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TEMPERATURE RISE OF COLD-FORMED STEEL BUILT-UP BACK-TO-BACK COLUMN UNDER STANDARD FIRE

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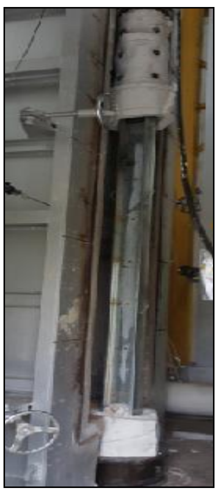
Graphical abstract



Abstract

Cold-formed steel (CFS) has been used for various applications in building structure. Due to its many advantages, the uses of CFS can be widened to build new or to renovate existing single one or two families private homes. However, the fire resistance of the CFS is a critical issue whereby inclined to lose its vigour when it is exposed to fire, compared to hot-rolled steel member. This study takes the opportunity to investigate the application of this material as column members subjected to the standard fire. Four columns were tested. One column with a static load was tested under the ambient condition, while the three other columns were loaded at different degrees of utilisation under the standard ISO 834 fire conditions. The increases of temperature on the column surface were monitored using thermocouple Type K and the analyses of this thermocouple reading was taken to evaluate the mean temperature of the column. The temperature behaviours of back-to-back column for all degrees of utilisation showed that, the web was a lower temperature compared to the flange due to the greater thickness of the web. Meanwhile, the failure temperature of the CFS could reach up to 651.0 °C for 30.0 % degree of utilisation with 8.0 minutes of resistant time.

Keywords: Cold-formed steel, Standard ISO 834 fire, Critical temperature, Critical time

1.0 INTRODUCTION

Cold-formed steel (CFS) structure is one of the most popular construction materials due to its various advantages. Its most popular use is as a structural framing for residential and light loading buildings. Constructions of lightweight building components such as the CFS have been used to build or renovate existing single- and two- families' private homes [1]. The applications of built-up shapes such as in a composing member truss have attracted many designers of light-steel framing to widen the applications of CFS to larger scale structures. In addition, the CFS built-up has several advantages in its production, handling, and mechanical strength. Therefore, it is suitable to be used for fast constructions of low rise ups to double storey buildings as well as emergency houses. However, the fire resistance of this material is a critical issue as it is susceptible to have a low level of stiffness when exposed to fire compared to other materials like hot-rolled steel member.

Many researchers had conducted the studies of CFS under high temperature. Most of these researches were mainly focused on the elevated temperature test and the finite element simulation of CFS at elevated temperatures [2, 3, 4, 5, 6, 7, 8]. However, there is still a limited amount of research data on individual tests of CFS exposed directly to the fire. A research conducted by Kankanamge [9] found that in the case of fire, the CFS beam always experienced the local buckling failure mode similar to those at the ambient temperature. Meanwhile, Chen and Young [10] concluded the Effective Width Method and the Direct Strength Methods were able to predict the CFS lipped channel column strengths at elevated temperatures.

In the meantime, Moura Correia *et al*. [11] concluded that the value of CFS restraint to extended thermal exposure was not a major influence on the fire behaviors of the columns while Li *et al*. [12] said that the effects of axial restraint to the failure temperature depended on the load ratio and the axial restraint stiffness ratio. Consequently, the differences between the buckling and the failure temperature of the restrained columns would increase with the reduction of the load ratio or the increase in the axial restraint stiffness [3]. Moreover, the review from Li *et al*. [12] mentioned that the failure temperature of the restrained column was determined by the temperature at which the axial force in the restrained column returns to its initial value.

A recent research which involved exposing CFS to direct fire was conducted by [13]. The smaller section of the built-up back-to-back (BTB) is studied by considering the stiffness of the surrounding structures, the type of section and the end support condition, while the columns were supported by the bolt. The main finding of their research was the end support conditions and the initial applied load level on the CFS columns might affect their fire performances. Therefore, the study of CFS exposure to direct fire is significant as it will better understand in considering this material for framing structure. Furthermore, the knowledge of construction hazard is important for firefighters as it provides significant and identifiable construction indicators which will help the firefighters to recognize the type of the structural component prior to entering a building. Hence, the objectives of this study is to evaluate the temperature rise of built-up BTB CFS columns which are subjected to standard fire as well as determining the failure time and the temperature related to the degree of utilisation.

2.0 MATERIAL AND METHOD

Lipped channel columns with the size of 200.0 mm web depth, 73.0 mm flange width, 17.0 mm lipped, 1.90 mm thickness, 2.50 mm round corner and centroid 20.38 mm from the web were bought from a local manufacturer. The height of each column was 3.0 m. Each column was constructed as a built-up section using two identical channels screwed back to back at 400.0 mm c-c along the length. A semi rigid support condition was constructed by screwing the column web to the steel angle to restrain any lateral movement. The column was placed at the centre of the circular steel plate to ensure the load could be distributed uniformly throughout the column's cross-section. The temperature rise in the column was recorded using a surface thermocouple Type K. Table 1 provides the notation for the thermocouple used in this study. Based on the recommendations of BS EN 13381-4:2013 (E) [14], the thermocouple was positioned along the column height as shown in Figure 1. It can be observed that thermocouple was attached to the column's section at the flange and the web. Besides that, a static test of the built-up BTB column was conducted at ambient temperature to determine the capacity of the column. According to this static test, a load ratio known as the degree of utilization is considered to evaluate the temperature rise in the column and finally determine the fire resistance of the column. During the fire test, the column was loaded at a constant load level as in real structure application. The load was left for constant until reach stable condition for 10.0 minutes before the fire induced. Then, fire was blown to the column inside the furnace until the column failed. The temperature rise in the column was monitored. The column was loaded using a hydraulic jack loading system with maximum loading of 1000.0 kN. The load applied was at 0.25 kN/s for both ambient and fire condition.

Table 1 Thermocouple notation for the column

Level	Thermocouple
T1	SpTC1, SpTC2, SpTC3
T2	SpTC4, SpTC5, SpTC6
T3	SpTC7, SpTC8, SpTC9

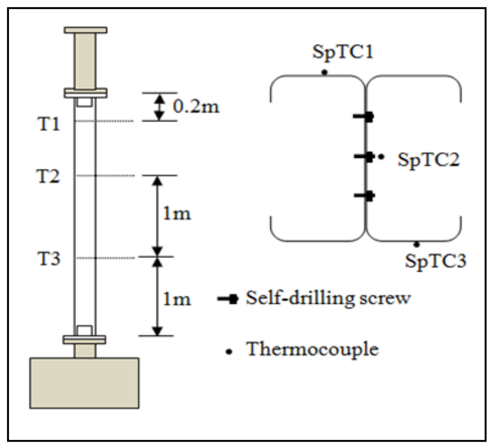


Figure 1 Location of thermocouple on the column

The standard fire curve in function of the temperature and time was $\theta g = 30 + 345\ log10\ (8t + 1)$ where θg is the gas temperature in unit °C in the fire compartment and t is the time in minutes. In order to determine the acceptance of the fire induced to the columns, BS EN 1363-1:2012 (E) [15] had the limit of 15.0 % percentage deviation (de) in the upper limit and lower limit of standard the temperature/time curve. The furnace used to have six fire blowers and its pressure was also monitored according to the recommended BS EN 1363-1:2012 (E) [15], pressure inside the furnace, which is approximately 8.50 Pa per metre the height of the furnace and must be within ± 5.0 Pa after 5.0 minutes of fire.

3.0 RESULTS AND DISCUSSION

Four thermocouples were placed inside the furnace to determine the temperature of the fire. The average value was demonstrated in Figure 2. All furnace temperatures that burned the four built-up BTB columns showed a consistent temperature rise according to the standard ISO 834 [16] fire curve. The temperatures and pressure in the furnace were within the limit given in BS EN 1363-1:2012 (E) [15].

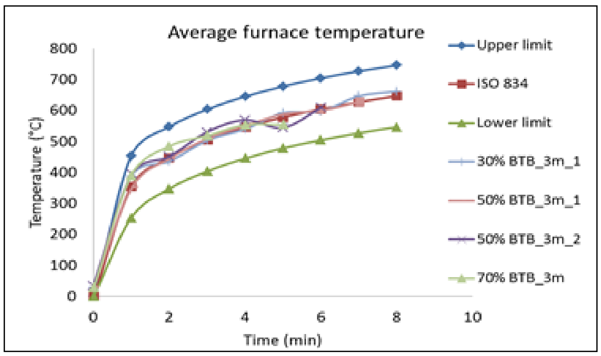


Figure 2 Average furnace temperature

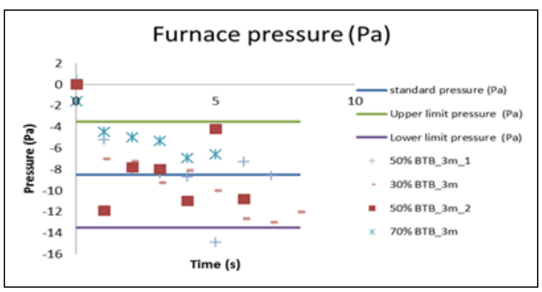


Figure 3 Furnace pressure inside furnace

3.1 Axial Strength of Cold Formed Steel Column

Prior to the fire test, a static test was required to determine the capacity of the columns. The strength of the built-up BTB columns obtained from the experiment was 188.0 kN. In this study, columns with 30.0 %, 50.0 % and 70.0 % load utilisation were used to evaluate the fire resistance of the columns. 56.40 kN, 94.00 kN and 131.60 kN load were applied to the column which represented 30.0 %, 50.0 % and 70.0 % load utilisation respectively. The results of static test were compared to the design method using EC3-1.3 with results of 124.67 kN. Meanwhile, the THINWALL software showed the result of 130.50 kN. This calculation was based on the pinned support column.

3.2 Temperature Rise in CFS Column

Figure 4 shows the recorded thermocouple at each station on the BTB column for different degrees of utilization. Only eight out of nine thermocouples give reliable results. This is the cause of an error such as positive, negative conductor touch to each other due to fracture of ceramic that cover both conductors due to impact during column failure in previous test. Thermocouples located at 200.0 mm from top support and loading is known as SpTC1-SpTC3. The rise of temperature at this location is below the standard fire ISO 834 [16] for all degrees of utilisation until the column fails. The temperature recorded for SpTC2 that located at the column web is lower than the SpTC1 and SpTC3 that located on the flange respectively. The same temperature behaviour of built-up I-section was found in the study conducted by [13] which the temperature at the web registered lower temperatures than the ones of the flanges. This might explain that the greater thickness of the web and the thermal conductance between the two CFS profiles [13]. This behaviour also found for all thermocouple at other level in the column. SpTC4 and SpTC6 is thermocouple placed at 1 meter from top of column flanges respectively. It was found that rise of temperature is faster compared to the top side. The rates of temperature rise are almost similar for SpTC4 and SpTC6. SpTC4 and SpTC6 for 70.0 % degree of utilisation have risen up to ISO 843 [16] fire curve at failure while for 30.0 % degree of utilisation, the column was failed at lower temperature. SpTC7-SpTC9 recorded the temperature for lowest side at 2.0 m from loading. It was observed that the SpTC7 and SpTC9 also recorded higher value in that level. In addition, the values in this level are slightly higher to the thermocouple at the middle level. The rate of temperature rise was also similar for different degrees of utilisation. It can be concluded that the rate of temperature rise of the BTB CFS column is constant for CFS and in-depended to the degree of utilisation.

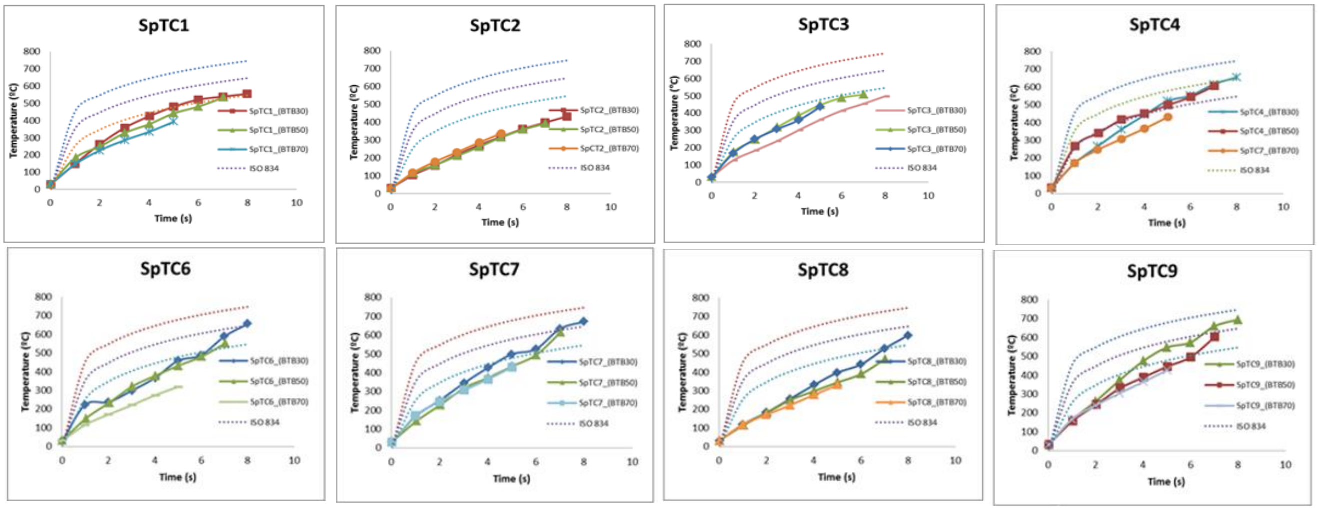
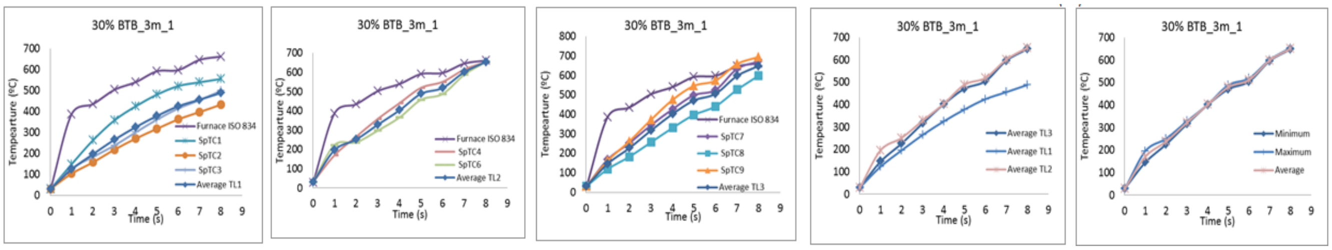


Figure 4 Temperature rise in built-up back to back column

3.3 Mean Temperature

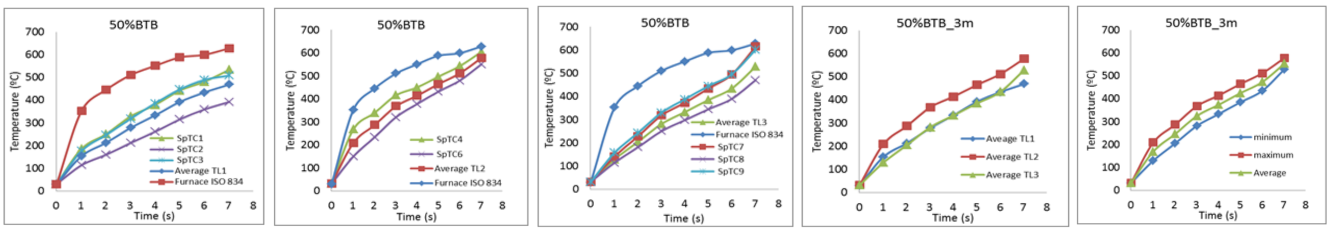
Figures 5-7 show the rise of temperature recorded on a BTB column fewer than 30.0 %, 50.0 % and 70.0 % service load which were exposed to standard fire. All of the columns had the same behaviour of temperature rise where the upper side of thermocouple registered lower temperature until the columns' failure. This might be caused by the thermocouple was located nearer to the ceramic fibre which supported the column end. The heat was shielded by a ceramic fibre that restricted the conductance of heat to this position. Thus, it was expected that the failure of 30.0 % degree of utilisation column failed the temperature increase in the column. Meanwhile, Figures 7(a)-(c) show the column temperatures in the BTB column. In the meantime, the middle and bottom level recorded temperatures that approached the standard ISO fire. The columns failed as all thermocouple at the middle level reached the temperature of ISO fire. The column with a 50.0 % degree of utilisation showed that the bottom side of the column had reached the temperature of ISO fire. Meanwhile, the column with 70.0 % degrees of utilisation were recorded none of the temperature had reached the ISO temperature at failure. This temperature behaviour was due to the high load applied, which caused the column to have large deformations and had reduced its stiffness faster when heat induced. According to the temperature recorded, the column with the lower degree of utilisation failed due the temperature of the column had reached the standard fire. For the moment, the columns with a higher degree of utilisation results the columns fail due structural failure, in particular through buckling. The buckling mode is due to the different degree of utilisation result in different failure mode.

The evaluation of mean temperature along the column was calculated by using the weighted area methods in which the temperature recorded were multiplied to the area of the column surface [13]. It was observed that the web temperature was lower than the flange temperature and average value lead to the lowest average value. Figures 5-7 (d) show the average value at each thermocouple level. It was found that all degrees of utilization column had recorded a non-uniform temperature at its cross-section for all different levels. The column with a 30.0 % degree of utilisation had a higher temperature at TL3 and TL2, while columns with 50.0 % and 70.0 % degree of utilisation had a higher temperature for TL2. This might be caused by T1's location was nearer to the column supported with ceramic fibre which caused it to register a lower temperature. Hence, it was ideal to account T2 and T3 to get the mean temperature in the column. Figure 5-7 (e) shows the minimum, maximum, and average values of temperature. While the columns with 30.0 % and 70.0 % degree of utilisation obtained close results with the temperature, hence the average value is used. On the other hand, the columns with a 50.0 % degree of utilisation, had a big difference in the value of temperature, thus, the minimum value is used. Table 2 tabulates the mean temperature of the column.



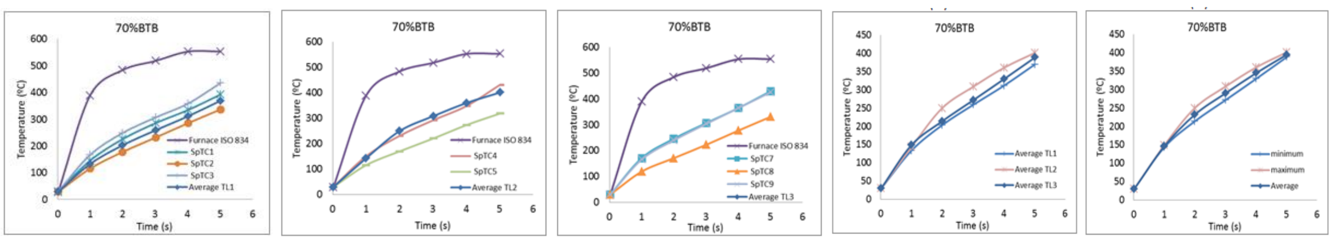
(a) (b) (c) (d) (e)

Figure 5 Evaluation of mean temperature along the column for 30.0 % degree of utilisation



(a) (b) (c) (d) (e)

Figure 6 Evaluation of mean temperature along the column for 50.0 % degree of utilisation



(a) (b) (c) (d) (e)

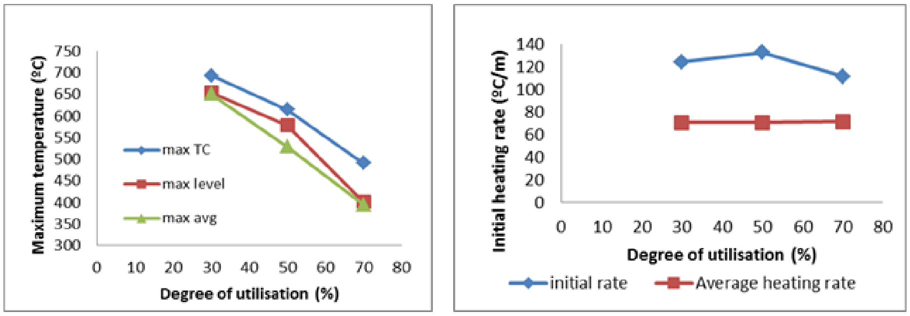
Figure 7 Evaluation of mean temperature along the column for 70.0 % degree of utilisation

Table 2 Mean temperature of the column

Time	Degree of utilisation (%)		
	30.0	50.0	70.0
0.0	31	32	30
1.0	171	130	146
2.0	239	205	232
3.0	324	282	290
4.0	403	333	345
5.0	480	385	395
6.0	512	435	-
7.0	599	529	-
8.0	651	-	-

3.4 Failure Time and Temperature

The philosophy of fire design is particularly concerned with preventing structural collapse before the specified fire resistance period. The design of the critical temperature or collapse temperature of structural element is considered uniform temperature. The evaluation of critical temperature is done by evaluating the results of the maximum recorded thermocouple from the experiment, the maximum values from the average of each level, and the maximum value from the mean temperature. Figure 8 (a) plots all the values for all degrees of utilisation. Furthermore, for fire safety reasons, the ideal critical limiting temperature was taken as the smallest value which was based on the maximum mean average. As expected, the resistant time was decreased as the load applied to the column was increased. Then, both the initial and average heating rates of the column were calculated. The Initial heating rate was calculated using the temperature recorded in the first minute, while the average heating rate was based on the temperature and time of the column failure. Figure 8 (b) showed the effects of load towards the heating rate of the column. The heating rate of the channel column does not depend on the load apply and it was also reported by [13]. The heating rate was almost constant for the BTB column at all load levels at 70.0 °C/min. The initial heating rate is generally higher at 123.0 °C/min for column because the first 1 minute, the rate of ISO 834 [16] is higher at 329.0 °C/m. The critical temperature was 651.0 °C, 529.0 °C and 395.0 °C and critical time was 8, 7 and 5 minutes for 30.0 %, 50.0 % and 70.0 % degree of utilisation respectively. As the degree of utilisation is increased, the critical temperature and time is decreased.



(a) (b)

Figure 8 (a) Evaluation of critical temperature (b) Heating rate of the column

4.0 CONCLUSION

This paper found that the temperature rise in cold-formed steel (CFS) is related to the degree of utilisation for BTB columns. Based on the comparison results of thermocouple recorded for all degrees of utilisation, it can be concluded that there was a constant rate of temperature rise of the BTB CFS column for CFS which depended to the degree of utilisation. The heating rate was 70.0 °C/min and the initial heating rate was 123.0 °C/min. The temperature behaviour of BTB column showed that, the web recorded a lower temperature compared to the flange due to the greater thickness of the web which affected the thermal conductance between the two CFS profiles. The same behaviour was also observed in all degrees of utilisation. The failure temperature of cold-formed steel could reach up to 651.0 °C for 30.0 % degree of utilisation with 8.0 minutes time resistance.

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