Behavior Analysis of Circular Steel Tube under Fire

Jihye Seo, Deokhee Won, and Woo-Sun Park

***Abstract*—Recently, a tremendous loss of lives open occurred by collapse of structures under fire. Steel members were applied main member as column and beam in building for good performance and construction efficiency. Fire resistance performance of steel structure was very important because it rapidly changed according to high temperature. Buckling behavior of steel structure under fire was imperative because it can local buckling failure by reduction of structural material properties by temperature. In this paper, Elastic buckling behavior of circular steel tube under fire was investigated through finite element analysis. Parameters for this analysis were selected diameter-thickness ratio, fire exposure area, and fire scenarios. Elastic buckling strength of circular steel tube was rapidly reduced subjected to the fire curve. Local buckling was occurred that this can be lead global failure. When fire resistance design of circular steel tube was performed, buckling behavior must be considered**

***Index Terms*—Fire, steel tube, FEA, buckling.**

I. Introduction

Structures in open spaces such as various kinds of industrial facilities and warehouses are being constructed on steel frame construction with a high fire risk. These steel structures that are rapidly degraded performance at high temperatures are liable to local and global buckling in fire and resulted in to fatal damages. Most typically, according to the Busan fire safety headquarters in Korea, the fire on April 2015 in Busan Yeonje used cars mart (land area 3166㎡) inflicted huge losses of property which 560 vehicle be completely destroyed and reported property damage about 3.5 billion. However, the cause of the fire has not yet finally revealed although the structures was demolished and completed the fire Identification. Burnt-out vehicles by fire due to containing diesel or gasoline lead to the fire having greater strength than normal fire. In this fire, the structure was constructed steel frames and estimated to be collapsed owing to buckling of circular tubular columns in the middle part that focused the fire. Structural fire design for steel structures is very important because the steel has changed drastically its properties depending on temperature. In case of steel structures, a yield failure is not only significant factor, but a loss of buckling strength from reduction of local or global modulus by fire is also highly possible. So, it is essential to analyses for the buckling behavior.

In the current building codes of Korea, the fire resistance rating is divided from 1 to 3 hours for each main member. Because it must prevent damage to enquired resistance time, the study on behavior of the steel structure in fire have been variously performed. Jang et al. (2003) [1] analyzed the behavior characteristics through the local buckling of steel beam at elevated temperature, Paik and Kang (2004) [2] was studied for the local and global buckling at elevated temperature of the H-shaped steel column under compression. In addition, Kang et al. (2005) [3], Kwon (2011) [4], and Choi *et al.* (2013) [5] have carried out studies on fire resistance of I and H-beam. In overseas, Gomes et al. (2007) [6] was performed a study on buckling length of the steel pillar in fire, Ng and Gardner (2007) [7] was researched on buckling of stainless steel columns and beam, Real et al. (2008) [8] was conducted a study on lateral torsional buckling of I-beams in fire, and there are lots of other various studies on buckling.

In this study, elastic buckling behaviors of circular steel tube in fire according to the thickness ratio, fire exposure area and fire scenario was analyzed using the finite element package ABAQUS 6.14 (2015) [9].

II. Verification of Analysis Method

In order to analyze the elastic buckling behavior of circular steel tube exposed on high temperature, the elastic buckling analysis was carried out based on heat distribution simulation through heat transfer analysis. To do this, it was applied a reasonable heat transfer analysis method and buckling analysis as follows.

To investigate the tube behavior for heat transfer analysis and elastic buckling analysis, material properties of steel are required regarding temperature. These properties can be divided two groups: thermal material properties in terms of conduction of fire heat and structural material properties in terms of change in material strength. The thermal material properties considered for investigating the conduction of fire heat are representative specific heat and conductivity. The structural thermal material properties considered elastic modulus, tensile strength; thermal expansion coefficient and so forth given in Euro codes 3[10] list the material properties of steel

Specific heat of steel (unit: J/kgK).

For $20^{\circ}C \le \theta_a < 600^{\circ}C$

$$c_a = 425 + 7.73\times10^{-1}\theta_a - 1.69\times10^{-3}\theta_a^2 + 2.22\times10^{-6}\theta_a^3 \quad (1)$$

For $600^{\circ}C \le \theta_a < 735^{\circ}C$

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$$c_a = 666 + \frac{13,002}{735 - \theta_a} \quad (2)$$

For $735^{\circ}C \le \theta_a < 900^{\circ}C$

$$c_a = 545 + \frac{17820}{\theta_a - 731} \quad (3)$$

For $900^{\circ}C \le \theta_a < 1200^{\circ}C$

$$c_a = 650 \quad (4)$$

where θ_a is the temperature ($^{\circ}$C) and c_a is the specific heat of steel.

Conductivity of steel (unit: W/mK)

For $20^{\circ}C \le \theta_a < 800^{\circ}C$

$$\lambda_a = 54 - 3.33 \times 10^{-2}\theta_a \quad (5)$$

For $800^{\circ}C \le \theta_a < 1,200^{\circ}C$

$$\lambda_a = 27.3 \quad (6)$$

where λ_a is the conductivity of steel.

Next, structural material properties that depend on a change in temperatures are ultimate strength, yield strength, elastic modulus of steel. They are specified in Eurocodes 3 as follows:

Ultimate strength of steel,

For $\theta_a < 300^{\circ}C$

$$f_u = 1.25 f_y \quad (7)$$

For $300^{\circ}C \le \theta_a < 400^{\circ}C$

$$f_u = f_y(2 - 0.0025\theta_a) \quad (8)$$

For $\theta_a \ge 400^{\circ}C$

$$f_u = f_y \quad (9)$$

In this study, a heat transfer analysis was performed in ABAQUS [9] for investigating the conduction of heat in terms of fire time after the onset of a fire. The basic energy balance for heat transfer analysis is assumed that thermal and mechanical problems are uncoupled in the sense that $U = U(\theta)$ only.

$$\int_V \rho \dot{U} dV = \int_S q dS + \int_V r dV \quad (10)$$

where V denotes the volume of the solid material of surface area S, ρ denotes the density of the material, $\dot{U}$ denotes the material time rate of internal energy, q denotes the heat flux per unit area of the body flowing into the body, r denotes the external heat supplied to the body per unit volume, and θ denotes the temperature of the material. q and r do not depend on the strain or displacement of the body. DC2D4, a four-node linear heat transfer element, is used for representing concrete and steel. Furthermore, the thermal material properties for heat transfer analysis under fire are the same as those described in the previous section. The average furnace temperature, measured using the thermocouples specified in the cotton pad test, is monitored and controlled such that it follows the relationship shown in Fig. 1. This thermal load is applied uniformly to the tube surface.

$$T = 345\log_{10}(8t + 1) + 20 \quad (11)$$

where, T denotes the average furnace temperature in °C and t denotes the time in minutes.

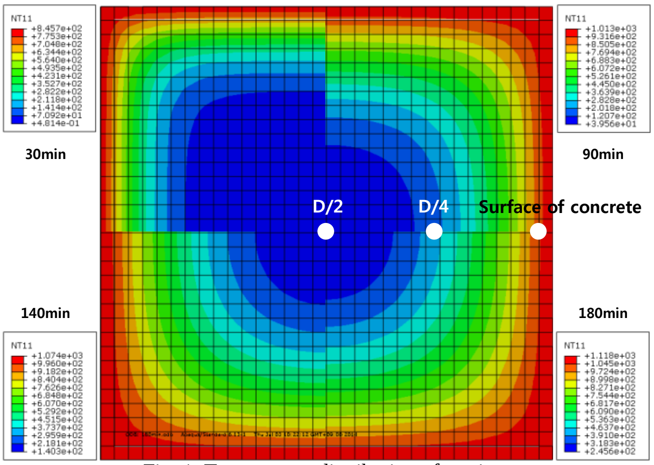


Fig. 1. Temperature distribution of section

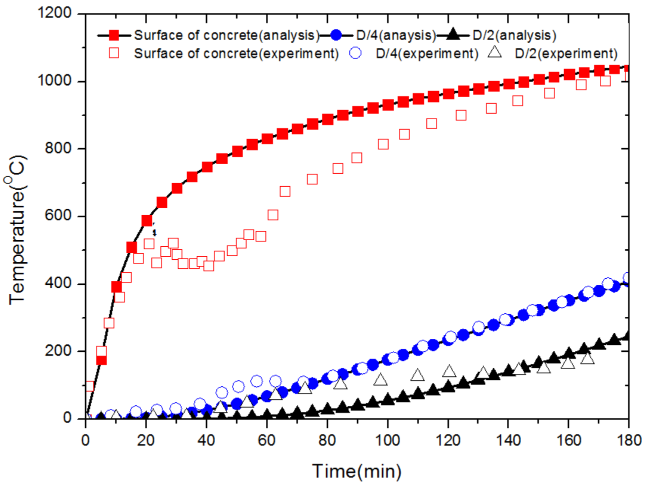


Fig. 2. Temperature of each location by exposure times.

Heat transfer analysis was applied to the verifying result of analysis method by Seo et al (2014) [11] using the material properties of Eq. 1-9. Prior researchers were reasonably verified considering thermal conductivity and specific heat and applying the standard fire curve of ISO-834 (1999) [12]. It has directly heated to the surface of cross section on rectangular CFT column. These method is confirmed by comparing the actual experiments data of Park (2007) [13], the comparison result shows that applying material properties in Eurocode. Fig.1 is appropriate for thermal distribution on cross section exposed to fire. The model applied in the experiments has a square section with outer tube thickness of 9 mm and width of 300 mm. where D is the diameter of the tube. As shown in Fig. 1 and 2 show a comparison of the temperature changes at the outer surface of the concrete and D/4 of the diameter, as obtained in the heat transfer analysis. The figures indicate that as time passes, the temperatures of outer concrete surface and D/4 of column diameter increase gradually, and the tendency of temperature increase as obtained through heat transfer analysis is similar to that obtained experimentally. The comparison results show that the analysis method is reasonable; thus, it can be used for investigating the conduction of fire heat in circular steel tube.

III. Elastic Buckling Analysis Method

Elastic buckling analysis results from the finite element analysis depend on diameter-thickness ratio (D/t), length-diameter ratio (L/D), and boundary conditions. In this section, the type of element used for circle steel tube in the elastic buckling analysis is C3D8R, a solid element. In order to obtain reasonable results for the solid modeling, it was selected for an optimum mesh size using elastic local buckling stress equation of Timoshenko, S. P., and Gere, J. M. (1961) [14] (Eq. 12).

$$\sigma_{cr} = \frac{Et}{a\sqrt{3(1-\nu^2)}}\frac{n^2-1}{n^2+1} \qquad (12)$$

where ν denotes Poisson's ratio of the material, a stands for the radius of cross section, t means the thickness of tube, n denotes the number of circumferential half wavelength(Fig. 3).

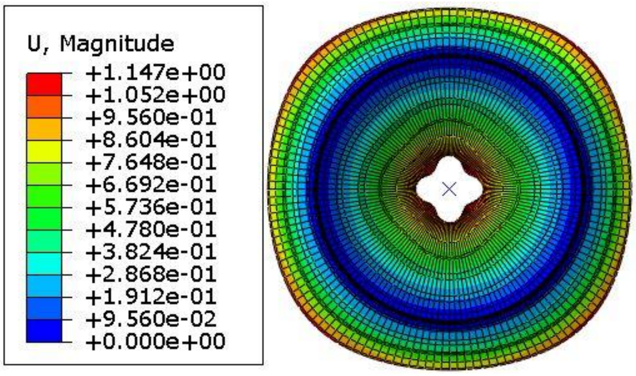


Fig. 3. Boundary condition.

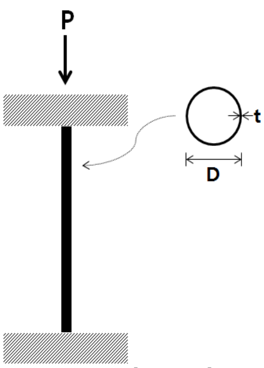


Fig. 4. Boundary condition.

Boundary condition (Fig. 4) of circular steel tube is assumed to be 6-degree of freedom fixed at both ends. In addition, circular steel tube was set to be diameter of 0.3 m and height of 1 m having elastic modulus of 210 GPa, Poisson's ratio of 0.3 for steel properties. Thickness of the tube is changed to 0.0032 mm ~ 0.006 mm as shown in Table I and selected the D/t ratio from 93.8 to 50. When a fire started, the fire heat is conducted from the outside to the inside of tube. At this time, it is likely to vary the thermal distribution according to the thickness of steel tube. This analysis is based on using the solid elements to reflect the thermal distribution in the analysis result.

However, in case of solid elements, since the buckling strength or shape are altered with regard to the size of mesh, it is necessary to compare and verify with the shell element. In this section, we compared the buckling strength as Table II. Table II is shown the result of elastic buckling strength that having the error value within 2.16% compared to the theoretical values. Furthermore, the compared buckling mode shapes of D/t 93.8 model are displayed in Table III. It is judged that applying be used the solid element model is permissible because buckling shapes between shell and solid element model are almost identically presented.

TABLE I: Dimensions of Circular Steel Tube

D/t	93.8	75	60	50
Thickness (m)	0.0032	0.004	0.005	0.006

TABLE Ⅱ: Result of Elastic Buckling Strength (Unit : MN)

	D/t 93.8	D/t 75	D/t 60	D/t 50
Timochenko	8.208	12.82	20.03	28.85
Shell	8.197	12.77	20.01	29.11
Solid	8.132	12.64	19.65	28.24
Error	0.93%	1.42%	1.93%	2.16%

IV. Buckling Behavior of Circular Steel Tube

In this section, the elastic buckling analysis of circular steel tube in fire is performed using the FEA method verified in the previous section. Changes in the structural properties of the tube elements are arrived at based on the temperatures obtained from the heat transfer analysis. The fire resistance of the tube in terms of fire time are investigated. In addition, parametric studies are performed through the selection of main parameters such as D/t ratio, fire exposed area and fire scenarios.

TABLE III: Parameters for Analysis

Parameter	D/t	Thickness (m)	P_{cr} (MN)
D/t	93.8	0.0032	8.22
	75	0.004	12.82
	60	0.005	20.04
	50	0.006	28.85

When buckling occurs, buckling behavior in case of having longer length-diameter ratio (L/D) of the steel tube is dominated by bending buckling (Euler buckling) (Galambos, 1998) [14]. Thus, an object model in this study is set to be a relatively short diameter (D) 0.3 m and length (L) 1 m to evaluate the effect of pure local buckling. Here, buckling behavior of circular steel tube are determined depending on the fire conditions, analysis conditions are selected with external fire conditions (fire curve), fire exposed area (level exposure), and diameter - thickness ratio (Table III).

Boundary conditions of circular steel tube is shown in Fig. 5 ~ Fig. 6, and are divided into three types according to fire exposure area. The exposure areas are respectively 100%, 50%, and 12.5% of cross section. Also, the finite element analysis is performed by fixing the horizontal and rotational displacement of x-axis and y-axis in order to occur the vertical displacement assuming a completely fixed condition of the model.

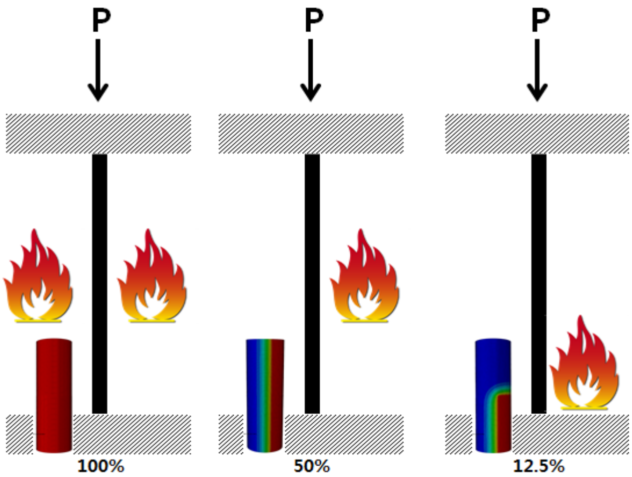


Fig. 5. Boundary condition under fire.

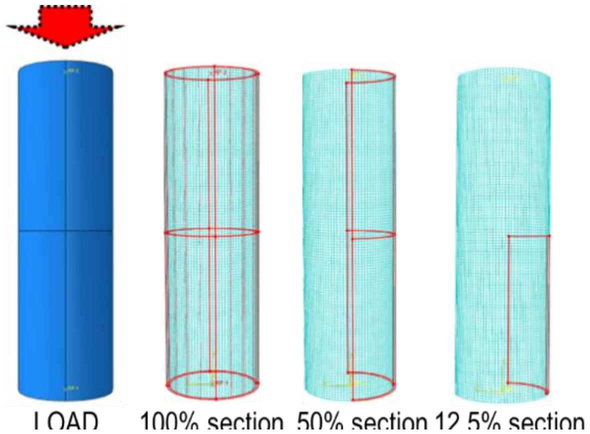
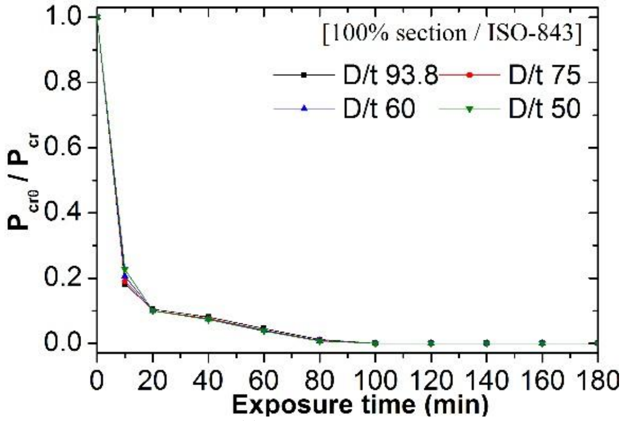


Fig. 6. Analysis models

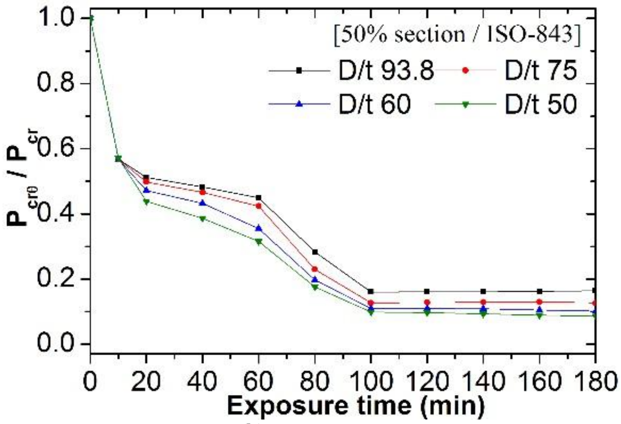
A. Diameter — Thickness Ratio (D/t ratio)

Fig. 7 illustrates the elastic buckling analysis result in terms of D/t ratio. The horizontal axis of graphs indicates the fire exposure time through two hours and a half, and the vertical axis means the critical load ratio ($P_{cr\theta} / P_{cr}$) corresponding to the exposure time to initial buckling strength. The influence on fire resistance of tube model has analyzed with D/t ratio.

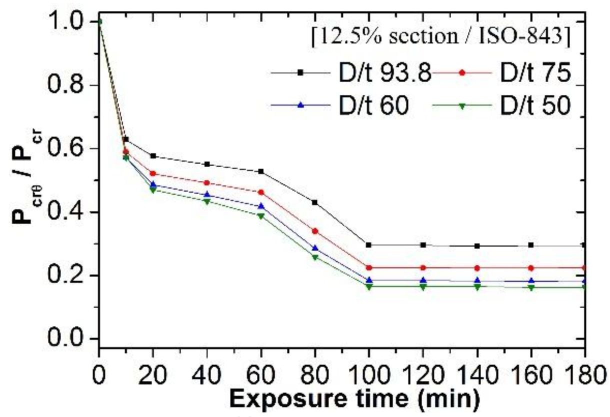
Fig. 7 (a) represents the case that entire surface of the circle steel tube is exposed to standard fire curve. The elastic buckling strength of tube is quickly decreased by 20% of initial buckling strength in 10 minutes after exposed on high temperature, and the buckling strength is gradually going down to 0% at 80 minutes. Fig. 7 (b) shows the result when the half section of steel tube is only exposed to fire. After 10 minutes on fire, the buckling strength is diminished to 57% of initial buckling strength. And starting 100 minutes, the buckling strength continues to decline by 20% or less regardless D/t ratio. Fig. 7 (c) is in partially exposed state to fire at the lower part of circle steel tube. The buckling strength is lowering of 60% those of initial strength, and all models have the elastic buckling strength below 30%. Fig. 7 (b) and (c) are partially exposed damage cases in fire. It is found that the smaller D/t ratio - in other words the thicker thickness of circular steel tube, the lesser damage of elastic buckling strength. It can be signified that the reduction of buckling strength for original model is larger than that of damaged model.



(a) 100% section



(b) 50% section



(c) 12.5% section

Fig. 7. Elastic buckling strength ratio with fire exposure times.

In addition, the buckling modes in the exposure area of 100% are similar to behaviors having the larger D/t ratio of tube. In case of partially exposed model (50% and 12.5%), it can be confirmed that they have a different buckling modes contrasted with evenly exposed model in fire and local buckling occurs in the exposed area to high temperatures.

V. Conclusion

In this study, the change in the elastic buckling characteristics of the circular tube in fire has been investigated using finite element analysis. In addition, the elastic buckling behaviors were analyzed depending on diameter-thickness ratio, fire exposure area, and fire scenarios. Such parametric studies were performed with the critical load ratio to initial buckling strength corresponding to the exposure time. The following conclusions were arrived at.

In case that the whole surface of circle steel tube is exposed on high temperature is 100%, the elastic buckling strength is decreased by 20% within 10 minutes occurring fire. In case of half section of exposure area, the strength is reduced to 20% or less for all models at 100 minutes. And the case with 12.5% of exposure area, the strength is declined to 30% or less at 100 minutes. Thus, the wider level exposure, the larger the amount of reduction of the buckling strength. Even though the steel tube is locally exposed to fire, the buckling strength can be remarkably increased the potential failures due to sharp drop compared to the original value.

Owing to damage of the circular steel tube, the lesser the D/t ratio, the greater the decrement of strength beside the initial buckling strength.

In this research, an effect on to the entire steel tube by local fire was analyzed through elastic buckling behavior. In the future, it is necessary to suggest the criteria for reviewing stability of circular steel tube in fire including a detailed analysis such as inelastic buckling behavior.

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