27	70	59	0.84
C23	273.1	12.7	3760	F-F	525	0	27	143	123	0.86
C25	323.9	6.35	3734	F-F	699	0	28	145	180	1.24
C26	323.9	6.35	3734	F-F	1050	0	24	93	105	1.13
C28	355.6	6.35	3734	F-F	1050	0	24	111	155	1.40
C29	355.6	12.7	3734	F-F	1050	0	25	170	155	0.91
C30	406.4	12.7	3734	F-F	1900	0	28	71	75	1.06
Romero et al. [4, 5], f_y=332-336 MPa:										
03	159	6	3180	F-P	396	0	29	25	18	0.72
04	159	6	3180	F-P	198	0	36	42	39	0.93
05	159	6	3180	F-P	594	0	34	14	13	0.93
17	159	6	3180	F-P	169	20	36	32	36	1.13
18	159	6	3180	F-P	337	20	42	16	21	1.31
21	159	6	3180	F-P	126	50	31	30	32	1.07
22	159	6	3180	F-P	253	50	38	23	21	0.91
Wainman et al. [6], f_y=348-355 MPa:										
1	244.5	6.3	3400	P-P	635.4	0	49	56	49	0.88
2	323.9	6.3	3400	P-P	1864	0	49	45	57	1.27
3	355.6	9.5	3400	P-P	900	0	49	142	164	1.15

* specimen did not fail during the test

f_c is measured cylinder strength of concrete. In [1] results for 100 mm cube samples are given, the ratio between strength of cubic and cylinder specimen is assumed $f_{c,cyl} = f_{c,cube(100)}$*0,97/1,25

length of the column is given between bottom and loading plate

P-P = pinned-pinned, F-F = fixed-fixed, F-P = fixed-pinned end conditions

FRR ratio is the ratio of calculated to measured fire resistance rating (FRR, minutes)

Material model

In this section stress-strain relationship and yield criterion for concrete is briefly discussed. Pressure-dependent Drucker-Prager yield criterion [13] is chosen for concrete. In Drucker-Prager model plastic yielding occurs when the equation (1) is satisfied. Two different geometrical descriptions of yield surface are studied, linear (eq. 2) and hyperbolic (eq. 3).

$$\sqrt{J_2(s)} + \alpha p = d \tag{1}$$

$$F = t - p tan\beta - d = 0 \tag{2}$$

$$F = \sqrt{\left(\bar{d}^0 - p_t^0 tan\beta\right)^2 + q^2} - p tan\beta - \bar{d} = 0 \tag{3}$$

where, J_2 is the second invariant of the deviatoric stress, p is the equivalent pressure stress and α and d are material constants, for further details see e.g. [13, 14].

As it can be seen in Figure 1 and Table II, linear formulation provides better results than hyperbolic one. As there is no general agreement when applying friction and dilation angles (referred further as β and ψ respectively), the effect of four descriptions is studied (two resulting in associated flow: β_1=36°, ψ_1=36°; β_2=30°, ψ_2=30°; and two resulting in non-associated flow: β_3=36°, ψ_3=30°; β_1=36°, ψ_1=15°). No significant changes are observed for abovementioned approaches. In Eurocode model linear elastic stress-strain relationship is assumed up to $0.4f_{c,\theta}$ with further hardening up to temperature dependent compressive strength $f_{c,\theta.}$ Descending branch is included as well. Use of more refined models, incorporating fracture of concrete can be found in [9, 10].

Influence of thermal properties

In this section the influence of different thermal properties that are used in heat transfer analysis is investigated. Concrete properties include moisture content, position of peak of specific heat (related to vaporization of free water). It is essential to incorporate thermal gap conductance between the steel tube and concrete core interface [7]. Emissivity of steel surface ε_m and the coefficient of heat transfer by convection α_c are equal to 0.7 and 25 W/(m^{2}K) respectively.

Literature study reveals measured moisture content in concrete in a range from less than 1 up to 6.6 %. Kim [2] reports moisture content as 6.6 % at the time of testing (from 30 to 60 days after casting). Lie [3] reports the moisture content corresponding to 85-95 % relative humidity. According to EN 1363-1 relative humidity level of 50% would result in moisture content of 1-3 %, while relative humidity level equal to 100% corresponds with 5% moisture. The detailed results of moisture content are given in [4, 5], where for normal strength concrete it ranges from 1 to 6.6 %, with a mean value of 3.2 %. The influence of these parameters can be found in Table II, under sets Th.1-3.

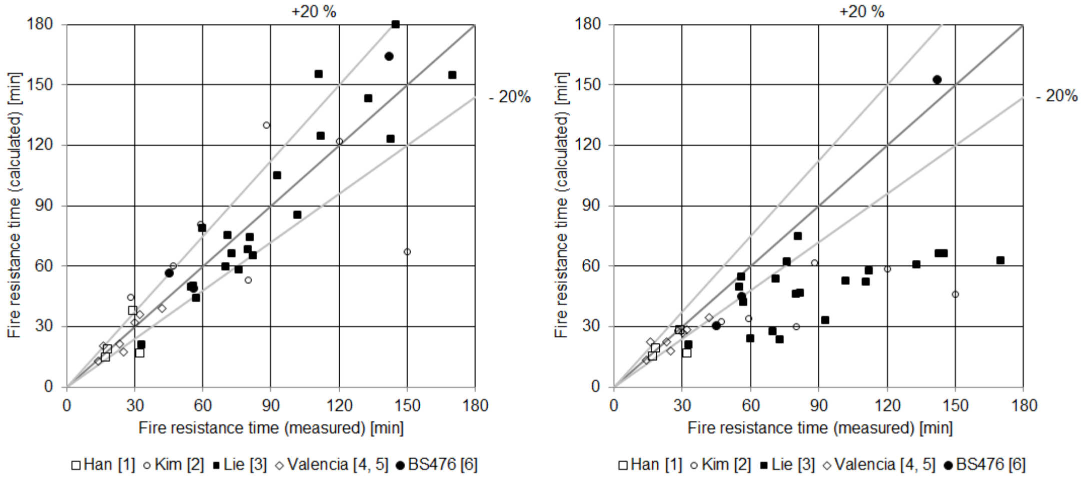

Figure 1. Comparison of results for linear (left) and hyperbolic (right) Drucker-Prager yield criterion.

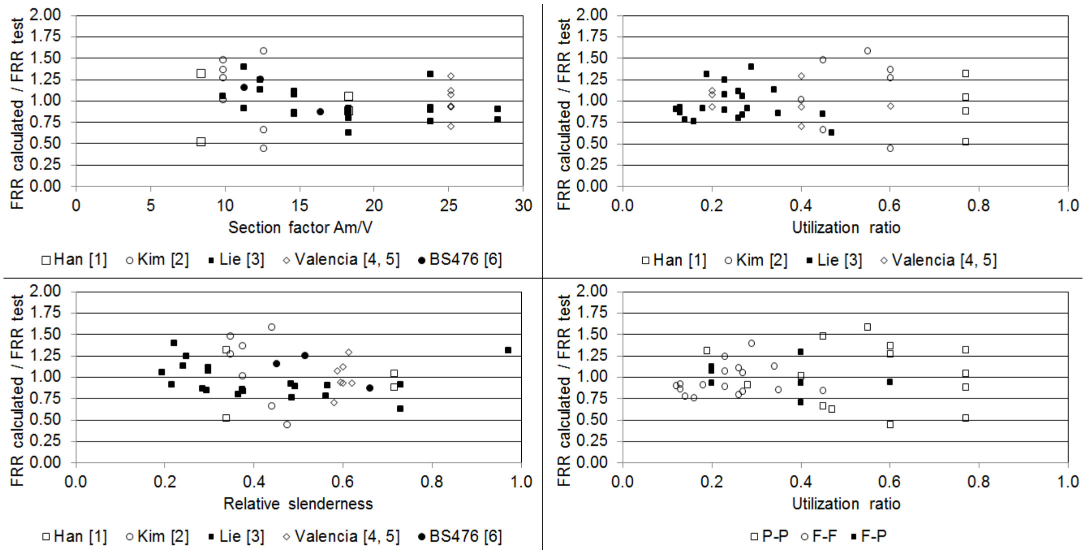

Figure 2. Ratio of time obtained from numerical solution to fire resistance time in the test plotted against different variables (linear Drucker-Prager yield criterion, utilization ratio acc. to authors).

Convergence of solution

Based on one of the analyzed specimens, C21 [3], it was noticed that some of the analyses ended prematurely after about 60 minutes, compared to 133 minutes obtained in the furnace test and 130–160 minutes in some of the simulations. For this reason an additional study is carried out. When the axial displacement response obtained from several numerical simulations is compared, it is observed the behavior is almost identical up to a point when convergence criterion is judged unlikely in Abaqus.

When after several iterations the ratio of the largest residual to the corresponding average flux norm (0.005) is exceeded analysis is aborted. By default, the check for increasing residuals in two consecutive iterations is made in Abaqus after 4 equilibrium iterations. If residuals in this check are increasing, analysis is aborted.

Improvement of the solution is possible by increasing the number of equilibrium iterations before the check for increasing residuals is made from default 4 to 8. This significantly changes the fire resistance rating of 4 specimens, bringing it closer to correct values. Such approach increases the computational time due to more iterations before the increment size cutback, however yields better results in some cases. Similar effect can also be achieved by modifying the default convergence criterion for the ratio of largest solution correction to the largest corresponding incremental value. The first approach is less invasive and yields better load-displacement path when solving the numerical problem.

Parametric studies

Parametric studies are carried out by arranging the models into sets with different parameters. Each set is described and a particular letter is assigned to it. Reference set contains the results for Eurocode-based material properties, linear Drucker-Prager yield criterion with β_1=36° and ψ_1=36°, 6 % moisture content with a specific heat peak at 115°C, thermal gap conductance equal to 100 W/(m^2K) and mesh size of 20x20x40 mm and 4 elements on the tube thickness. No coefficient of friction between steel and concrete interface is introduced. Initial global imperfections are of magnitude L/1000).The difference between the reference and each set is as follows:

Th.1 – 3 % moisture content (for detailed results see Table I),
Th.2 – Thermal gap conductance equal to 200 W/(m^2K)
Th.3 – Thermal gap conductance equal to 10e5 W/(m^2K)
B.1 – initial imperfection L/2000, B.2 – Initial imperfection L/500
B.3 – linear combination of buckled shapes: first and third mode (L/1000)
B.4 – initial imperfection L/1000, third buckling mode
Y.1 – hyperbolic yield criterion,
Y.2 – stress strain relationship according to Lie [12]
Y.3 – constant thermal expansion of steel $\alpha=6*10^{-6}$ utilized e.g. in [8, 10]
M.1 – mesh size 20 x 20 x 20 mm, 4 elements on tube thickness

TABLE II. RESULTS FOR SELECTED SETS (41 SPECIMENS EACH).

Source	**mean FRR(calculated)/FRR(test) ratio std. dev. of FRR(calculated)/FRR(test) ratio**											
	ref set	**set Th.1**	**set Th.2**	**set Th.3**	**set B.1**	**set B.2**	**set B.3**	**set B.4**	**set Y.1**	**set Y.2**	**set Y.3**	**set M.1**
[1-6]	1.06	1.00	1.01	0.94	1.08	1.03	1.08	1.10	0.69	1.20	1.06	1.04
	0.28	0.26	0.27	0.26	0.29	0.28	0.29	0.40	0.26	0.41	0.29	0.30
[1]	0.98	0.94	0.99	1.01	1.00	0.96	0.99	1.04	0.88	1.04	0.99	0.97
	0.36	0.33	0.30	0.25	0.38	0.31	0.36	0.44	0.24	0.42	0.37	0.37
[2]	1.21	1.12	1.16	1.05	1.26	1.16	1.28	1.46	0.59	1.55	1.27	1.19
	0.47	0.43	0.46	0.42	0.50	0.45	0.51	0.58	0.23	0.60	0.51	0.53
[3]	1.02	0.96	0.89	0.89	1.01	1.00	1.04	1.04	0.57	1.09	0.99	0.99
	0.20	0.20	0.18	0.18	0.20	0.21	0.20	0.25	0.20	0.32	0.19	0.21
[4, 5]	1.04	1.00	1.01	0.93	1.04	1.02	1.01	0.95	0.95	1.17	1.04	1.02
	0.21	0.19	0.17	0.31	0.16	0.21	0.16	0.28	0.21	0.30	0.20	0.17
[6]	1.19	1.10	1.09	0.99	1.24	1.00	1.20	1.10	0.85	1.40	1.20	1.20
	0.21	0.20	0.22	0.22	0.23	0.42	0.21	0.65	0.20	0.33	0.22	0.22

TABLE III. RESULTS FOR REFERENCE SET AND TH.1 SET ARRANGED ACCORDING TO BOUNDARY CONDITIONS (P-PINNED, F-FIXED).

		[1-6]	**P-P**	**F-F**	**F-P**
reference set	mean	1.06	1.11	1.04	1.04
	std. dev.	0.28	0.38	0.20	0.21
Th.1	mean	1.00	1.05	0.96	1.00
	std. dev.	0.26	0.34	0.18	0.19

The results for abovementioned sets are presented in Table II. Additional study regarding mesh size 10x10x20 mm with 4 elements on tube thickness based on specimens with diameter not bigger than 273 mm does not reveal any remarkable differences except for eccentrically loaded columns. For these results improved comparing to reference model (FRR ratios for specimen 17, 18, 21, 22 are 1.11, 1.21, 1.10 and 0.95 respectively). No difference is observed regarding comparison between models with four and two elements on tube thickness. No significant changes are observed for other studied parameters, i.e. influence of friction, reversed contact surfaces assignment, and location of the peak value of specific heat (115 vs. 165°C).

Based on Table I and III one can conclude that for fixed-fixed and pinned-fixed boundary conditions standard deviation is relatively low which supports the opinion, that proposed model can be used for such columns. For specimens with pinned-pinned boundary conditions used method gives a relatively good estimation of mean FRR ratio, however the discrepancy between the results is far from negligible (Figure 2).

Eccentrically loaded columns

Linear Drucker-Prager model gives unsafe results for columns from [4], while hyperbolic formulation gives safer results for columns, which are 0.86, 1.24, 0.89 and 0.96 for specimens 17, 18, 21, 22 respectively. When influence of the direction of eccentricity in relation to initial out-of-straightness (first buckling mode, L/1000) of the column is studied, it is advised that superposing load eccentricity and out-of-straightness of the column give the highest bending moments.

CONCLUSIONS AND FUTURE WORK

A numerical model for predicting fire response and resistance time was presented. It is concluded that it allows to model the behavior of concrete filled tubular columns, especially when they are considered as a part of braced structure (non-sway collapse) with fixed-fixed or fixed-pinned boundary conditions. When using Abaqus, it is advised to increase the default number of equilibrium iterations after which increasing of the residual forces in two consecutive iterations check is made, due to premature end of the analyses. A study consisting of several sets of parameters, 19 of which are presented here revealed good agreement between test and numerical results based on analytical data from 41 tested specimens. The best agreement was found for model incorporating linear Drucker-Prager yield criterion, with stress-strain relationships according to Eurocode. 3 % moisture content in concrete, combined with thermal gap conductance of 100 W/(m^2K), named here Th.1. Two elements on the tube thickness are enough to capture the response and fire resistance time of the column. Further research will focus on response of CFT columns exposed to localized fire with use of Fire Dynamics Simulator and Abaqus coupling for heat transfer analyses.

ACKNOWLEDGMENTS

This article was financially supported within the project "Engineer of the Future. Improving the didactic potential of the Poznan University of Technology" - POKL.04.03.00-00-259/12, implemented within the Human Capital Operational Programme, co-financed by the European Union within the European Social Fund. Majority of the computations were carried out in Poznan Supercomputing and Networking Center.

REFERENCES

1. Han, L.H., X.L. Zhao, Y.F. Yang and J.B. Feng. 2003. “Experimental study and calculation of fire resistance of concrete-filled hollow steel columns,” *Journal of Structural Engineering*, 129(3):346-356.
2. Kim, D.K., S.M. Choiz, J.H. Kim, K.S. Chung and S.H. Park. 2005. “Experimental study on fire resistance of concrete-filled steel tube column under constant axial loads,” *International Journal of Steel Structures*, 5(4):305-313.
3. Lie, T.T. and M. Chabot. 1992. “Experimental Studies on the Fire Resistance of Hollow Steel Columns Filled with Plain Concrete. Internal report No. 611,” Institute for Research in Construction, National Research Council of Canada, Ottawa.
4. Moliner, V., A. Espinos, M. Romero, and A. Hospitaler. 2013. “Fire behavior of eccentrically loaded slender high strength concrete-filled tubular columns,” *Journal of Constructional Steel Research* 83:137-146.
5. Romero, M., V. Moliner, A. Espinos, C. Ibañez and A. Hospitaler. 2011. “Fire behavior of axially loaded slender high strength concrete-filled tubular columns,” *Journal of Constructional Steel Research*, 67:1953-65.
6. Wainman, D.E. and R.P. Toner. 1992. “BS476:Part 21 Fire Resistance Tests. The Construction and Testing of Three Loaded CHS Columns Filled with Concrete,” British Steel Report No. SL/HED/R/S2139/1/92/D.
7. Ding J. and Y.C. Wang. 2007. “Realistic modelling of thermal and structural behavior of unprotected concrete filled tubular columns in fire,” *Journal of Constructional Steel Research,* 64:1086-1102.
8. Espinos, A., M.L. Romero and A. Hospitaler. 2010. “Advanced model for predicting the fire response of concrete filled tubular columns,” *Journal of Constructional Steel Research,* 66:1030-1046.
9. Lu, H., X.L. Zhao and L.H. Han. 2011. “FE modelling and fire resistance design of concrete filled double skin tubular columns,” *Journal of Constructional Steel Research*, 67(11):1733-1748.
10. Hong, S. and A.H. Varma. 2009. “Analytical modeling of the standard fire behavior of loaded CFT columns,” *Journal of Constructional Steel Research*, 65(1):54-59.
11. Schaumann, P. V.K.R. Kodur and O. Bahr. 2009. “Fire behaviour of hollow structural section steel columns filled with high strength concrete,” *Journal of Constructional Steel Research* 65(8-9):1794-1802.
12. Lie, T.T. 1984. “A procedure to calculate the fire resistance of structural members,” *Fire and materials*, 8(1):40-48.
13. Drucker D.C. and W. Prager. 1952. “Soil mechanics and plastic analysis or limit design,” *Quarterly of Applied Mathematics*, 10(2):157-162.
14. ABAQUS 6.12. 2012. “ABAQUS Documentation”, Dassault Systèmes, Providence, RI, USA.