Deformation and Heat Transfer on Three Sides Protected Beams under Fire Accident

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Abstract. Fire accidents are common in oil and gas industry. The application of passive fire protection (PFP) is a costly solution. The PFP is applied only on critical structural members to optimise project cost. In some cases, beams cannot be protected from the top flange in order to accommodate for the placement of pipe supports and grating. It is important to understand the thermal and mechanical response of beam under such condition. This paper discusses the response of steel beam under ISO 834 fire protected, unprotected and three sides protected beams. The model validated against an experimental study. The experimental study has shown good agreement with FE model. The study revealed that the beams protected from three sides heat-up faster compare to fully protected beam showing different temperature gradient. However, the affects load carrying capacity are insignificant under ISO 834 fire.

1. Introduction

Offshore and onshore facilities continuously experience fire accidents [1-4]. In 2015 two major offshore fire accidents were reported after Deepwater Horizon [5]. On 4TH December 2015 at Azeri platform fire accident among 63 workers only 33 were rescued. The rescue operation was affected due to bad weather and the fire continued several weeks [6]. Similarly on 2ND April 2015, PEMEX processing platform blowout followed by fire took four workers’ lives and causes massive structural damage [7]. Fire accidents are common due to various hydrocarbon processes related activities [8]. The necessity to maintain structure stability during fire accident is important to minimise structural damages and live losses during fire accidents. Typically, the structures are required resist fire about one to two hours, for safe evacuation. The Passive fire protection (PFP) is the best most suitable solution to maintain structure integrity during fire accidents without increasing section size and weight [9]. Under hydrocarbon fire structure can collapse within 5 minutes. PFP maintain steel temperature below 400 °C for selected time interval depending on project requirements. The most commonly used PFP is intumescent coating and cementitious.

Intumescent Coating: This type of fireproofing can swell up to 40 times in volume when exposed to fire to maintain integrity. The fire-resistance chemicals swell the PFP exposed to fire due to the exothermic reaction.

Cementitious Coating: This type of material made up of volcano ash (vermiculite), mineral fibre, etc. Typically 40-50 mm thickness enough for 2 hours fire protection. After continuous exposed to fire PFP degrade and heat penetrate into the structural member.
Normally, columns can be protected from all sides, which make them less critical member compared partially protected beams support top slab. In some cases, the PFP application on the top flange of beam cannot be suitable due to pipe supports and grating.

Under normal composite construction steel beam exposed to fire from three sides. The thermal response of fire in composite construction such as convection and radiation effects initiated from the web and bottom flange which is well documented [10, 11]. The top flange hides under a concrete slab, fall ceiling or steel deck, which heated at the end. When the top flange cover during the fire, the temperature of bottom flange and the web have a high-temperature gradient. However, when the bottom flange and the web are protected then the temperature of top flange receive high heat flux. The details of such conditions are not discussed broadly in existing literature and design codes [12, 13].

The objective of this paper is to determine the thermal and mechanical response of steel beam protected from three sides under ISO 834 fire. The model has been validated against experimental study. Later on, the model used to model protected and three sides protected beam to observe the behaviour of a beam under fire.

![Figure 1. Specimen details, location of point load and thermocouple locations [14]](image)

2. Experiment Details

The experiment was conducted by Science Partner SP’s technical research institute of Sweden [14]. The unprotected beam was tested according to EN 1365-3 with the total length of 5400 mm and an effective span length of 5200 mm as shown in Fig 1. The section of HEB 300 was with the grade of S355. Two-point static load was applied on 1400 mm from the support with the intensity of 100 kN each point load. The temperature measured using thermocouple on seven different location and deflection measured at the mid span of the beam [14].

The beam was unprotected and exposed to fire in a horizontal furnace from three sides. The top surface of flange covered with lightweight concrete blocks. The test was conducted according to EN 1365-3 specification under EN 1363-1 standard and ISO 834 fire. In SP’s Round Robin test report, the temperature versus time curves plotted by applying thermocouple at different stations as shown in Fig 2 for about 45 minutes. The experimental data of this study used to validate FE model.

3. Modelling Details

The beams were modelled using Ultimate strength for offshore structure (USFOS) FEM software. The heat transfer analysis performed using FAHTS (Fire and Heat Transfer Stimulation). The boundary conditions of model assumed simply supported beam. Unprotected beam exposed to standard fire ISO 834 using standard mechanical properties of carbon steel such as conduction, specific heat, thermal elongation and stress-strain reduction factor with respect to temperature suggested by EN 1993-1-2. The top surface of flange covered with lightweight concrete blocks therefore in model no heat flux transmitted from top flange. For fully protected beam the effective heat transfer coefficient value “k” in W/m2K used after trial and error analysis to get approximately model temperature 400 °C after 2 hours fire exposure. These k-values applied to three sides protected beam. The bare surface consider from top flange and allowing direct transmission of heat flux to observe temperature gradient with time.
The temperature data in experiment recorded up to 45 minutes. Therefore, modelling duration for unprotected beam limited to 45 minutes. The remaining two cases fully protected and three sided protected beam model for 120 minutes as recommended for the safety standard by EN 1993-1-2 for about 2 hours resistance.

**Figure. 2.** Experimental and FE Modelling results
4. Results and Discussion

4.1. Model Validation

Modelling results such as temperature time curve and failure mode were compared with the test observation at point 1a, 1b, 2, 3a and 3b point [14]. The data for the point 4 and 5 data was not available in the report. The temperature profile of top flange on station 1a and 1b similar with the experimental test, but after 40 minutes, the observed results were slightly underestimated compared to test results as shown in Fig. 2. The behaviour was observed due to neglecting the effects of heat transfer from lightweight concrete blocks in model for simplicity. These concrete blocks resist heating up to first 30 minutes. After absorption the concrete started to transfer heat from hot surface to a cool surface which eventually increased the temperature of the top flange. This may cause the difference of ~100 °C between top and bottom flange as shown in Table 1. Whereas, station point no 2, 3a and 3b showing good agreement with the experimental results due to direct heat transfer from web and bottom flange as shown in Fig 2.

![Figure. 3. Fully protected beam](image)

4.2. Temperature-Time Curve

Fully protected beams has capability to effectively secured mechanical properties of steel for a longer duration under fire. As the temperatures-time curves shown in Fig 3. The temperature of the protected beam observed 400°C after 2-hour. The web of the beam heated slightly faster than top and bottom flange. The web has high surface area and less thickness compared to flanges. As the similar behaviour can be observed in case of the unprotected beam where flange heat up faster compared to the top and bottom flanges as shown in Fig 2. But when a beam protected except from top flange, the temperature of top flange rose significantly with time as observed in Fig 4. After 30 minutes the temperature of three sides protected beam exceeded more than 600°C.
Whereas, in case of the protected beam the temperature of top flange was recorded below 150°C. Approximately, 50% of three-sides protected beam increased more than 500°C in 45 minutes as shown the temperature profile in Table 1. In contrast, fully protected beam tremendously resist temperature and maintain the temperature below 400 °C for a long time as shown in Fig 3.

![Figure 4: Three sides protected beam](image)

**Table 1. Temperature Comparison**

| Protection            | Section | Temperature °C | Failure Time |
|-----------------------|---------|----------------|--------------|
|                       | Top     | 10 min | 20 min | 30 min | 40 min | 45 min |           |
| Experiment (Unprotected) | Flange  | 201    | 440    | 634    | 745    | 770    | 30 minutes |
| Web                   | 395     | 659    | 775    | 838    | 842    |        |            |
| Bot Flange            | 359     | 645    | 769    | 833    | 841    |        |            |
| Unprotected (FE Model) | Top     | 192.5  | 453.3  | 604.2  | 672.9  | 693.5  | 30 minutes |
| Web                   | 420.2   | 713.3  | 798.4  | 868.7  | 886.9  |        |            |
| Bot Flange            | 295.2   | 632.9  | 739.1  | 846.4  | 877.8  |        |            |
| Three Sides Protected (FE Model) | Top     | 173.2  | 421.1  | 624.4  | 731.7  | 746.1  | 115 minutes |
| Web                   | 62.8    | 137.5  | 224.9  | 306.4  | 342.4  |        |            |
| Bot Flange            | 45.5    | 76.3   | 110.4  | 147.4  | 166.6  |        |            |
| Fully Protected (FE Model) | Top     | 45.5   | 75.9   | 107.9  | 140.3  | 156.3  | 120 minutes |
| Web                   | 56.8    | 95.1   | 131.1  | 165.8  | 182.5  |        |            |
| Bot Flange            | 45.5    | 75.9   | 107.9  | 140.3  | 156.3  |        |            |
4.3. Failure Modes

According to codes, mechanical properties are assumed to contribute nothing if the temperature exceeds more than 400 °C [12]. Normally, the elastic modulus of steel affected by 50% as the temperature of steel exceeds more than 500 °C. In this case, the web heated faster than the top and bottom flanges which caused beam section to deform rapidly.

Based on failure criteria described in EN 13501-2, the failure load bearing capacity shall be deemed to have occurred when both of the following criteria have been exceeded.

a) Deflection \( D = \frac{L^2}{400d} \) (mm)

b) Rate of deflection \( \frac{dD}{dt} = \frac{L^2}{9000d} \) (mm/min)

Where, \( L \) is the clear span of the specimen in mm and \( d \) is the distance from the extreme fibre of the cold design compression zone to the extreme fibre of the cold design tension zone of the structural section, in mm [13].

According to limit of section HEB 300 and span 5200 mm the values of the failure load bearing capacity is \( D = 225.33 \) mm and \( \frac{dD}{dt} = 10.02 \) mm/minute.

Unprotected beam has shown deflection more than 225.33 mm after 30 minutes and the deflection rate of 10.02 mm/minute after 27 minutes, which can be observed from Fig 5. FE model deflection mode and experiment have good agreement as shown in Fig. 5. Fully protected beam has shown sufficient strength to resist fire load efficiently more than 2 hours. However, three sides protected beam shown deflection of 225.33 mm after 103 minutes and the deflection rate of 10.02 mm/minute after 115 minutes as shown in Fig 5. Three sides protected beams also shown enough strength to maintain mechanical properties almost 2 hours. However, due to the unprotected surface failure occurred earlier than 2 hours.

![Figure 5. Time-Deflection Curve](image)
5. Conclusion

Following are the conclusions drawn based on the current analysis:

1. The experimental study has shown good agreement with FAHTS-USFOS modelling results, which allows the author to model different cases.

2. Fully protected flanges and web temperature was almost uniform throughout the section. Secondly, fully protected beams have tremendous fire resisting capability. The temperature of web increased rapidly compared to flanges due to small thickness and large surface area of HEB 300 section.

3. Modelling results have shown that 3 sides protected steel gets damaged or unstable quickly compared to a fully protected beam. However, the difference was not significant under ISO 834 fire. Under ordinary fire conditions, the unprotected top flange can be neglected, but under severe conditions such as hydrocarbon fire, the effects should be taken into account to maintain structural integrity.

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| Description       | 30 minutes | 45 minutes |
|-------------------|------------|------------|
| Experimental      |            |            |
| USFOS Model Validation |          |            |
| Full PFP          |            |            |
| Three Sides PFP   |            |            |