Journal of Mechanical Engineering *Vol 16(1), 227-236, 2019*

Performance Based Approach of Cellular Steel Beam (CSB) Exposed to Fire

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ABSTRACT

This paper presents a numerical analysis of simply supported cellular steel beam (CSB) at elevated temperatures. Currently, CSB is increasingly used as the main structural element in multi-storey buildings, warehouses and any steel structures. Typical steel beams are mainly used as a dwelling load bearing capacity. CSB is one of the options to replace the former steel beam. Several advantages can be gained when adopting CSB as the main structural element in structures. However, several drawbacks have restricted the structural performance of CSB under applied load, especially under fire exposure. Fire is one of the major catastrophe that may endanger any structural steel member in a steel frame building under certain duration. It is important to reduce the member temperature induce by fire exposure to prolong the time before the CSB failed. Experimental data available in the literature review will be used to validate with numerical simulation in this research.

Keywords: *Performance based approach, finite element method, large deformation, fire, elevated temperature, cellular steel beam (CSB).*

ISSN 1823-5514, eISSN2550-164X

Received for review: 2017-06-05
Accepted for publication:2018-08-03
Published:2019-04-01

Introduction

Vertical deformation and Vierendeel bending failure mechanism are two main drawbacks that might jeopardize the structural behavior of CSB at elevated temperature. The bending failures are due to thermal loading stress loading at elevated temperatures. Fire is the main threat to fire safety of any structural steel building. Proper fire protection material was put in place in the strategic location of steel beams to subdue any fire expose that may harm any isolated steel beams and finally the whole structural building. Few researchers have conducted investigation on the structural behavior of fully and partially protected CSB [1,2]. Traditionally, prescriptive based approach was used to determine the level of fire protection system to be apply onto structural steel member. This approach can be retrieved from the available codes in the market, namely Eurocode 1, Eurocode 3 and Eurocode 4 [3,4,5]. However, these available codes are only depending on standard fire test results alone. Different types of nominal fire curves, namely external fire curve, slow heating fire curve hydrocarbon fire curve and large pool hydrocarbon fire curve due to severity and behavior of the fire itself can be found in the codes [3,4,5]. However, nominal fire curve does not agree with the real fire exposure due to different phases of the real fire exposure. It is more realistic response of the structural steel element when considering real fire exposure. Due to some limitations, slow heating fire curves were chosen as fire exposure for numerical analysis purposes in validating the experimental program conducted previously by the researchers [6].

Literature Review

Prescriptive based approach

The simplest way to determine the level of fire protection is by adopting structural design fire codes [3,4,5]. In these codes, four different design stages were involved. The first stage involves the design fire scenarios and the second phase is related to reciprocal design fires. The third phase is analyzing temperature evolution inside the structural element. Meanwhile, the last phase involves analyzing the mechanical response of the structural elements when exposed to fire. However, a definite safety fire response is highly concern due to actual fire exposure to the structural element. Several realistic fire behaviors were not considered in this traditionally approach, namely fire intensity fire density, fire distribution and structural element connection between different element. Performance based approach is rather more realistic approach to cater for this type problem [7].

Performance based approach

Performance based approach requires the structure to be analyzed using numerical analysis tools by carry out heat transfer analysis and static analysis. Results of material properties such as non-linear stress-strain diagram, gained from the experimental investigation were collected and were used for numerical simulation analysis. Hence, structural behavior of any structural element can be predicted, especially due to fire exposure [8]. In this approach, structural performance of structural member exposed to fire are depends on three main stages of analysis, namely fire behavior, heat transfer analysis and structural mechanical response [8]. By adopting this approach, eventually enable to reduce the cost of using fire protection material by applying thinner fire protection material instead of thicker material.

Cellular steel beam (CSB)

The use of CSB as the main beam structural member is due to several advantages. It allows serviceability pipes and ducts to pass through the main web section of the CBS without compromising the structural strength and integrity. In addition, the overall self-weight of the CSB is lesser than the naked steel beams which subsequently reducing the usage of the steel material. In the face of all the advantages, there are few drawbacks that might be jeopardized the strength capacity and stiffness of the structural steel member when exposed to fire. Large deformation, web post buckling and Vierendeel bending failure mechanism are critically failure mode that has been reported in the literature review [9-13]. These failure modes on CSB will subsequently leads to massive destruction for the whole structural building. It is important to investigate the fire resistance performance of CSB at elevated temperatures where the maximum temperature distribution and deflection can be located and analyzed. At later stage, improvement to the fire safety level can be introduced to enhance the fire resistance performance of CSB by applying fire protection material, namely intumescent coating. Various thickness of intumescent coating will be applied onto CSB for future research undertaken and hence the structural behavior can be predicted and improvised.

Experimental Investigation

Validation process were conducted to complement the experimental investigations retrieved from available data [6,14,15]. The experimental investigations were conducted on a simply supported symmetrical composite CSB exposed to slow heating fire curve of nominal fire test as shown in Figure 1. The CSB sizes used for this research are UB 406 x 140 x 39 kg/m and UB 406 x 140 x 39 kg/m. The former CSB used as the top Tee web section while the later used for the bottom Tee section. Meanwhile, the web steel beam size used was 575 x 140 x 39 kg/m. The thickness of the web section is 6.4 mm, lesser than the thickness of the upper and bottom flange section of 8.6 mm. A 150 mm thick concrete slab was cast on top of CSB to hold on inside the fire furnace. A point load of 90 kN was apply at two different locations on top of the concrete slab simultaneously with fire exposure action. A full interaction between the concrete slab and the CSB were put in place by using high density of shear connectors. There are various location of thermocouples has been installed along the beam section as mentioned by [6,15]. However, six locations have been selected due to some limitations and constraints. The locations of the thermocouples are located at 500 mm along the beam illustrated as in Figure 2. Two points loads were applied at the middle of the beam. Figure 2 shows the locations of thermocouples which located at web and flange of CSB which labelled as TA1, TA2, TA3, TA4 and TA5 as in Figure 3 [6,14,15]. The concrete slab was attached to the top of CSB using strut connectors and it will behave as the composite beam under elevated temperature.

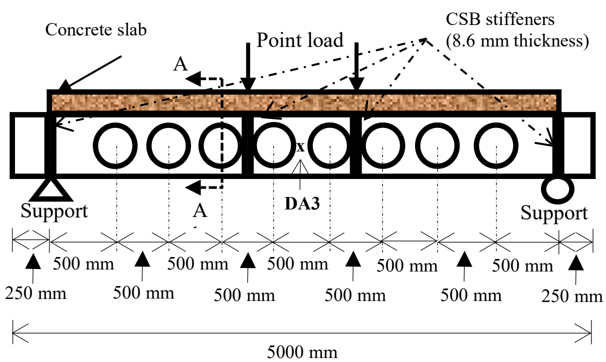


Figure 1: Composite concrete slab–cellular steel beam [6,15]

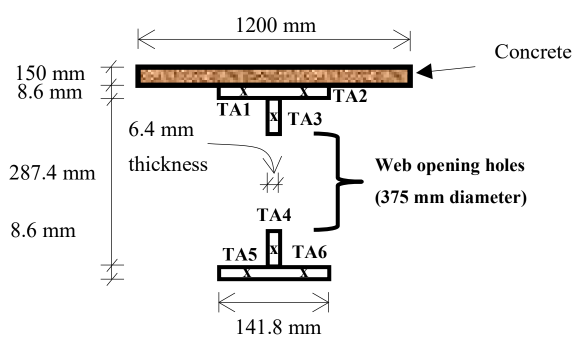


Figure 2: Thermocouples location viewed from cross section A-A of the composite concrete slab–cellular steel beam [6,15]

Numerical Simulation

General purpose of ABAQUS finite element program were used for the simulation analysis. Three dimensional linear, finite-membrane-strain, fully integrated, quadrilateral shell element (S4) analysis were used to simulate structural behavior of the composite CSB when expose to fire. For concrete slab, composite continuum shell element was selected to model the slab. Full interaction between CSB and concrete slab were considered during the numerical analysis by applying tie constraint to make full use of heat transfer distribution between both elements. Material nonlinearity were considered for both CSB and concrete slab due to steel and concrete material stiffness changes due to its time temperature dependent. The material nonlinearity for both steel and concrete were obtained as per recommendation in design fire codes [3,4,5]. The steel grades used in the experimental tests is S355 with the yield strength of 442 kN/m^2.

Heat transfer analysis

First stage analysis of CBS under elevated temperature refers to heat transfer analysis. In this analysis, transient heat transfer analysis was used for the temperature distribution along the CSB member due to time temperature dependent of slow heating fire curve. At this stage, slow heating fire curve were used to replicate the fire exposure as conducted during experimental investigations [6,15]. Fire exposure were exposed to all surface of the CSB including the web opening sections. The duration of the fire exposure is approximately 4800 seconds. Heat transfer from fire exposure were transferred to the surface of the CSB by method of convection and radiation process. The convection coefficient of 25 W/m^2K and 9 W/m^2K were used respectively, for exposed and unexposed surface of the CSB as per recommendation in design fire codes [3,4,5]. Thermal conductivity and specific heat properties for both CSB and concrete slab were obtained from design fire codes [3,4,5].

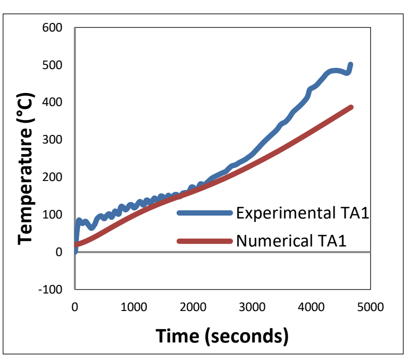
Static analysis

In the second stage analysis of CBD under elevated temperature, static analysis was conducted by applying two point loads on top of the concrete slab simultaneously incorporates nodal temperature from the heat transfer analysis. For nonlinear effect, non-linear plasticity model was chosen for CSB while concrete damage plasticity model was selected for concrete slab. The stress strain diagram of steel and normal concrete were calculated and obtained as per recommendations from the fire design codes [3,4,5]. Under static analysis, the stress versus strain should consider the plastic behavior which represent the nonlinear behavior of material before it reached the failure mode.

Results and Discussions

From the results of heat transfer analysis, the overall predicted CSB temperature agrees well with measured temperature of fire exposure time of 4800 seconds as illustrated from Figure 3 to Figure 5. Figure 3 shows the comparison between the experimental and numerical modeling recorded by thermocouples labelled as TA1 and TA2 which located at bottom of the top flange CSB beam. There are some differences between the experimental and modeling because the heat did not distribute equally along this area. Figure 4 shows the comparison between the experimental and numerical modeling for thermocouples which labelled as TA3 and TA4. Meanwhile, Figure 5 shows the comparison between experimental and modelling for TA5 and TA5. It can be clearly seen that measured temperature of thermocouples TA3, TA4, TA5 and TA6 have similar behavior between experimental and numerical modeling using ABACAQUS. However, predicted temperature of TA1 and TA2 are slightly under estimated as compared to measured temperature of thermocouples TA1 and TA2. Upper flange beam section exhibits the lowest temperature profile as compared to web beam section and bottom flange beam section. However, there are no significant different for temperature profile between the web beam section and bottom flange beam section. Figure 6 illustrates the predicted temperature profile of CSB at 4800 second fire exposure by using ABAQUS software.

Meanwhile, Figure 7 shows the comparison between the predicted and measured vertical deformation of CSB at location DA3 as shown in Figure 1. DA3 is located at the middle span of CSB beam where it is expected that the beam has the highest deflection under two point loads. It can be clearly seen that steady deflection occurs between 0 to 3500 seconds. But, the deflection plunges dramatically beyond that point until the CSB failed at approximately 200 mm downward for both predicted and measured deflection. Figure 8 shows the comparison in vertical deformation between the experimental results and numerical modeling using ABAQUS software. There is good agreement in terms of views, shapes and location of deflection under elevated temperature up to 600^0C and 4800 seconds.



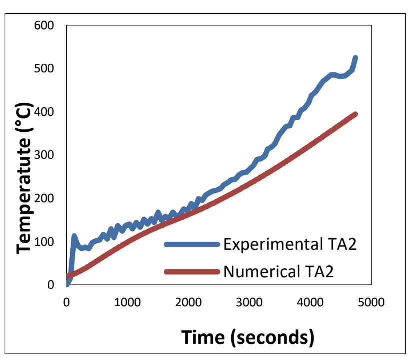


Figure 3: Comparison between experimental and numerical modeling of thermocouples labelled as TA1 and TA2 of CSB

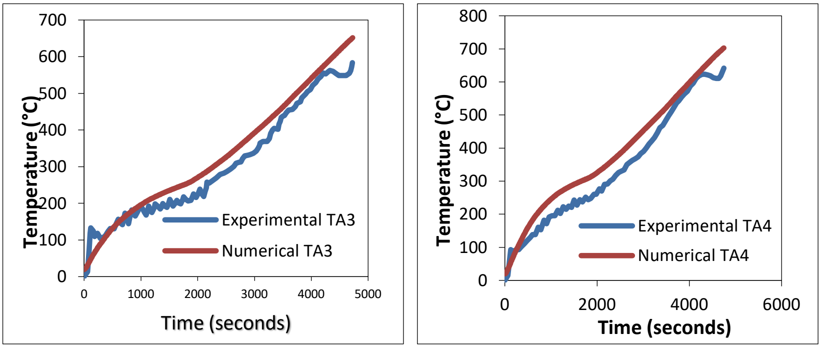


Figure 4: Measured and predicted temperature for TA3 and TA4 of CSB

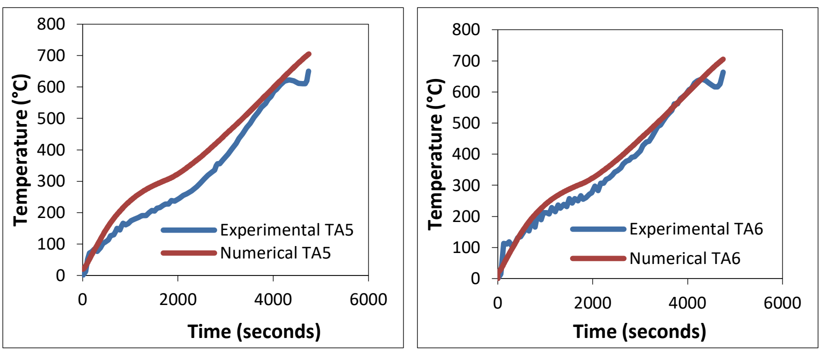


Figure 5: Measured and predicted temperature for TA5 and TA6 of CSB

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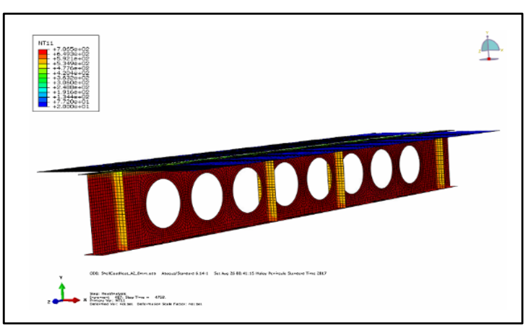

Figure 6: Predicted maximum temperature profile of CSB model at elevated temperature (4800 seconds)

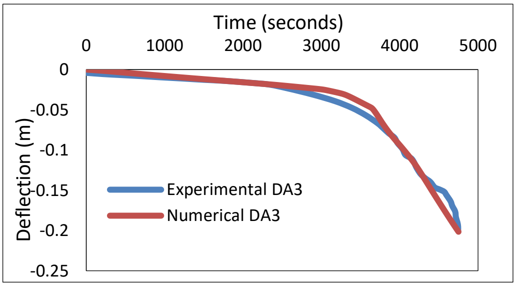

Figure 7: Measured and predicted vertical deformation in the middle and centered of CSB

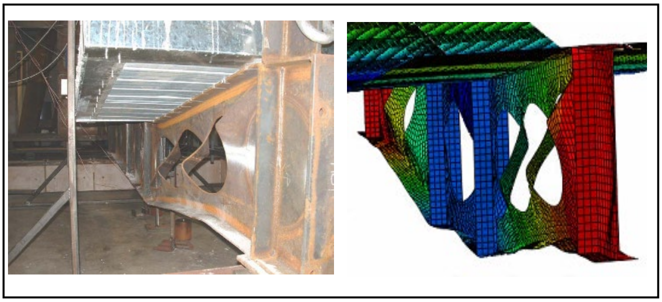

Figure 8: Comparion between predicted maximum vertical deflection using ABAQUS simulation failure mode against the experimental test of CSB under fire loading and static loading [15].

Conclusion

From this study, general purpose of ABAQUS finite element program can correlate both thermal analysis and static analysis of CSB at elevated temperature against the experimental investigation conducted by [6,15]**.** From the numerical results of the heat transfer analysis, the predicted temperature agrees well with the measured temperature profile along the cross section of the CSB. However, upper flange beam section exhibits the lowest temperature gained in comparison with web beam section and bottom flange beam section. The upper flange section located in the upper most part of the beam section where the heat source need to travel far from contact surface at the bottom flange beam section until to the upper flange beam section. In addition, full interaction between the top surface of the upper flange beam section and the bottom surface of the concrete slab contribute to lesser temperature profile in the upper flange beam section. Temperature lost dissipate from the upper flange beam section to the concrete slab. The predicted temperature at TA1 and TA2 are underestimated than the measured temperature of the experimental investigation by 114°C and 130°C of temperature differences. The reason is due to difficulties to predict and analyze the temperature distribution along the beam section especially in the upper flange beam section due to its interaction with the concrete slab. However, predicted temperature in the web beam section and bottom flange beam section are almost similar with the measured temperature as illustrated in Figure 5 and Figure 6. Apart from these factors, geometrical effect also contributes to decreasing temperature. Thicker beam section will induce longer time for the heat to be distribute from one section to another section. The web beam section is thinner by 2.2 mm as compared to upper and bottom flange beam section with 8.6 mm thickness. From Figure 8, the maximum mid span vertical deformation occurs at the center of the CSB due to symmetrically beam. Higher vertical deflection cause by the combination between the heat transfer analysis and static analysis which leads these drawbacks. It can be predicted that higher vertical deflection is caused by the removal some parts of the web section. The presence of web opening leads to reduction of strength and stiffness which leads to higher vertical deformation of up to 200 mm. The strength and stiffness of the CSB will subsequently reduce due to this action. To overcome this problem, a suitable fire protection material needs to be introduce to limit the temperature along the whole section of the CSB. Intumescent coating is the most reliable fire protection material in the market due its less expensive than other materials. This type of coating will be introduced in my current research that might limit the temperature member of CSB and hence improve the structural stability of the CSB at elevated temperature. Investigation on the failure modes of vertical deformation and especially Vierendeel bending failure mechanism will be done at later stage.

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