NUMERICAL STUDY ON COMPARTMENTAL EQUIVALENCE OF FIRE RESISTANCE RATING BASED ON AREAS BENEATHS METHOD

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ABSTRACT

Structural steel is most widely adopted construction material due to its eco-friendly nature, stiffness and ductility when subjected to external imposed loading. Nowadays, fire resistance of structural steel has been a serious concern among designers since the steel have to fulfill the deflection criteria requirement of EN 1363-1. However, the code provision provides fire resistance rating for a standard curve which might be different for different compartment which we term as natural curve. So, this study is performed to propose the computation method for development of natural fire curve which is actual fire resistance rating of structural steel from standard fire furnace rating based on ISO 834 standard to compartmental fire resistance rating based on natural iBMB curve. The steel section adopted in the study is from the O-NES tower office compartment. Further, numerical simulation will be performed to validate the documental experimental result. The modelling parameters of calibrated numerical model will then be used to simulated steel section of O-NES tower office compartment to obtain fire resistant rating. Also, study will be performed to predict equivalence of fire severity based on areas beneath the standard and compartmental temperature-time curves for office (iBMB). From the study it was observed that the studied section can fulfill the rating requirement. However, office compartmental (iBMB) equivalence of fire resistance rating based on areas beneath for SB45 was more than 3 hours. Although the studied structural steel section satisfies the Ministrial Regulation criteria for compartmental fire but could not satisfy the requirement of standard fire furnace test criteria based on ISO 834.

Keywords: *Fire resistance rating, ISO 834 standard, Compartmental fire, Area beneath, Natural iBMB curve*

1. INTRODUCTION

The actual performance-based fire design of steel structure should be design based on natural compartmental fire curve with the boundary condition as per the actual room conditions. In traditional practice fire design of steel structure was done by using the standardized fire curve like ASTM E119 or ISO 834.[1] In many cases the fire design is uneconomical due to greater concrete cover of structural member as well as disadvantages of aesthetical view of building. Structural fire design based on boundary condition for typical compartmental fire curve for residential and office buildings is iBMB natural fire curve. These formulated simplified empirical fire curve was used as part of performance based fire design for compartmental fire [2]. Based on Ministerial Regulation [3] criteria the structural steel section should depict fire resistant rating of more than 3 hours.

The factors affecting the compartmental fire are ventilation factor, thermal property of inside material, fire load and geometry of compartment play a critical role in the development of these fire curves [4]. The behavior of compartment fire is described by three main phases, namely growth, fully developed and decay period [2][5]. For each kind of structure parametric fire curves are mostly valid for steel structure [2].

Growth is the initial phase of fire development. During this stage, combustion is restricted to certain areas of the compartment that may however result in significant localized rises in temperature. It may happen that many fires may not surpass this initial stage of fire development, due to insufficient fuel loads, limited availability of air supply, or human intervention.

The rate of increase in temperature is directly proportional to the heat release rate. Therefore, during this stage there is a large increase in the temperature of the compartment with temperatures reaching to about 1000℃. The duration of this phase depends on the volatile matter that is present in a compartment. As the rate of generation of volatile material decreases, or when there is insufficient heat available to generate such volatiles, the phase begins to cease gradually.

As the word "decay" clearly suggests, there is a decrease in the fire intensity during this phase due to the decrease in the available fuel and the rate of fuel combustion. This phase occurs when the quantity of volatile matter continues to decrease and is consumed, after the initial stages of fire. Different phase of fire curve is shown in Fig 1.

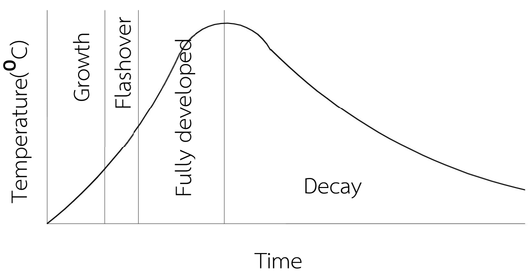

Figure 1 Fully developed natural fire (different phase).

2. IBMB FIRE CURVE

A parametric natural fire model is presented, which is derived on the basis of simulations with heat balance models for realistic natural fire design, taking into account the boundary conditions of typical compartments in residential and office buildings. These so-called iBMB parametric fire curves are formulated with the help of simplified empirical equations which can easily be used for structural fire design as part of a performance-based natural fire design concept [2].

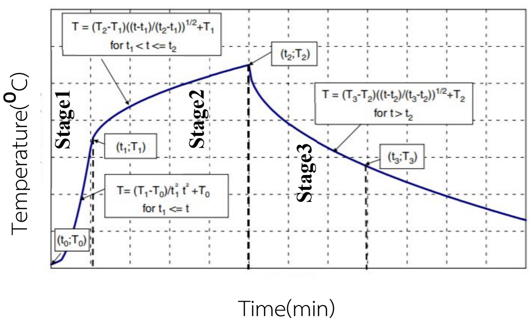

Figure 2 Mathematical description of 3 stage iBMB parametric fire curves [2].

In Fig. 2, stage 1 is growth phase for residential and office buildings, where rate of heat release find by $\boldsymbol{t^2}$ approach.

$$Q(t)=\boldsymbol{Q_0}(\frac{t}{t_g})^2$$

Where, $\boldsymbol{Q_0}$=1MW, $\boldsymbol{t_g = 300\ s}$ which is time of fire growth with the medium fire growth rate for office and residential building.

Rate of heat released is replaced by minimum value of fuel-controlled and ventilation control fires.

Ventilation-controlled:

$$\boldsymbol{Q_{max,v} = 1.21 A_W \sqrt{h_W}\ \ MW}$$

Fuel-controlled:

$$\boldsymbol{Q_{max,f} = 0.25 A_f\ \ MW}$$

Where,

$$\boldsymbol{Q(t)_v = 0.1 A_W \sqrt{h_W}\, x H_{net}}$$

$$\boldsymbol{Q(t)_f = m A_f\,(t) x H_{net}}$$

Burning rate area per unit area can be assumed m=0.02kg/(m^2s), x = 0.7 and $H_{net,wood}$ = 17.3MJ/Kg. [2]

$$\boldsymbol{Q_{max} = MIN\{Q_{max,v};\ Q_{max,f}\}}$$

At end of stage 2, seventy percentage of fire load is consumed and then rate of heat release decrease linearly until the stage 3 (completely burned).

3. FINITE ELEMENT METHOD

Structural fire design upgrade from a prescriptive approach to performance-based approach [6]. For modern approach advanced mathematical model is essential. Although tremendous research has been performed during last decade, the testing of structural component under fire is always challenging. Hence, nowadays researchers are using advances numerical tools including ANSYS, ABAQUS, MARC, VULCAN, LS-DYNA, etc. to predict fire behavior of structural steel [6]. The recent study on fire resistant steel was performed by Khanal and Chaisomphob, 2020 [7]. The research focusses on study of structural steel subjected to fire using solid element formulation in numerical tool LSDYNA. However, current study focusses on studying behavior of steel using shell element formulation as the change of element formulation decreases computational time and memory requirements.

Several standardized furnace testing conditions have been provided by ASTM, NIST, and UL manual which is challenging even in the period of current research. Even though, the standards have provided standard fire tests, it was observed that structural steel performance in a real case is different than standard fire tests. The past large-scale fire tests and incidents such as Cardington (8-storey steel frame building) (1995,1996, UK), fire test in William street (1992, Australia), Broadgate (1991, UK) [6] [8] exposed the Euro code.

Hence, a methodology was proposed within current study to study the behavior of steel section to actual fire scenario. Modeling was carried out for numerical simulation of structural steel beam based on ISO 834 standard fire curve and material definition for steel were calculated based on Euro code. Modeling was carried out by using LS-DYNA explicit solver code. A
3D shell element consisting of 5 integration points was modelled in the numerical tool which uses Belytschko-Tsay shell element formulation. The
*MAT255 which is temperature-dependent piecewise linear plastic material model was used for this analysis [9]. Moreover, for the application of thermal load, the *LOAD_THERMAL_VARIBLE was used. Based on mesh convergence study size of mesh equal to 10mm was adopted for all elements. Nonlinear material property in fire was controlled by*CONTROL_THERMAL_NONLINEAR. Load equal to 100 kN, was applied as a four-point bending test by *LOAD_NODE_SET. Also, *BOUNDARY_SPC_SET was adopted as simply supported boundary condition. The explicit solver was adopted for the numerical simulation using*CONTROL_IMPLICIT_GENERAL card IMFLAG=0. Finally, the model is analyzed and the required data was extracted as d3plot file while post-processing.
Hence, a numerical study was first performed for methodology verification and then actual beam specimen was modelled and obtained results was discussed.

4. RESULTS AND DISCUSSION

4.1. VERIFICATION OF FEM BASED ON EN1363-1 DEFLECTION CRITERIA

According to ASTM E119[1] for the fire furnace test exposed area should not be less than 100 sq. ft (9 m²), the specimen should not be less than 9 ft (2.7 m). Sample specimen sized 4200 mm span has been used with simply supported boundary condition for fire test which was obtained based on testing of Łukomski M et al., 2017 [10]. The sample specimen was restrained on all four edges. Point load of magnitude 100 kN has been applied which can be idealized as equivalent to effect of the overlying slab as shown in Fig 3 [10].

The mathematical model/FEM of fire-resistance rating for HEB 300 hot-rolled S355 grade steel beam was performed by LS-DYNA. The result was compared with the finding from ISO 834 fire standard furnace test results (Beam1 and Beam2) [10] which is based on the deflection criteria. From Fig 4.

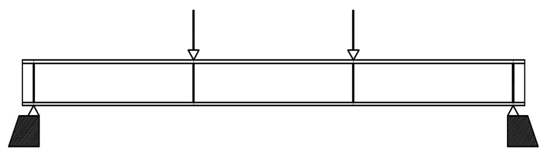

Figure 3 H-beam sample with loading [10].

The salient points of the test results were captured with significant accuracy by the numerical model.

The fire resistance rating from the numerical analysis was obtained to 32 minutes while from the test results it was obtained to be 33minutes. Hence, the adopted modelling methodology was adopted to simulate the actual structural steel section of O-NES tower and is discussed in subsequent section.

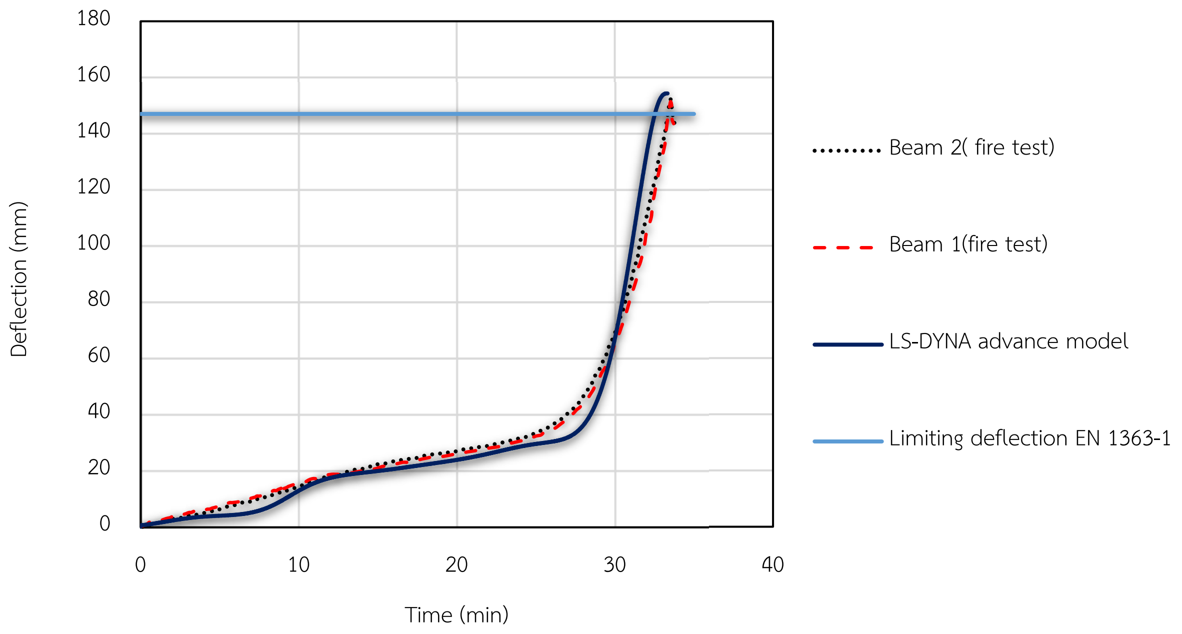

Figure 4 Deflection curve (EN 1363-1) [6].

4.2. CASE STUDY

The selected structural member for this study is an actual H-beam from O-NES tower steel structural secondary beam for office compartment, which is under construction.

The beam section is H-450X200X9X14 (SB45) and SS400 structural steel. For FEM model L_{tot} =4400mm, support to support length is L_{sup} = 4200mm and exposed in fire length is L_{exp} =4000mm. According to EN 1365-3 value of deflection $D_{lim=}$ 98mm and rate of deflection $\frac{dD}{dt_{lim}} = 4.36mm/min$.

The parametric natural fire curve for office and residential buildings (iBMB), which is derived based on heat balance models [2] (Fig 5).

Area (A_f)=1094.81m²

Height (H)= 3.3 m

Area of openings (A_w) = 153.252 m²

Average height of opening (h_w) = 3 m

Ventilation factor ($A_w(h_w)^{1/2}$ [4] = 256.44$m^{3/2}$

Opening factor, O [11] =$A_w(h_w)^{1/2}/A_t$= 0.11324$m^{1/2}$

Average thermal property of enclose (b) [5] = 1500 J/($m^2 s^{1/2} k$)

Total area of enclosing components (including opening) A_t = 2344 m²

Total area of enclosing components (without opening) A_T= 2190.775 m²

Rate of heat release,

$$(Q_{max}) = MIN(Q_{max,v}, Q_{max,f})$$
$$(Q_{max}) = MIN(310.3,273.7)\ MJ$$
$$= 273.7\ MJ$$

q= 1300 MJ, which is taken as an upper value for residential and office buildings [5].

Total fire load (Q)= $q_x x A_f$ = 1423253 MJ [2]

Room temperature (T_o) = 20°C

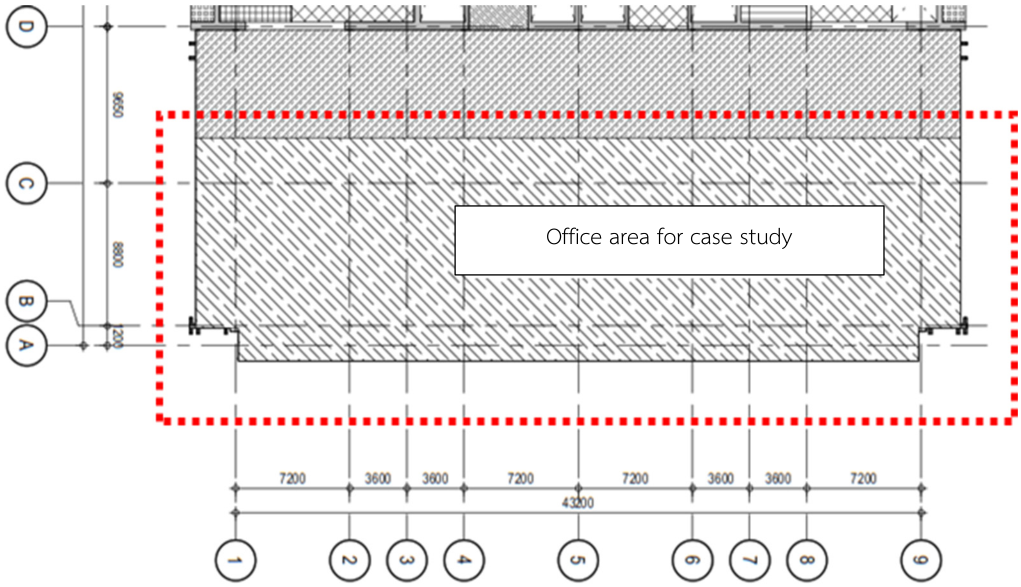

Figure 5 Office floor plan

Table 1: Data for iBMB parametric curve (O-NES TOWER).

K = 0.0962>0.04		
T_1 = 980°C	t_1 = 600sec = 10 min	Q_1 = 800 MJ
T_2 = 1340°C	t_2 = 4240sec = 71 min	Q_2 = 995477.1 MJ
T_3 = 660°C	t_3 = 6400sec= 107 min	Q_3 = 426975.9 MJ

Where, T= temperature, t= Time and Q=Rate of heat release

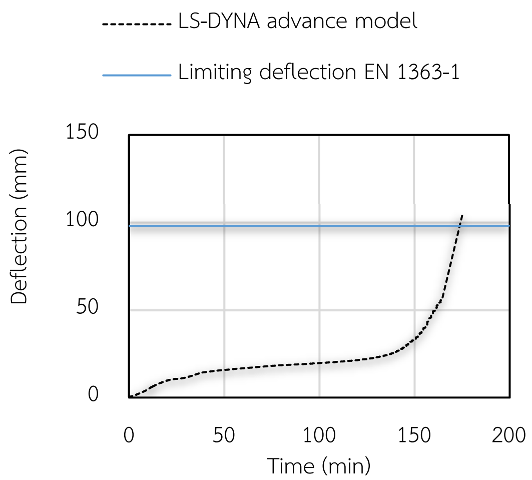

Figure 6 Deflection curve for SB45 (EN 1363-1)

Fire resistance rating of H-450X200X9X14 (SB45) hot-rolled steel beam based on EN 1363-1 limiting deflection criteria was 2hr 53min 24 sec. which is based on ISO834 standard fire curve.

Fig 2 shows the temperature growth curve for three sections of the parametric temperature-time curve for the office compartment. As shown in Fig 6, the key point of the parametric iBMB curve was calculated for an office compartment in Table 1. Calculation of equivalent fire resistance rating of SB45 based on the area beneath the standard and iBMB fire curve. The reference temperature was taken as 150^{0}C [12].

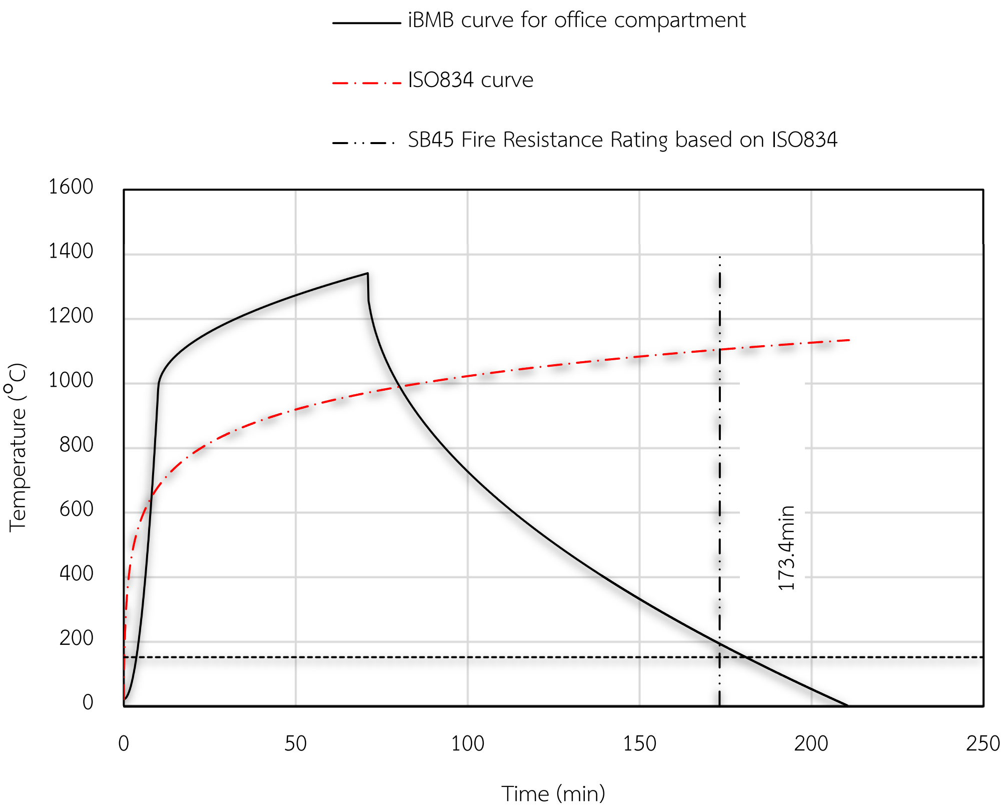

Figure 7 Equivalence of fire resistance rating based on areas beneath the standard and compartment temperature–time curves.

For ISO834 curve (Fig 7),

t_1 = 10 seconds = 0.167 minutes for T = 150 °C and t_2 = 10404 seconds = 173.4 minutes for T = 150 °C

Area enclosed by ISO curve, reference temperature and failure time of SB45 is given by Equation 10.

$$\boldsymbol{A_{ISO834} = \int_{t_1}^{t_2}(20 + 345\log10(8t+1))d} \quad (1)$$

For iBMB fire curve (Fig 7 and Table 1),

$$\mathbf{A_{iBMB} = A_{section1} + A_{section2} + A_{section3}} \quad (2)$$

$$\boldsymbol{A_{section1} = \int_{3.667}^{10}\left(\frac{960}{100t_1^2} + 20\right)dt} \quad (3)$$

$$\boldsymbol{A_{section2} = \int_{10}^{71}\left(360 * \sqrt{(\frac{(t-10)}{61})} + 980\right)dt} \quad (4)$$

$$\boldsymbol{A_{section3} = \int_{71}^{t_x}\left(-680 * \sqrt{(\frac{(t-71)}{36})} + 1340\right)dt} \quad (5)$$

The equivalent area of A_{iBMB} with respect to A_{ISO834} from Eq 1, Eq 2, Eq 3, Eq 4, and Eq 5.

$$\boldsymbol{A_{iBMB} = A_{ISO834}}$$

$$\boldsymbol{\int_{71}^{t_x}\left(-680 * \sqrt{(\frac{(t-71)}{36})} + 1340\right)dt = 90928.38}$$

$$\boldsymbol{t_x = t_{iBMB} > 180.92min}$$

5. CONCLUSION

The current paper studies behavior of hot rolled structural steel subjected to fire numerically. A documented steel section was simulated in explicit solver of LSDYNA and the results from test was compared with numerical results. Likewise, the similar modelling methodology was followed to analyze the actual structural steel section of ONES tower. Based on the numerical results several findings are enumerated as follows:

- The study showed office compartmental (iBMB) equivalence of fire resistance rating based on areas beneath for SB45 was more than 3 hours.
- Moreover, the studied structural steel section satisfies the Ministerial Regulation criteria for compartmental fire but could not satisfy the requirement of standard fire furnace test criteria based on ISO 834.
- The explicit solver of numerical model could capture salient points of the rating curve from actual test.
- The actual fire rating of structural components of building frames should be evaluated based on design natural fire rather than based on standard fire curve. The code provision provides fire resistance rating for a standard curve which might be different for different compartment which we term as natural curve.
- The studied structural steel of ONES tower can fulfill the rating requirement.

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