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FIRE RESISTANCE PERFORMANCE OF CELLULAR STEEL BEAM (CSB) AT ELEVATED TEMPERATURES

Fariz Aswan Ahmad Zakwan*, Renga Rao Krishnamoorthy, Azmi Ibrahim, Abdul Manaff Ismail

Faculty of Civil Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia

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*Corresponding author
fariz838@ppinang.uitm.edu.my

Graphical abstract

Abstract

Cellular steel beam (CSB) is getting more and more popular to be used as the main structural member for steel building structure in the United Kingdom (UK). Despite quite costly to erect and assemble a steel structure member compared to concrete, it has several advantages in terms of lightweight material, higher strength, easy to assemble and aesthetic value. Even though the use of CSB is quite significantly positive, the negative side also needs to be addressed. Any steel structures are prone to fire exposure scenario. The strength of CSB will be significantly decreased when exposed to elevated temperature due to fire. Large deformation from experimental procedure will be clearly seen after the time-temperature curve reach critical stage. Vierendeel bending mechanism and web-post buckling are some of the drawbacks of the CSB at elevated temperature. In this paper, general purpose ABAQUS Finite Element (Version 6.14) on large deformation of protected and unprotected CSB at elevated temperature is proposed. Performance based approach is introduced to validate the numerical analysis with the experimental results from the available Compendium of UK Standard Fire Test Data produced by British Steel Corporation Research Services, Swinden Laboratories, UK..

Keywords: Cellular steel beam (CSB), elevated temperature, performance based approach, critical temperature, Finite Element Method (FEM), large deformation

1.0 INTRODUCTION

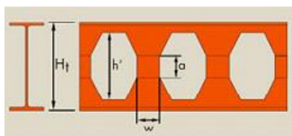
Cellular steel beam (CSB) is getting more and more attention in the civil engineering community and commonly used for long spans and heavily loaded floor system. Basically CSB can be used as underneath the roof structures and also slab structures. This types of system can significantly reduce the cost, improve strength and also advantageous for design purposes. In terms of roof structures, installing CSB would boost up the performance of the ratio between load bearing and weight of the beam. Moreover, it is cheaper to assemble the CSB rather than roof truss due higher cost to assemble roof trusses. Meanwhile, for slab structures, the total weight of the CSB is much less than solid steel beam due to its opening on the web section removed from the CSB. Shapes of the web opening can be made customize into various looks of circular shape, octagonal shape, hexagonal shape and also sinusoidal shape. Hence, the CSB with various types of web openings permits the distributions of services or technical installations such as pipes and ducts to pass through the web openings of the CSB without having to reduce clear height between bottom and upper floor [1]. Figure 1 shows various types of opening of the CSB available at present.

Steel structure can be critically exposed to high temperature if fire broke out in any building. One of the notable incident related to fire is partial or complete collapse of World Trade Centre complex, New York City, United States in 2001. Beyler *et al.* [2] has performed an analysis of thermal exposure on

World Trade Centre steel structures due to plane impact. This study is very crucial to determine the level of fire exposure which affect the high temperature increase on the structural member. When exposed to extreme high temperature, large deflection will occurred in solid steel beam due to stress increase where the beam can no longer sustain the increase thermal load [3]. It is important to embark new numerical analysis in validating the experimental investigation, where prediction can be made on the level of fire resistance of steel beam. The strength of the steel beam will be reduced significantly when exposed to fires. In addition to that, the strength of the CSB with web opening will further reduced due to removal parts of the opening in the web section [3]

(a)

(b)



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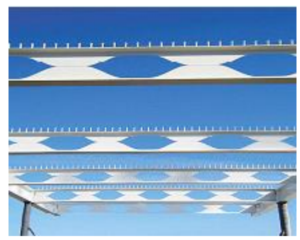
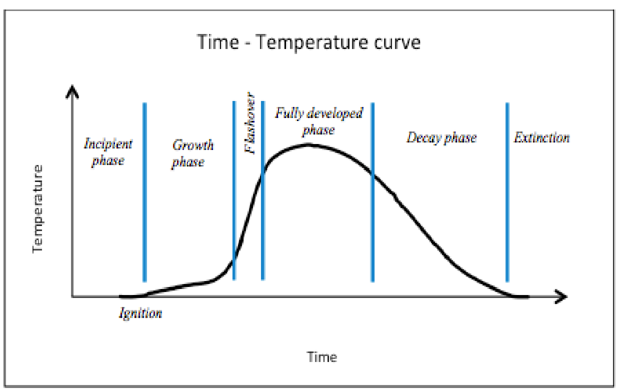
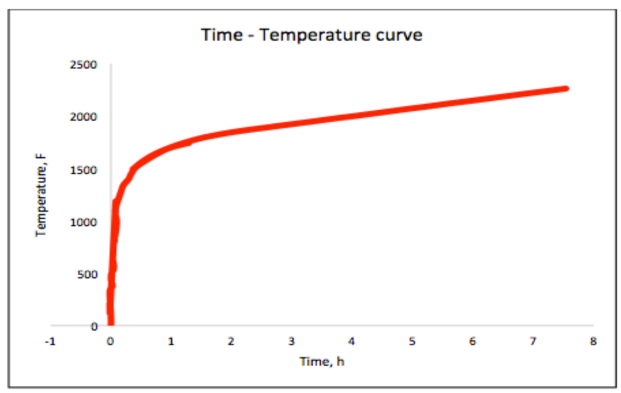


(d)

Figure 1 Various types of cellular/castellated steel beam opening; (a) circular opening, (b) hexagonal opening, (c) octagonal opening and (d) sinusoidal opening [4]–[7]



(a)



(b)

Figure 2 Time-temperature curve (a) in compartment fire [12] and (b) in Standard Test Methods [8]

2.0 LITERATURE REVIEW

2.1 Performance Based Approach

The two standards that involve with design method, are the prescriptive based approach and performance based approach. Traditionally prescriptive based approach of fire protection design is based basically on fire resistance requirements outlined in standard fire test and specifically prescribed in national building codes [8], [9]. Generally, there is still no fire resistance requirement which is based on 'realistic fire' exposure to structural element [10]. Performance of structural member exposed to real 'fire exposure' highly depends on various factors such as thermal load distribution in the structural member, geometry types of steel section, fire scenario, end restraints, connection configuration, load level and failure criteria in evaluating fire resistance [11]. Parkinson *et al.* [10] stated that the time-temperature curve outline in the standard fire test does not agree with the time-temperature curves in real compartment exposed to fire as shown in Figure 2. As the temperature in the compartment increases, the mechanical properties of the steel member drops until the steel member failed. At this point, it is considered as critical temperature. Generally, critical temperature is taken as around 538°C depending on the type and size of the steel member [10]. From the proposed approach [10], comparison between time-temperature curve of unprotected steel at elevated temperature and also time-temperature curve of protected steel at elevated temperature are shown in Figure 3 respectively.

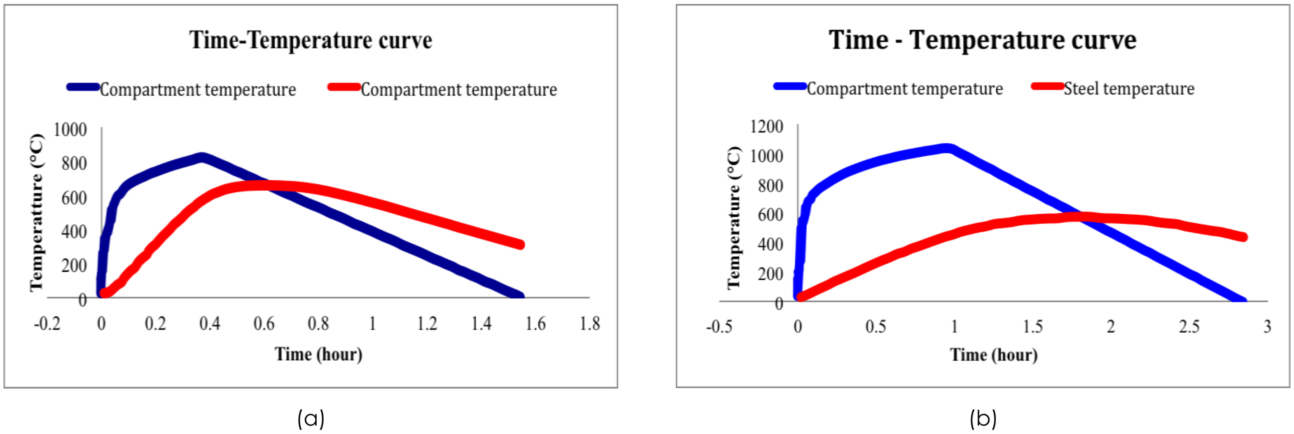


Figure 3 Comparison of time temperature curve for; (a) unprotected steel exposed to fire and (b) protected steel exposed to fire [10]

Parkinson *et al.* [10] stated that with the introduction of a new simple method, it could help civil engineering society to take the responsibilities to reevaluate the fire protection guidelines for the structural steel member at elevated temperature. There are several factors that affect the fire resistance of restrained beam. A particular previous research [11] concentrated on the effect of fire loads onto the performance of fire resistance of retrained beam. When beams and column exposed to extreme fire, large deflection will occur. There are still lack of research pertaining to the behaviour of restrained beam at elevated temperature [11]. The research stated that there is still lack of reliable and simple method for assessing fire response of restrained steel beam. In this paper, a simple and reliable method is proposed for assessing the restrained beam under fire load [11]. The proposed new method was validated against finite element analysis. Local buckling is one of the factor that affect the behaviour of restraint beam. Second factor that affects the behaviour of restraint beam is fire-induced force. Deflection effect is the third factor that may affect the performance of the restraint beam. Finally, the last factor is fire scenario. It can be divided into standard and 'realistic' fire scenarios. In standard fire exposure, when the fire is increase, the steel temperatures also increase. In 'realistic' fire exposure, the fire is suddenly decreased at maximum temperature at which the fire undergoes a decay or cooling phase. From the result obtained by [11], it can be seen that the measured midspan deflection is the same with Finite Element Method (FEM) analysis. The midspan deflection of proposed approach shows a steady approach compared to FEM results until it reach catenary point. The proposed approach can be used for performance based fire design of restrained beam. When the deflection increases, the tensile catenary action will strengthen the fire resistant of the beam.

2.2 Cellular Steel Beam (CSB) At Elevated Temperature

2.2.1 Unprotected Cellular Steel Beam (Csb) At Elevated Tempearture

Vassart *et al.* [13] performed a comprehensive fire test of unprotected CSB with composite floor and analysed the tensile membrane action. In that research, large scales of composite floor attached on top of the CSB were exposed to natural fire (open burning of fiber board + wood crib for extra fire load) in a fire chamber. [13]. The mechanical deflection started to increase at elevated temperature when the strength and stiffness of the steel is decreasing parallel with elevated temperature. Local buckling at web section takes place due to incremental load from elevated fire load. It can be clearly seen that the structure itself can sustain the extreme fire load and also the membrane action happened at floor plate, which agrees with [14] and [15]. Form the simulation results, web-post buckling in the web section occurs during fire exposure which agrees with experimental results. It can be conclude that the CSB does not affect the integrity of tensile membrane action produced in the slab during fire event. When a steel beam exposed to elevated temperature (fire), critical failure of large deflection will fully appeared due to strength and stiffness reduction of the steel beam. Steel beam subjected to applied lateral load will increase the critical temperature of the steel beam in which catenary action will comes in helping to resists the applied lateral load. From the results [3], it is mentioned that there were five parameters that may affect large deflection behaviour of a CSB. They are the expansion ratio, the dimension of the web opening, shape of the web openings, opening arrangements and axial restraint to the beam.

2.2.2 Protected Cellular Steel Beam (Csb) At Elevated Temperature

The required thickness that needs to be installed in CSB is based on the recommendation made by the steel manufacturer via calculating the Section Factor (A/V). By adopting this Section Factor, the required thickness of the intumescent coating is increased by 20%. Recent tests reported about the prediction of cellular beam behaviour using intumescent coating cellular [16][17]. Bailey [18] investigated the cause due to higher temperature in the holes along the web-post of the CSB. It was reported that solid beam exhibit higher temperature in comparison to CSB for both sample. For unprotected, unloaded steel beam, it was observed that the temperature variation in the web-post of CSB did not increase compared to solid web steel beam. This scenario led to the introduction of a new design approach to cater the performance of intumescent coating in the web-post section. Three different types of coating were applied on the solid beams and CSB. They were water-based intumescent coatings with 0.8 mm thickness, solvent-based intumescent coatings with 0.8 mm thickness and solvent-based intumescent coatings with 2.1 mm thickness. For the first type of coating, CSB exhibited higher temperature compared to solid beam. But after 65 minutes, the solid beam temperature started to increase jump over the CSB. The results shows that the average temperature for CSB also much higher in comparison to solid beam. It can be observed that the intumescent coating almost ‘slipping down’ away from the surface of the web and flange section of the beam for both cellular and solid beam. This scenario occurred due to fire resistant coating could only sustain until 90 minutes of fire exposure. In comparison to the holes of CSB, the intumescent coating around the holes can hold the elevated temperature exposed around the holes. For the second types of solvent-based intumescent coating (0.8 mm thickness), the test results shows the temperature at centre of the web-post and web for cellular and solid beam. The temperature at the centre of CSB started to increase significantly than solid beam. The condition of the intumescent coating after fire test completed were ‘pulled-back’ from the end of the holes for CSB. Due to this scenario, [18] makes an assumption that higher temperature occurred for CSB in this region are caused by the ‘pulled-back’ action in comparison to solid beam. The last intumescent coating applied on the steel beam is 2.1 mm thickness solvent-based intumescent. It can be clearly seen that the temperature at midpoint web-post of CSB is higher compared to solid beam after 20 minutes of fire exposure. The ‘char’ were move away from the holes of the CSB and moving towards the furnace burner. By making a comparison between water-based and solvent-based intumescent coating, the difference temperature between the web-post temperature and flange beam section temperature is increase when the coating thickness also increased. From the results obtained from [18] for all beam including the coating, it can be conclude that the higher temperature level in the web-post area were due to ‘char’ were ‘moving away’ from the holes. The ‘char’ were tends to move away from the holes and getting move towards the furnace burner. Because of the lack of test results available, it is very difficult to specify general rules as mention by SCI. They suggested that more test procedure needs to be done in order to study the performance of the intumescent coating around holes of the web-post. Apart from that, the author also mentions that more research work needs to be explored by investigating whether the ‘pulled-back’ scenario will occur during real fire or not.

3.0 SUMMARY

As a conclusion, several researchers have discussed several drawback of CSB at elevated temperature. Large deformation, Vierendeel mechanism and web-post buckling are some of the negative effects. The strength of the beam was severely compromise and deterioted upon unprotected CSB exposed to elevated temperature. Local buckling at web-post was clearly visible due to overload of thermal load coming from the fire. From the test conducted by [18], intumescent coating were placed at CSB as a protection layer. At the end of the test, the web-post temperature is relatively high in comparison with flange temperature. This due to the ‘char’ was generated surrounding the CSB during fire exposure. The ‘char’ were pulled back surrounding the opening at the web sections that leads to higher temperature recorded. It is crucial to investigate the fire resistance of protected CSB at elevated temperature. Even though, investigate on the performance of CSB with different opening shapes has been discussed, but there are still lack of research that related with experimental and numerical investigation. The author will like to point out that circular type of opening will be further investigate due very limited research related to CSB with circular opening shape at elevated temperature. From this paper, the author is proposing an investigation using general purpose ABAQUS on large deformation of protected and unprotected CSB elevated temperature. Detailed investigation will be scrutinized on the large deformation along with local buckling effects on the CSB due to elevated temperature. In addition, a performance-based approach will be enforced to verify the numerical simulation of the protected CSB against available test data. It has been said that performance based method is the best reliable approach rather than prescriptive approach due to its reliable 'realistic' fire exposure. Prescriptive approach only rely to the fire resistance guidelines outlined in the codes [8], [9] which are very limited at certain extend.

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