Finite Element Analysis of Coated (Intumescent Coating Protection) Cellular Steel Beam (CSB) Expose to Fire

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Abstract. Traditionally, standard composite steel beam section acts as a load bearing structural element to sustain an external load. However, in the event of fire, an additional fire load acts on the composite steel beam section. The combined action of the former and latter would accelerate the vertical deformation of the beam. In the case of cellular steel beam (CSB), the vertical deformation predicted to be higher. Due to these circumstances, the structural behaviour of the composite CSB were compromised leading to the critical failure mode of web-post buckling and Vierendeel bending failure. Therefore, it is crucial to evaluate the behaviour of the composite CSB at elevated temperature under both loading action. In this research work, validation process was initiated between the numerical simulation analysis of CSB exposed to the fire with the readily available experimental data work. The validated model was then used to simulate the composite CSB with newly added fire protection material of intumescent coating. From the finite element simulation, the predicted vertical deformation slightly decreased for thicker intumescent coating application onto the beam surface. In conclusion, by applying the intumescent coating, further improvements were predicted for the vertical deformation and subsequently maintains the strength of the composite CSB at elevated temperature.

1. Introduction
Composite steel beam is widely used as the main load bearing structural element for building structures, namely flooring system and roof system. Interaction between concrete slab connected with steel beam creates an increased composite steel beam stiffness against external load at elevated temperature. Fire exposure threat affecting the performance of composite steel beam under fire load. In the last few years, a new type of steel beam was used to accommodate new trends and current needs involving construction building industry. This type of steel beam allows pipelines and conduits to move straight through the web steel beam section. Web opening section were introduced through the web steel beam section of I or H shape. There are several shapes of the web opening available in the market, namely circular, hexagonal, octagonal and sinusoidal shape as illustrated in Figure 1. Commonly, circular web opening shape was the preferred choice due to its shape that can fits circular pipelines and conduits straight the web opening section. This type of steel beam is commonly referred as cellular steel beam (CSB). With the full interaction in the middle of concrete slab and composite CSB, the composite beam increase the bending moment resistance between 50% to 100% and also increase the flexural resistance in comparison with standard steel beam [1, 2]. However, the stiffness of the CSB were slightly reduces due to some parts of the web section were omitted and removed. This scenario leads to several failure
conditions occurred along the web opening section. Even though the stiffness of the CSB were reduced, the strength of the beam was not compromise.

![Composite Steel Beam](image)

**Figure 1.** Various shapes of web opening section of steel beam; (a) hexagonal web opening, (b) circular web opening, (c) sinusoidal web opening and (d) octagonal web opening [3–6].

In normal practice for building structures, both passive and active fire protection method were installed and utilized to protect the structural element against unexpected fire hazard. These types of fire protection system provided adequate fire safety during fire risk exposure. Passive fire protection material is classified into a few types of protection, namely board systems, concrete encasement, intumescent coating and spray-on systems [7]. Intumescent coating is widely used for passive fire protection system due it’s easier to install the intumescent painting surrounding the structural element as opposed to other types of protection material. For this reason, intumescent coating was selected for this current research. For coated composite CSB, the steel beam stiffness and strength will reduce significantly at elevated temperature. It is believed that the strength of steel beam deteriorated and weaker beyond 550°C of fire exposure and hence critical failure mode occurred before collapse. Vierendeel bending failure mechanism, web-post buckling and vertical deflection are some of the critical failure conditions. Consequently, adopting fire safety material onto the beam could reduce these drawbacks and hence improved the beam stiffness and strength. Thus, a reliable performance-based approach needs to be executed to explore fire resistance behaviour of coated composite CSB when bare to fire. This approach considers important consideration that contribute to fire protection behaviour of the beam, namely fire density, fire distribution, boundary condition and connection between other steel member which were not captured when selecting prescriptive-based approach. The latter design approach can be retrieved from available fire design regulations of BS5950: Part 8, BS EN 1991-1-2, BS EN 1993-1-2 and BS EN 1994-1-2, which were adopted until today. This design approach calculate the fire protection material thicknesses based on fire temperature limit which is up to 550°C when bare to standard fire curve [8]. From then onwards, the depth of the fire safety material was determined straightforward without having to consider important factors as mentioned in performance-based approach previously.

Therefore, a general purpose ABAQUS finite element program were used in present research to replicate and predict the structural behaviour of the coated composite CSB when expose to fire. Numerical simulation model of composite CSB when expose to fire were validated against the available experimental results. Temperature distribution and vertical deformation of composite CSB at elevated temperature were modeled and verified with the previous work conducted by [9–12]. From then onwards, parametric investigations were initiated by applying various intumescent coating thickness to explore the behaviour of the composite CSB at elevated temperature.

2. **Cellular steel beam (CSB) and its behaviour**

2.1. **Cellular steel beam (CSB)**

The usage of CSB as the main structural steel member is gaining momentum due several advantages as mention in Chapter 1. In term of self-weight, CSB is much lighter than standard steel beam which reducing the usage of steel material itself. Even though some portion through the web steel beam section of CSB were omitted, the structural strength and integrity is maintained as per standard steel beam. However, several drawbacks need to consider when analyzing the CSB at elevated temperature. Vierendeel bending failure mechanism, web post buckling and large vertical deflection are critically failure mode that has been reported in the literature [2][10][13–15]. Only vertical deformation results
were reported in this research while other drawback will be discussed in the next research paper. The predicted maximum temperature and maximum deflection together with the composite CSB member when expose to fire can be located and further discussed. With the supplementary fire safety material of intumescent coating, which is covering the composite CSB, the level of fire safety can be improved. Therefore, different depth of intumescent coating layer was studied in this research. Hence, the nature of coated composite CSB at elevated temperature can improved significantly. In this research, coating thickness of 0.1, 0.3, 0.5, 1.0, 1.5, 2.0 and 5.0 mm were chosen to explore the structural behaviour of the CSB when bare to fire and applied load.

2.2. Prescriptive-based approach
The Prescriptive-based approach is the easiest and safest approach to assess the behaviour of an particular structural component at elevated temperature. This approach is purely referred to standard fire resistance test according to the guidelines stipulated in standard fire codes of BS EN 1991-1-2, BS EN 1993-1-2, BS EN 1994-1-2, BS EN 1363-1, BS 476-20 and ISO 834. The appropriate depth of the fire safety material can be obtained directly form the design regulations. However, there are some factor that needs to be consider when adopting this approach. In this approach, it does not deal with the current nature of fire that differ than standard fire exposure which considering cooling stage. Another reasonable fire nature also needs to be consider in the fire design regulations due to its nature regarding fumes discharge, fire distribution, fire density and fire intensity that affecting structural building when expose to fire [16-17]. In addition, it also does not consider the temperature distribution along the structural element in the course of fire exposure. Consequently, it is exceptional to embrace reliable performance-based technique that able modelled and simulate the performance behaviour of structural member at elevated temperature by considering all crucial factors.

2.3. Performance-based approach
In this more advanced approach, it is quite complicated to analyze the structural behaviour of the structural steel elements. However, by performing performance-based approach by means of numerical simulation, it able to model and simulate complicated structural steel element at elevated temperature. The mechanical properties obtained from the experimental test were used and to be include in the numerical simulation analysis. Two different stages can be implemented in this approach, namely heat transfer analysis (temperature behaviour of structural member) and static analysis (mechanical behaviour of structural member) [18]. Commonly, passive fire safety material was used to insulate the steel beam member by reducing the temperature distribution along the steel member when expose to fire. Hence, intumescent coating material were used in this research to provide full insulation of the composite CSB when expose to fire by reducing the CSB temperature. Due to this scenario, it is expected that the vertical deformation will subsequently reduce due to temperature drop in steel beam member. Therefore, it can predict the most suitable thickness of intumescent layer to be insulated onto the composite CSB. It is crucial and important to adopt a dependable performance based concept, that needs to be acknowledge in the present steel construction [7].

3. Specification of Cellular Steel Beam (CSB)
One sample of bare composite CSB when expose to fire were chosen from the experimental results conducted by Nadja [9] at University of Ulster, Northern Ireland. The symmetrical unprotected composite CSB A2 (SUC-CSB-A2) was selected and verify against numerical analysis performed in this current study. Two parameters were used for validation purposes, namely maximum temperature distribution and mid-span vertical deflection. The SUC-CSB-A2 sample were bare to a slow heating fire curve as stated in fire design regulations of ISO 834, BS EN 1991-1-2 and PD 7974-1. After validation process has completed, parametric investigations were initiated to figure out the fire protection behaviour of protected SUC-CSB-A2 which is insulated with intumescent coating material. Table 1 presented detailed geometrical properties for composite SUC-CSB-A2 with additional concrete slab on the steel beam surface.

The geometry detailed of the composite SUC-CSB-A2 is depicted in Figure 2. For the first parameter, only one cross-section of fire thermocouples location selected along the beam segment as presented in
Figure 2(c). Therein are six fire thermocouples attached to the beam section, namely TA1, TA2, TA3, TA4, TA5 and TA6. For the second parameter, the maximum vertical deformation location (DA1, DA2, DA3, DA4 and DA5) were located as shown in Figure 2(d). However, point DA3 were presented with regards to mid-span vertical deformation.

### Table 1. Geometrical properties of composite SUC-CSB-A2 and concrete slab.

| Steel beam section size | The finished depth of bottom tee steel beam section | Width of upper flange steel beam section | Width of bottom flange steel beam section | Thickness of upper flange steel beam section | Thickness of bottom flange steel beam section | Thickness of web steel beam section |
|-------------------------|--------------------------------------------------|------------------------------------------|-------------------------------------------|---------------------------------------------|---------------------------------------------|----------------------------------|
| UB 406 x 140 x 39       | 575 mm                                           | 141.8 mm                                 | 141.8 mm                                  | 8.6 mm                                      | 8.6 mm                                      | 6.4 mm                           |
| Steel grade             | Diameter of circular web opening                 | Thickness of concrete slab               | Width of concrete slab                     | Normal concrete grade                       | Yield strength steel reinforcement         |
| S355                    | 75 mm at 500 mm center to center                 | 150 mm                                   | 1200 mm                                   | 35 N/mm²                                    | 460 N/mm²                                   |

**Figure 2.** Composite SUC-CSB-A2 model: (a) front view; (b) cross section B-B view; (c) fire thermocouples position at cross-section A-A; (d) front view location vertical deflection [9][11-12].

### 4. Numerical modelling

In this non-linear investigation, the stress-strain behaviour for the steel beam and concrete slab were obtained from design codes BS EN 1991-1-1, BS EN 1991-1-2, BS EN 1993-1-1, BS EN 1993-1-2, BS EN 1994-1-11 and BS EN 1994-1-2. For both ends of the coated steel beam, boundary conditions were applied as similar with experimental set up. For experimental program conducted by Nadjai [9], the interaction in the midst of concrete slab and the composite CSB was connected by using shear stud. However, in this current research, shear stud was not considered in the numerical analysis. But instead full interaction constraint was adopted in the middle of the underlying surface of concrete slab and topmost surface of the composite CSB by means of tie constraint to replicate the shear stud function.
Both heat transfer and static analysis were used during the computational finite element analysis program.

During heat transfer analysis stage, a four-node linear heat transfer quadrilateral shell element DS4 model were chosen for bare composite SUC-CSB-A2, concrete slab and intumescent coating. For heat transfer step, the heat from fire exposure were transmitted to the steel beam surface by the process of convection and radiation. The fire exposure started from the bottom fire furnace and equally expose to all surface of the CSB and intumescent coating, which is underneath the concrete slab. The value of the convection used were 25 W/m²K and 9 W/m²K for bare and protected steel beam surface as stated in fire design regulations. The radiation value on steel surface was taken as 0.8 as taken from fire design regulation. In addition, the radiation value on intumescent coating surface was taken as 0.825. In terms of steel beam and concrete properties at elevated temperature, the thermal properties and conductivity were taken out the fire design regulations. The specific heat and thermal conductivity for the steel beam and concrete slab used in the numerical analysis were illustrates as in Figure 3. The intumescent coating properties were retrieved from previous research conducted by Krishnamoorthy [19-20].

![Figure 3. Thermal properties for; (a) steel , (b) steel, (c) concrete and (d) concrete [21–23]](image)

For static analysis step, the Newton-Raphson method were employed numerically to execute the material non-linearity equations and geometrically by consolidating the iterative and incremental procedures. An applied load of 90 kN were imposed at two location on the top of concrete slab as illustrates in Figure 2(a) and Figure 2(d). General static analysis was selected to solve the nonlinear behaviour of the composite SUC-CSB-A2 model. A non-linear analysis of finite membrane-strain, fully integrated linear shell element S4 model were chosen for both bare composite SUC-CSB-A2 model and concrete slab. The material nature for steel beam and concrete slab were taken from previous research work [12][20]. In addition, concrete damage plasticity material behaviour was chosen to model the nonlinear plasticity concrete slab behaviour at elevated temperature. The concrete slab and steel beam density are taken as 2400 and 7850 kg/m³ respectively.

5. Results and discussions
Figure 4 and Figure 5 and shows the predicted and measured maximum temperature distribution at point TA1, TA2, TA3, TA4, TA5 and TA6 of composite SUC-CSB-A2 model. The fire exposure duration for all points is 4700 seconds (78.3 minutes). The overall forecast maximum temperature agrees well with measured maximum temperature at 4800 seconds fire exposure time. From the figures, the forecast maximum temperature is slightly less than the measured maximum temperature for point TA1 and TA2. This behaviour is likely due to point TA1 and TA2 placed in the intermediate section of the top flange beam section which is fully connected to concrete slab. Parts of heat in this section were dissipated through to concrete slab which affecting the temperature distribution through the top flange beam section. Due to this scenario, the outcome from experimental temperature output is different than forecast temperature output. Experimental outcome does not consider the interaction between both steel section and concrete slab, while numerical analysis does capture the effect of the full interaction during simulation analysis procedure. However, TA3, TA4, TA5 and TA6 predicted slightly overestimate value of maximum temperature as compared to experimental data. The behaviour for these four locations were
believed caused by the interface reaction when fire exposure hit on the steel beam surface. Convection, radiation and material properties values does have a compelling significance onto the fire safety behaviour of composite CSB at elevated temperature. Meanwhile, Figure 6(a) shows the forecast and measured critical vertical deflection located in the middle of the web section and centre of the composite SUC-CSB-A2 model. From the figures, the forecast critical vertical deflection agrees well with the measured maximum vertical deflection at the end of the 4800 fire exposure duration. Point DA3 forecast the critical vertical deflection of 0.21 m as compared to measured vertical deformation of 0.2 m as shown in Figure 6(a). Figure 6(b) shows the forecast critical vertical deflection at point DA3 of composite SUC-CSB-A2 model which is coated with different depth of intumescent layer. The vertical deflection is slightly decreasing when adopting deeper intumescent layer.

Figure 4. Forecast and measured maximum temperature for point TA1, TA2 and TA3 for composite SUC-CSB-A2 model at the end of 4800 seconds fire exposure.

Figure 5. Forecast and measured maximum temperature for point TA4, TA5 and TA6 for composite SUC-CSB-A2 model at the end of 4800 seconds fire exposure.

Figure 6. Predicted and measured maximum vertical deformation for point DA3 for composite SUC-CSB-A2 model (fire exposure 4800 seconds); (a) validation process, (b) applying different depth of intumescent coating layer.
Figure 7(a) illustrates the forecast critical temperature distribution of composite SUC-CSB-A2 model which were obtained through ABAQUS software. Figure 7(b) illustrates the forecast critical vertical deflection of composite SUC-CSB-A2 model when bare to 4700 seconds fire exposure. The beam model was fully covered with 5.0 mm thickness of intumescent layer. Detailed summary of the maximum vertical deflection for all intumescent coating thickness is summarizes in Table 2 as referred to Figure 6 (b). However, there are no significant effect on adopting various intumescent layer onto the composite CSB even though the vertical deflection were slightly drop as presented in Table 2. Adopting deeper intumescent layer onto the protected composite CSB model does slightly contribute in predicting critical vertical deflection drop as compared to bare composite CSB model.

![Figure 7(a) Composite SUC-CSB-A2 model at elevated temperature (4800 seconds); (a) forecast critical temperature distribution, (b) forecast predicted vertical deflection (with 5.0 mm intumescent coating thickness).](image)

Table 2. Summary of predicted maximum vertical deflection at point DA3 of composite SUC-CSB-A2 model expose to fire exposure of 4800 seconds.

| Intumescent coating thickness (mm) | Maximum vertical deformation (mm) | Deflection decrease (mm) | Percentage deflection decrease (%) |
|----------------------------------|----------------------------------|--------------------------|-----------------------------------|
| No coating                       | 208.599                          | 0                        | 0                                 |
| 0.1                              | 202.453                          | 6.146                    | 2.946                             |
| 0.3                              | 200.985                          | 7.614                    | 3.65                              |
| 0.5                              | 200.169                          | 8.43                     | 4.041                             |
| 1                                | 200.082                          | 8.517                    | 4.083                             |
| 1.5                              | 199.233                          | 9.366                    | 4.49                              |
| 2                                | 199.098                          | 9.501                    | 4.555                             |
| 5                                | 198.859                          | 9.74                     | 4.67                              |

6. Conclusion

The nonlinear structural behaviour of composite SUC-CSB-A2 model under combined fire load and applied load has been investigated and discussed in this paper. A nonlinear finite element model has been created based on composite SUC-CSB-A2 model and verified with available experiment results. The predicted maximum temperature distribution and mid-span vertical deflection of composite SUC-CSB-A2 model has been well justified with experimental results. From the parametric investigation, employing deeper intumescent layer onto the beam model has significantly decrease the mid-span vertical deflection. It shows that adopting thicker intumescent layer does not make a significant difference in terms of mid-span vertical deflection. Therefore, the techniques of applying intumescent layer protection onto the beam model needs to be change to other techniques. Future research related to partial fire protection techniques needs to be investigated in order to obtain its behaviour when expose to fire and under applied load.
7. References

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