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Study on the Application of Passive Fire Protection on FPSO Topside Structures

FPSO Topside 구조의 Passive Fire Protection의 적용에 관한 연구

2013년 8월

서울대학교 대학원
조선해양공학과
Martin Friebe

STUDY ON THE APPLICATION OF PASSIVE FIRE PROTECTION ON FPSO TOPSIDE STRUCTURES

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지도 교수 장 범 선

이 논문을 공학석사 학위논문으로 제출함

2013년 8월

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2013년 8월

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Abstract

Study on the Application of Passive Fire Protection on FPSO Topside Structures

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Fire is a continuous threat to FPSO topside modules as large amounts of oil and gas are passing through the modules. As a conventional measure to mitigate structural failure under fire, passive fire protection is widely used on main structural members. However, wider use of PFP can cause considerable cost for material purchase, installation, inspection and maintenance. The installation time can be a burden since the work should be done nearly the last stage after all equipment and pipes are installed. Thus, the minimal use of PFP can be beneficial to the reduction of construction cost and schedule delay. This paper presents a study of how the minimum passive fire protection for adequate safety can be achieved through a series of thermal elasto-plastic FE analysis. It aims at better understanding of the structural behavior with different PFP applications under plausible fire exposure.

Keywords: Passive fire protection, collapse time, heat transfer analysis, nonlinear FE analysis

Student Number: 2011-21172

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1. Introduction

Fire is a continuous threat to FPSO topside modules as large amounts of oil and gas are passing through the modules. As a conventional measure to mitigate structural failure under fire, passive fire protection is widely used on main structural members. However, wider use of PFP can cause considerable cost for material purchase, installation, inspection and maintenance. The installation time can be a burden since the work should be done nearly the last stage after all equipment and pipes are installed. Thus, the minimal use of PFP can be beneficial to the reduction of construction cost and schedule delay. This paper presents a study of how the minimum passive fire protection for adequate safety can be achieved through a series of thermal elasto-plastic FE analysis. It aims at better understanding of the structural behavior with different PFP applications under plausible fire exposure.
Passive fire protection plays a role in improving fire safety of offshore structure by slowing down heat transfer from fire to structure. However, a wider use of PFP leads to considerable increase in cost for material purchase, installation, inspection and maintenance. It also causes topside weight issues

Thus, there are lots of demands to minimize the use reasonably based on a fire simulation. First, time history of heat flux or temperature under certain fire scenarios are calculated from a CFD based fire simulation. Second, structural behaviors, especially the strength reduction due to the temperature increase, are analyzed through nonlinear FE analysis [4].

The objective of this study is to investigate the effect of different PFP applications to the collapse time aiming at finding a better application pattern to ensure longer collapse time with less application area. In a simple beam model, the use of beam model is validated by comparing the structural behavior under heat load with shell FE model. Then coatback length is investigated by a parametric study.

The finding from this study is applied to a FPSO topside module and how PFP application area and coatback area affects on the collapse behavior is studied in the model. A series of fire simulation are performed for different applications of PFP and the collapse times are compared.

2. State of Art

The local effects of passive fire protections are studied by Amdahl and Holms in 2008 [4]. Christian Anderson suggests and performed a fault tree analysis, a rather statistical approach; however he does not carry out any thermal or structural simulation [1]. Jord Baer performs a thermal stress analysis on a topside module, considering only the effect of PFP, but without considering different PFP layouts, nor the effect of coatback [8]. We can therefore say that the study of the effect of PFP on topside structures has been already studied in recent years; however, the effect of coatback has not been included and examined yet.

3. Object of Passive Fire Protection

3.1. Physical Concepts of Heat Transfer

In heat transfer, heat conduction is the transfer of heat energy by diffusion and collisions of particles within a body due to a temperature gradient. The diffusing and colliding objects transfer disorganized kinetic and potential energy. Conduction can only take place within an object or material, or between two objects that are in direct or indirect contact with each other. Conduction takes place in all forms of matter, such as solids, liquids, gases and plasmas.

Whether by conduction or by thermal radiation, heat spontaneously flows from a body at a higher temperature to a body at a lower temperature. In the absence of external drivers, temperature differences decay over time, and the bodies approach thermal equilibrium.

In conduction, heat flows within and through the body itself. In contrast, in heat transfer by thermal radiation, the transfer is often between bodies. Also possible is transfer of heat by a combination of conduction and thermal radiation. In convection, internal energy is carried between bodies by a material carrier. In solids, conduction is mediated by the combination of vibrations and collisions of molecules, of propagation and collisions of objects, and of diffusion and collisions of free electrons. In gases and liquids, conduction is due to the collisions and diffusion of molecules during their random motion. Photons in this context do not collide with one another, and so heat transport by electromagnetic radiation is conceptually distinct from heat conduction by microscopic diffusion and collisions of material particles and phonons.

In the engineering sciences, heat transfer includes the processes of thermal radiation, convection, and sometimes mass transfer. Usually more than one of these processes occurs in a given situation.

3.2. Passive Fire Protection

Passive fire protection, PFP, is an integral component of structural fire protection and fire safety in a building. PFP attempts to contain fires or slow the spread, through use of fire-resistant walls, floors, and doors or maybe applied as an intumescent on critical structural members.

An intumescent is a substance that swells as a result of heat exposure, thus increasing in volume and decreasing in density. Intumescent are typically used in passive fire protection. These intumescent produce a light char, which is a poor conductor of heat, thus retarding heat transfer. Typically, these materials contain a significant amount of hydrates. As the hydrates are spent, water vapor is released, which has a cooling effect. Once the water is spent, the insulation characteristics of the char that remains can slow down heat transfer from the exposed side to the unexposed side of an assembly. Soft char producers are typically used in thin film intumescent for fireproofing structural steel as well as in fire-stop pillows [10]. In the following Figure 3-1, the thermal conductivity values of an intumescent are shown. The PFP material is rated as H-30 and should therefore maintain its integrity for 30 minutes and the insulation criteria for a period of 30 minutes under the presence of a hydrocarbon fire. The figure clearly shows, that with increasing temperature, the conductivity will decrease and therefore protect the structure from excessive heating [9].

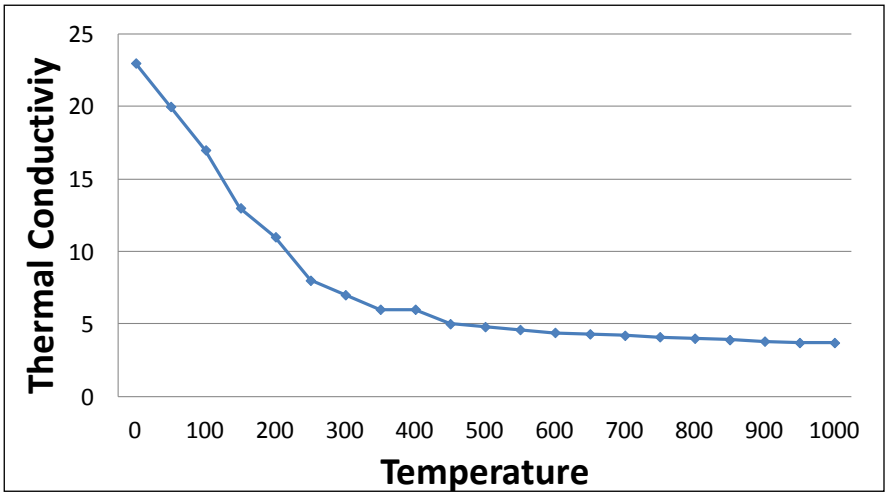


Figure 3-1 Thermal conductivity of PFP versus Temperature

It is assumed that the steel temperature for unprotected member would not exceed 400C. In cases where this is not possible, passive fire protection PFP needs to be considered. The material yield strength and Young's modulus are reduced as per temperature increase ac-cording to EN 1993-1-2 [6]. Below a steel temperature of 400C, degradation of the material properties is clearly negligible.

Local fracture and collapse is acceptable as long as escalation of the event to another fire area or impairment of the main safety function from other fire areas is avoided. The check for the structural integrity is done by checking the plastic utilization factor and the axial stresses in each element.

3.3. Critical Elements

Elements of structural relevance or liquid holding pipelines of defined segments shall be protected by fire class insulation to prevent hazard escalating. In this study the critical elements are the module support columns, which are the load members; and also the load carrying girders.

3.4. Structural integrity

The PFP analysis is divided into two parts roughly. In the first part, the heat flux and the resulting temperature under certain fire scenarios are investigated for each structural member.

The second part then, USFOS utilizes the resulting temperature output by FAHTS in order to analyze and estimate the structural behavior due to performance reduction as per the temperature increase.

It is assumed that the steel temperature for unprotected member would not exceed 400C. In cases where this is not possible, passive fire protection PFP needs to be considered. The material yield strength and Young's modulus are reduced as per temperature increase according to EN 1993-1-2 [6]. Below a steel temperature of 400C, degradation of the material properties is clearly negligible.

Local fracture and collapse is acceptable as long as escalation of the event to another fire area or impairment of the main safety function from other fire areas is avoided. The check for the structural integrity is done by checking the plastic utilization factor and the axial stresses in each element [2].

4. Software

4.1. Thermal Response Methodology with FATHS

The thermal response analysis are performed using the finite element tool FAHTS, where detailed ray tracing gives the heat flux at the individual structural component surfaces as shown in Figure 4-1. The thermal model is automatically transferred to surface beam and shell elements in order to receive the correct heat flux and thermal gradients over the cross section, caused by uneven fire exposure and/or partly protected members, see Figure 4-2. The heat exposure, radiation heat flux and convective heat flux, is varying from point on the structure depending on the actual points coordinates and surface orientation, e.g. if the surface is facing against or away from the fire, etc.

Different surfaces receive individual heat flux, and for the column, only outer side will experience the fire.

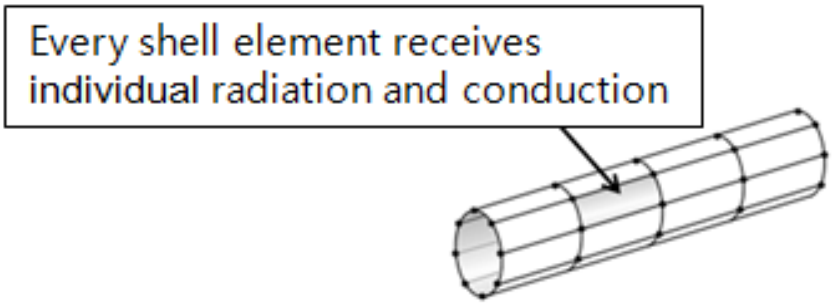


Figure 4-1: Heat flux input to the finite element model

Radiation between the inner surfaces will transfer heat from the most exposed side to colder parts, see following Figure 4-2. Heat fluxes consider radiation and conduction where latter one has less importance due to its slow process.

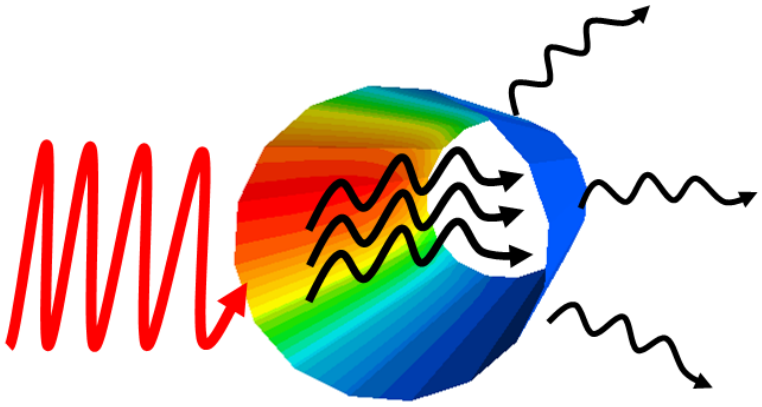


Figure 4-2 Internal Radiation inside a pipe

4.2. Mechanical Response Methodology with FATHS

The mechanical response analysis are performed using the nonlinear FEM program USFOS. The program includes nonlinear geometry effect, material yielding and thermal effect such as expansion, yield stress and Young's modulus degradation. USFOS calculates instability of individual components as well as system collapse. Heat exposures on different components are exported from FAHTS to USFOS automatically [3]. The analysis procedures are as follows. First the mechanical loads are applied in a static analysis during the first time step, from there then the obtained temperature history is applied on each time step, which was obtained by FAHTS earlier.

The structure is then analyzed by USFOS, which does the collapse analysis and accepts the structure only if the global stability is preserved at all stage of the temperature history and the deformation should not lead to escalations or extreme deformations.

USFOS calculates the plastic utilization factor. Suppose a beam as in Figure 4-3 is given. For large bending moments, the beam will undergo plastic deformation. Let *M* be the bending moment at a given location on the axis of abeam with a rectangular cross section. When is *M* sufficiently large, the magnitude of the normal stresses at the top and bottom of the cross section are equal to the yield stress. But, the magnitude of the normal stress cannot exceed the yield stress σ, so therefore the area which is plastic will grow and the elastic area will shrink. The ratio of the plastic area divided by the total cross section area is called the *plastic utilization*.

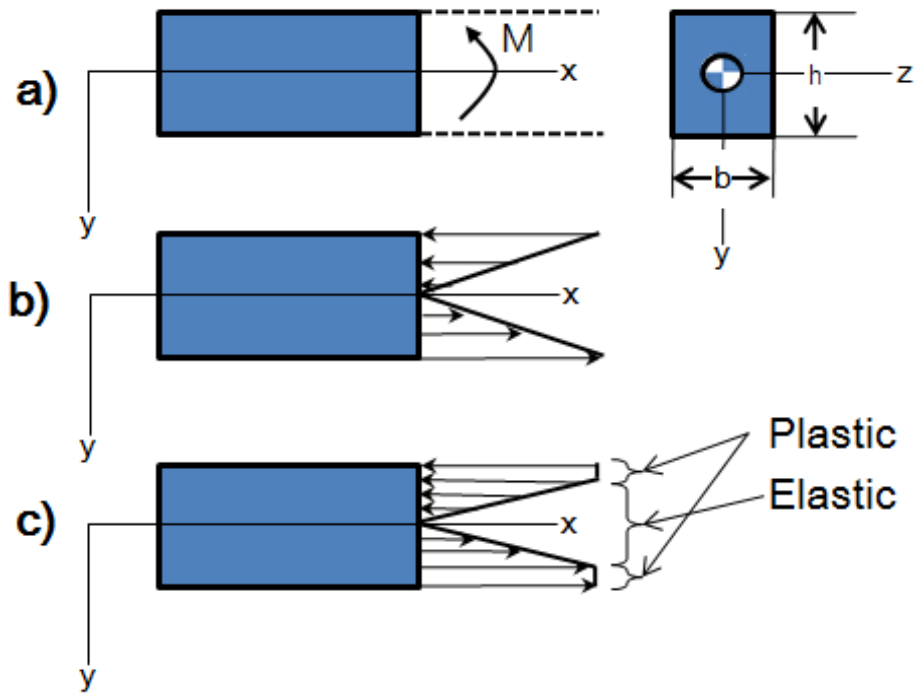


Figure 4-3: Plastic Utilization

4.3. Generation of Fire Scenarios using FATHS

For the fire scenario a Hydrocarbon fire behavior is chosen, modeled

as a ball fire constant ball fire, with a constant heat flux over time. The software commands of FAHTS follow the NPD and ISO-348 regulation, which state the following: “Heat fluxes of Hydrocarbon fires reach up to 250kW/m^2 for fuel controlled fires and up to 170kW/m^2 for ventilation controlled fires [5].”

The hydrocarbon fire, as a command input in FAHTS, is by default defined to follow the “heating curve” of the ISO-348, which assumes a constant heat flux of 200kW/m^2. The average temperature is given by ISO-834, which develops according to the following relationship:

$$T=345\log_{10}(8t + 1) + 20$$

Where
T is the average furnace temperature, in Celsius
t is the time, in minutes

The initial temperature is T=20 at t=0, and the temperature increases as time increases. The heat source is a constant ball fire with a heat flux of 200kW/m^2 from inside to outside. Inside the fire ball, the heat flux develops according to the heating curve, or for simplification a constant heat flux value of 200kW/m^2 can be assumed. The heat flux inside the radius of 5m is constant, as recommended by the NPD and the ISO-348 for small ball fires and pool fires [5].

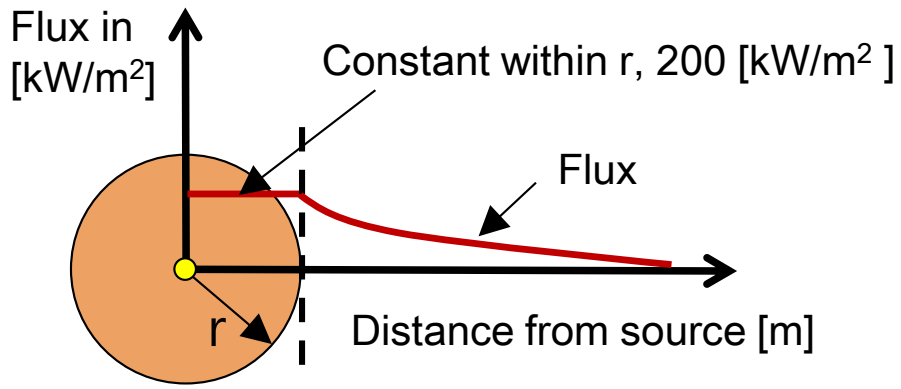


Figure 4-4 Fire Scenario Input

5. Study on the effect of coatback

5.1. General

When unprotected steel is attached to structural steel with PFP applied, it has been normal to protect also the secondary, attached steel a certain length, the so called “Coatback distance”. The reason for the protection of the attached member is the possibility for “heat leakage” from the hot unprotected member to the protected member. The main reason for using Coatback is to avoid deformations for example through uneven heating could lead to curvature and deformations. In Figure 6 an example on typical secondary steel-main steel connection is shown.

An important objective of the design is to avoid buckling of columns, i.e. ensure that column forces remain axial. To increase the safety margins in the systems, PFP Coatback shall be applied to attachments to the mid-section of PFP protected columns.

Conventionally, 450mm of Coatback has been used. Based on the limitation of dimensioning fire scenarios to durations under 1 hour and based on thermal response modeling, 450 mm will be used for Coatback of these attachments in order to ensure adequate safety. Note also that there are a very limited number of such attachments and the extensive application of coatback can be very costly.

Two different cases are simulated in the following, which are then discussed on which result will be then implemented into the simulation of the topside structure. The first study shows the correlation between shell and beam element models. Next the effect of the coatback length is discussed.

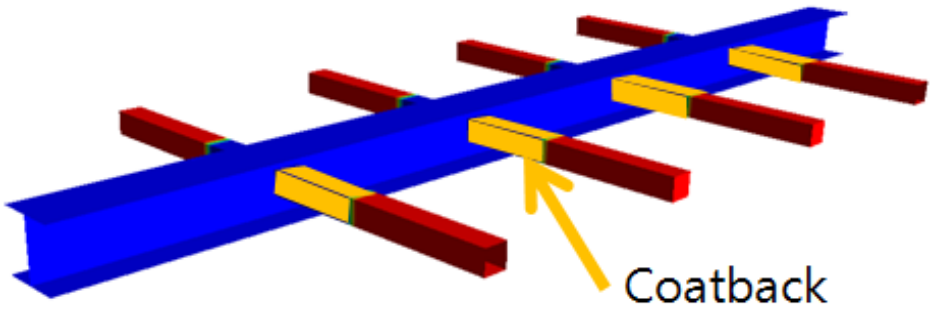


Figure 5-1 Location of coatback

5.2. Model and heat load

The first part of this study is a simulation of a simplified beam. The beam is modeled as shown in Figure 5-2. The total length of the

structure is 5m and its profile can be seen from the Figure respectively. The load applied on the beam is a uniform load of 30kN/m over the whole structure. Four stiffeners are attached on each side of the beam and have a profile as shown in Figure 5-2.

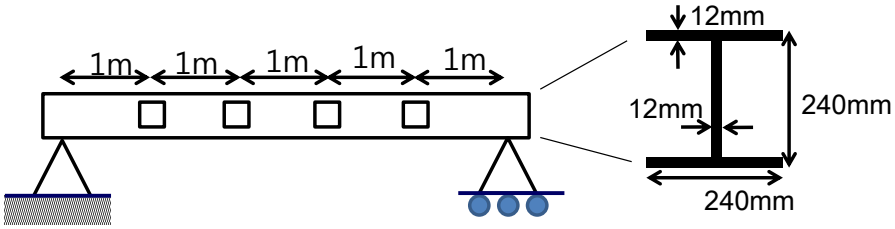


Figure 5-2 Model dimensions

The fire scenario is a constant heat flux of 200kW/m^2, which fully surrounds the structure as shown in Figure 5-3. The fire has a duration of 60 minutes and the point being measured is at the attachment of the stiffeners.

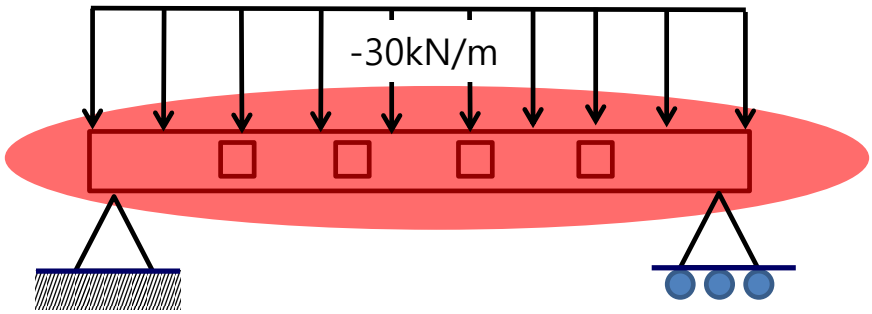


Figure 5-3 Applied loads and location of fire

5.2.1. Case Study I - Shell vs. beam element model

The first simulation compares the result of the shell and beam elements. It is well known that shell elements give more exact results, but therefore take more time for computation. Therefore the model from Figure 5-2 once modeled by beams and once by shell elements is compared. Both ends are clamped and a uniform load of 30kN/m is applied over the whole structure.

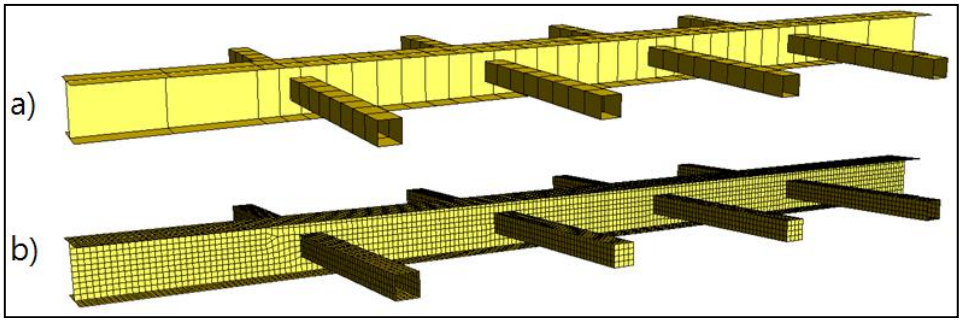


Figure 5-4 Beam modeled with beam (a) and with shell elements (b)

The vertical deflection in the middle of the beam is examined and plot versus time. Two different cases for each the beam and shell element are studied. The first case is the vertical deflection with coatback and the second one without coatback.

The result clearly shows in Figure 5-6 that the deflection in the case with coatback converges at around 0.1m. In the case of no coatback, the deflection reaches 0.09m after about 25 minutes for shell elements and 0.11m for beam elements. The deflection history of the beam, which is modeled without coatback behaves similar. The shell element type, converges to 0.18m and to 0.2m for beam element type as depicted in Figure 5-5. Then the structure very quickly loses its stiffness after 20 minutes and it collapses at around 35 minutes for both, beam and shell element type. From this result it is assumed that beam elements and shell elements give the almost identical result and for saving the computational time, only the beam elements on the topside structure are used.

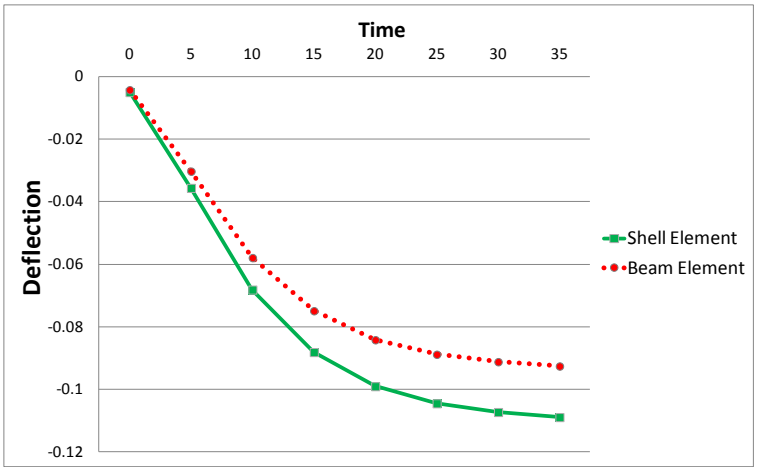


Figure 5-5 Deflection of beam with coatback

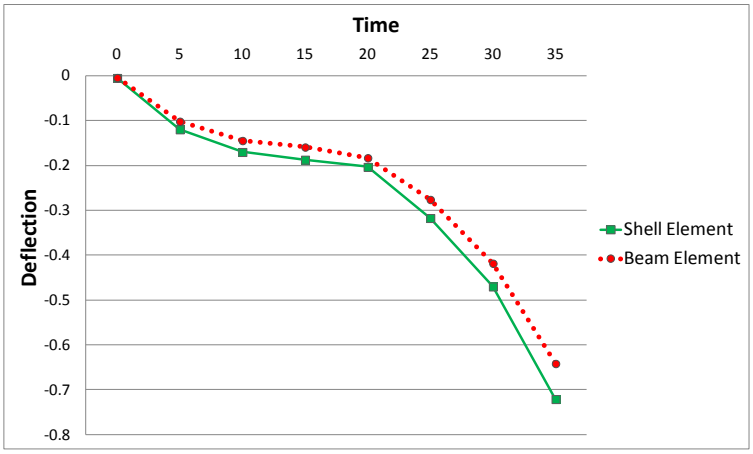


Figure 5-6 Deflection of beam without coatback

Figure 5-7 depicts the temperature level in the system after 1 hour fire exposure for different Coatback length, 0mm vs. 450 mm.

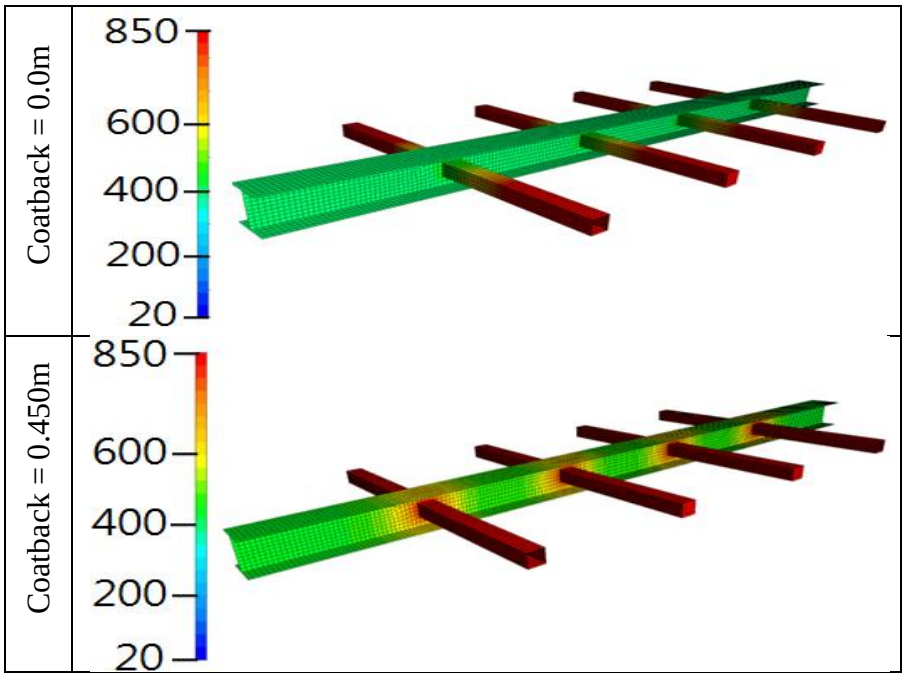


Figure 5-7 Temperature development for different Coatback lengths

5.2.2. Case study II - length of Coatback

This case study also uses the same beam model as shown in the previous section, also the fire scenario follows the constant heat flux, which surrounds the entire structure. The feature of this study is that the effect of coatback with varying coatback lengths is examined.

The location at, where the temperature is measured is the point, where the stiffeners are attached to the beam. As can be seen in Figure 5-7, the temperature increases less with longer coatback length. The effect of the coatback on the temperature becomes insensitive as the coatback length increases to over 30~35cm, and becomes negligibly small after 45cm. But with increasing coatback length, the collapse time which can be saved gets shorter.

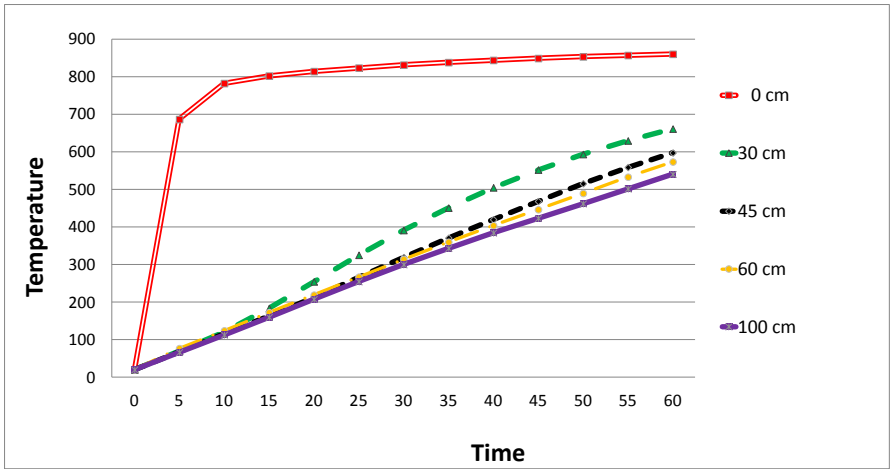


Figure 5-8 Temperature increment with varying coatback length

In Figure 5-8 the deflection with respect to time is shown. It is clearly to see that the deflection varies with time quite significantly. In case of a coating of 100cm, the structure converges to a deflection of 0.1m, but if the coating is reduced to 45cm, the structure loses its stiffness very rapidly at around 27min., with 30cm, at around 23min. and with 0 cm, at around 21min. respectively. With increasing coatback length the coatback effect gets smaller and smaller.

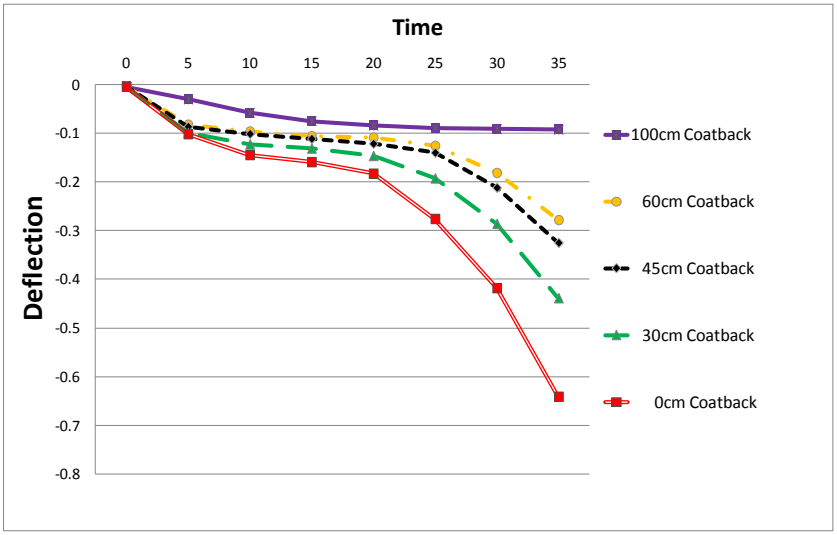


Figure 5-9 Deflection of beam with varying coatback length

5.2.3. Case study III - Coatback with respect to loads

In study 5.2.3, the same beam as in previous case studies is examined, modeled with beam elements and the load as follows is varied respectively from 15.0kN/m, 22.5kN/m, 30.0kN/m and 37.5kN/m. The fire scenario is a constant heat flux of 200kW/m^2 and surrounds the structure entirely. The deflection in behaves respectively to the Figure shown in 5-10. It clearly shows that an increasing load reduces the collapse time. Members with higher loads therefore need to be protected adequately. This result is utilized in the case study of the topside module.

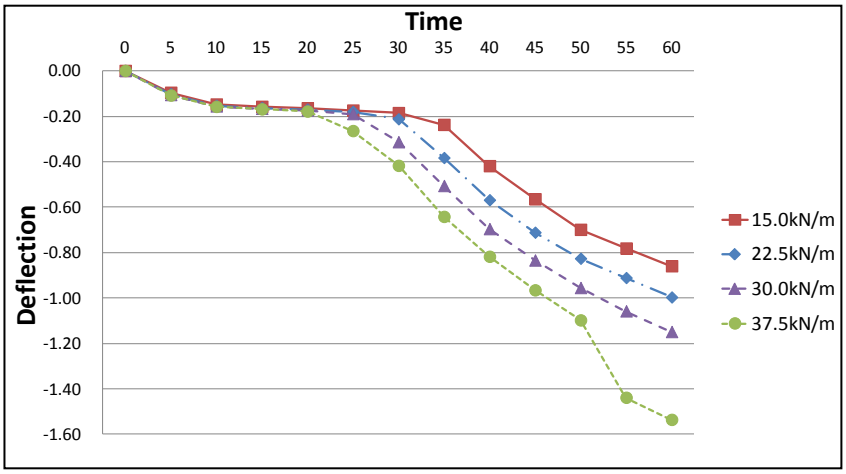


Figure 5-10 Deflection with varying loadfactors

5.3. Discussion

Concluding it can be said that the simulation with beam elements is - sufficient and does not need to be done with shell elements. Therefore modeling and computational time can be saved and still it is possible to obtain the results of nearly the same accuracy.

Also, the historical application of 45cm of coatback length seems to be sufficient and does not need to be extended. Also, structural elements undergoing high loads need to be PFP protected in order to maintain high collapse times.

6. Topside Module Study

6.1. Introduction

A floating production, storage and offloading unit, or short FPSO, is a floating vessel used by the offshore oil and gas industry for the processing of hydrocarbons and for storage of oil. An FPSO vessel is designed to receive hydrocarbons produced from nearby platforms or subsea template, process them, and store oil until it can be offloaded onto a tanker. As many fire hazards on the FPSO are present, the best way to protect the topside modules must be studied carefully. The usage of PFP plays an important role, but the extensive usage may impact negatively the safety cost.

In this chapter, an FPSO topside module is used for the study on the influence of different application of PFP and coatback. From the above results, beam elements are used for modeling and 45 cm of coatback is adopted

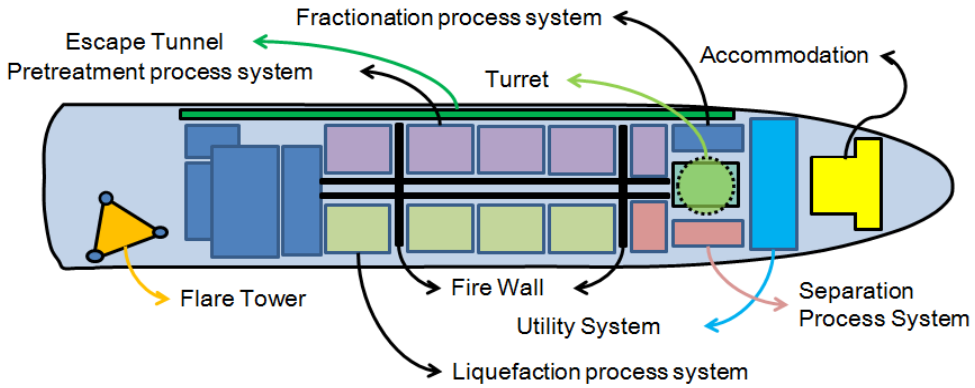


Figure 6-1 FPSO layout

6.2. Model description

Primary equipments are in the followings and the layout is presented in Figure 6-2.

Upper deck

- Wash Water Feed Pump (×5)
- Scavenger Buffer Drum
- Injection skid (×2)

- Wash Water Cartridge Filter

Mezzanine deck

- H_2S Absorber

Process deck

- 1st Stage Separator (x2)

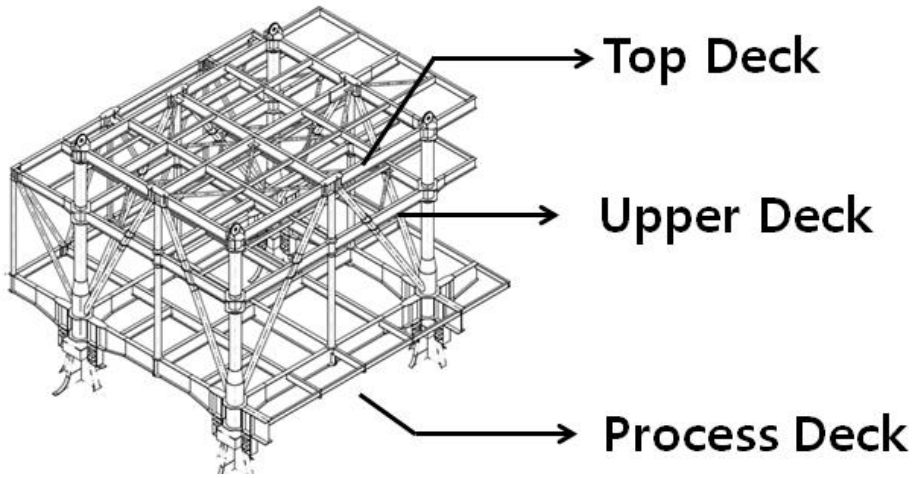


Figure 6-2 Layout of the module

In the following properties of the surrounding air is given. These values are the average properties of air at 20°C.

Air	Density	1,273kg/m^3
	Heat Capacity	1,000K/kgC
	Conductivity	0,024W/mC

Table 6-1 Thermal properties of air

6.3. Fire Scenario

The fire scenario is a constant fire at six different locations over 60 minutes. The heat flux has been considered as constant of about

200kW/m^2 and is applied as a ball fire. No fire mitigation system has been applied. The six different fire locations are shown in Figure 6-3.

The thermal loads are taken as to be constant and modeled by FAHTS. The detailed temperature development is calculated and imported directly into USFOS where the mechanical response analysis is conducted.

Due to the symmetry of the structure, only three out of nine possible cases for each deck are chosen. The three different fire locations on each the top deck and three on the upper deck are chosen according to following criteria. The fire location one is close to the vertical member, which carries the load downward. The location three is in between two columns effects to columns at the same time. Location five is in the middle of the module and affects mostly the horizontal members and all the stiffeners.

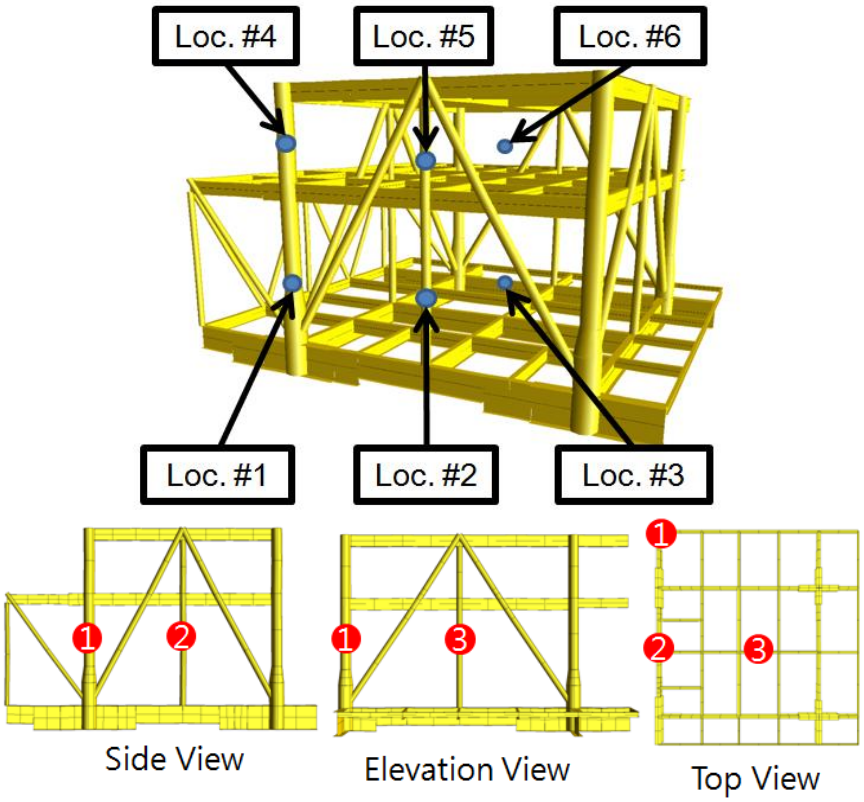


Figure 6-3 Ball fire locations

6.4. Loads and Boundary Conditions

Vertical Acceleration is set to normal gravity load, i.e. 9.81m/s^2. To ensure that the structure is not critically sensitive to lateral load, the supports are restrained as described in Figure 6-4. All supports are free to rotate [8].

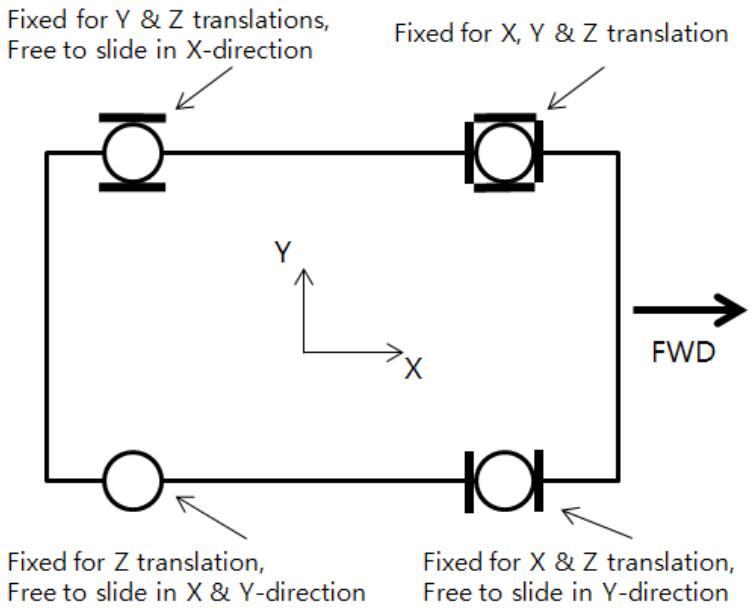


Figure 6-4 Boundary Condition at module supports

The precise load distributions such as equipment loads, piping loads and etc. are taken from the topside layout. Figure 6-6 to 6-8 depicts wet weight in *ton* and locations of equipment for each deck and input into USFOS.

Figure 6-5 Equipment loads on Process Deck

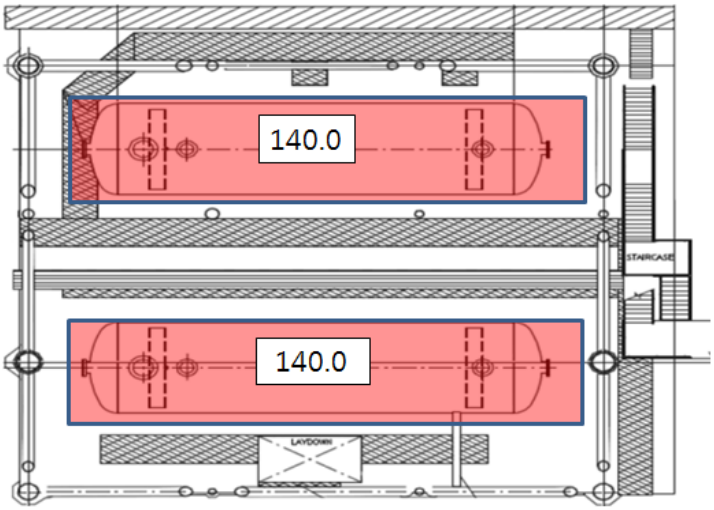


Figure 6-6 Equipment loads on Upper Deck

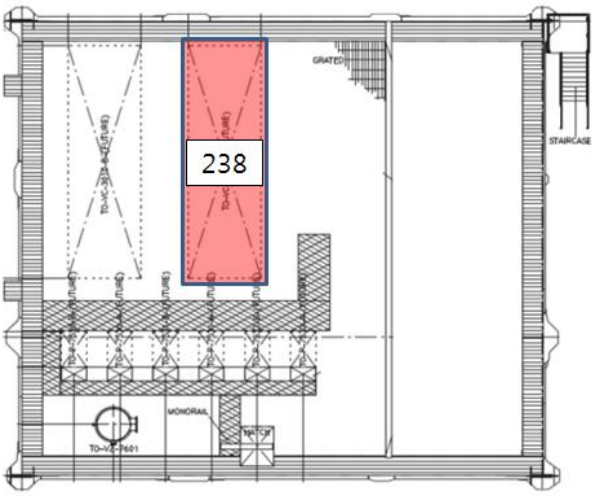


Figure 6-7 Equipment loads on Top Deck

Mechanical loads are applied in Figure 6-8 as beam loads ranging from 1,200N/m to 4,000N/m on the Top deck. Also the self-weight of the structure and equipment are considered and applied on beams. Additionally 0.2g of vertical acceleration is considered and applied on the structure.

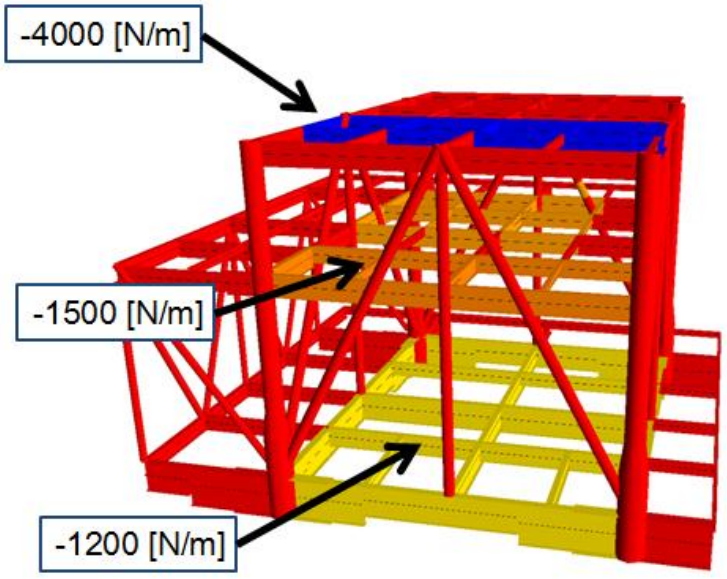


Figure 6-8 Applied beam loads on module

6.5. PFP Extent

PFP is applied to preserve adequate strength of module structure under fire. Possible variations in the fire loads are also taken into account. Total six cases are defined as follows and Figure 6-9 and 6-10 depict how PFP are differently applied. Case V focuses on the effect of coatback. Case IV limits the coatback area to secondary members connecting to the area which equipment load is applied to. Case VII uses full coat back for secondary members connected to primary member which are partially protected in Case V

Case I:	No PFP
Case II:	PFP on vertical primary members
Case III:	PFF on horizontal primary members without coatback
Case IV:	Full PFP
Case V:	PFF on horizontal primary members with coatback
Case VI:	PFF on horizontal primary members with reduced coatback
Case VII:	PFF on horizontal primary members with full coat back
Case VIII:	PFP protection around load concentration

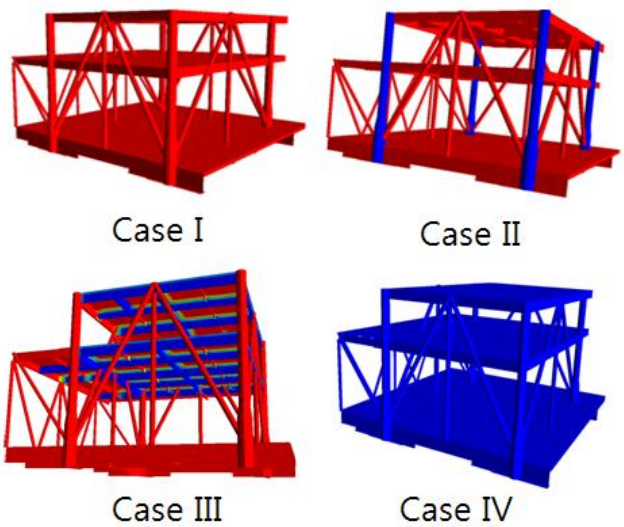


Figure 6-9 Variable PFP patterns

Figure 6-10 Variable PFP patterns

7. Results

7.1. Structural Integrity – First Set

Figure 7-1 summarizes collapse time for eight cases for each fire location. Figure 7-3 shows plasticity distribution and the resulting structural consequences at the moment of collapse in case of no PFP. During the fires some part of structure reaches plastic utilization of 1.0, full plastic condition, but, the deformation of module does not seem striking for structure integrity. On the whole, it can be seen that the fire at location # 3 is the most critical to the collapse time.

The shortest collapse time is achieved by not applying PFP in Case I, which is also reflected by the highest plastic utilization compared to any other case. The longest duration of the structure is achieved by fully applying PFP on the entire structure as shown in Case IV. It drastically increases the collapse time to more than two hours and it also prevents all members from becoming plastic. However, full PFP is not a practical solution since the cost for the PFP is too high. When applying the PFP on the vertical members Case II, the collapse time rises significantly for fire location # 1 and # 2 by preventing the primary vertical members from high plastic utilization. The required collapse time of at least 30 minutes is not satisfied. However, its effect becomes weaker for fire location # 3 since the main fire damage happens at horizontal members and the collapse initiates from those members. Whereas applying the horizontal PFP as in Case III leads to substantial increase of collapse time for location #2, however, relatively small change for location #1 and #3.

The use of coatback Case V on all secondary members connected to the primary members has a considerable influence on collapse time as identified in Figure 7-1. When the coatback is limited to the members connected to the load as depicted in Case VI, the reduction of collapse time is negligible. It is because the plasticity near the load area is larger than any other area and the application of coatback is more effective to other area. Therefore, a selective application of coatback is an efficient way to save PFP coating while not deteriorating structural strength significantly. Case VII however does not improve the collapse time of the structure, even considerably more PFP is used. It is because structural collapse initiates from the failure of main members not from secondary members. The coat back on the secondary members delays the failure of the secondary members, but its effect on the entire

collapse is ignorable. It has influence on the temperature increase of primary members, however, its effect becomes dull as it goes beyond 450 mm proved in the previous case study

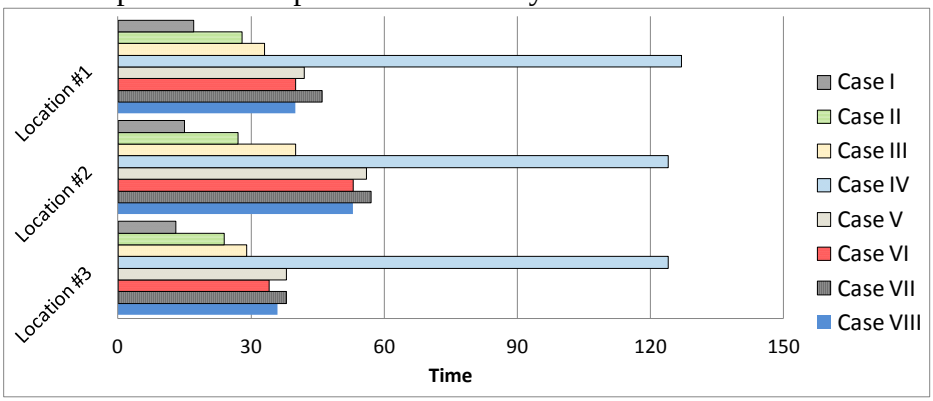


Figure 7-1 Comparison of collapse time for different PFP

The following Figure 7-2 shows the averaged collapse time for each PFP pattern and the according percentage of PFP usage. As a reference line, the case I and case IV are chosen, which are no PFP and full PFP respectively. The higher the vertical distance of the points to the efficiency curve, the higher is also the efficiency of the PFP. It can be seen, that for example case III and case VI use almost the same amount of PFP, but the collapse time of case VI is significantly higher. Also interesting to note is that case VI, VI and VIII achieve almost the same length of collapse time, but with case VIII having a higher efficiency than VI and VIII.

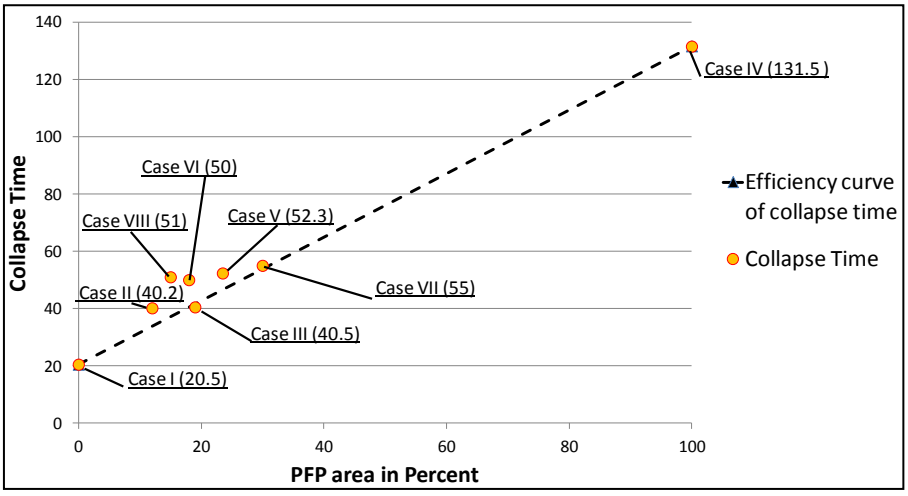
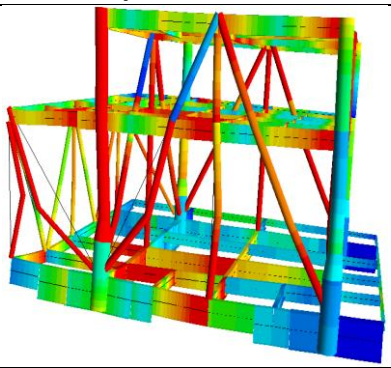
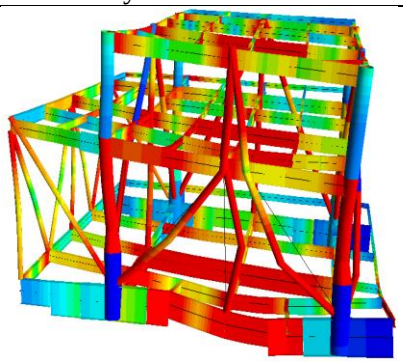
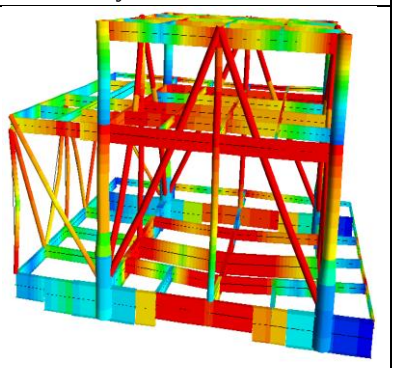
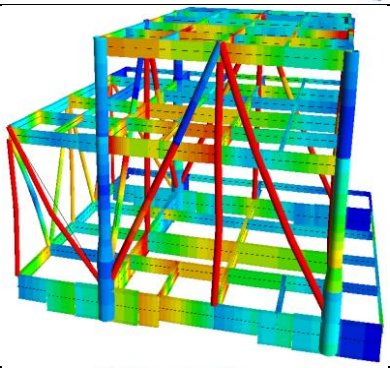
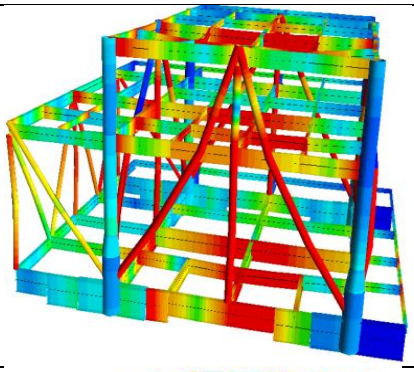
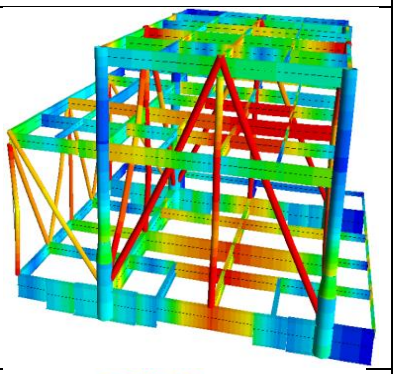
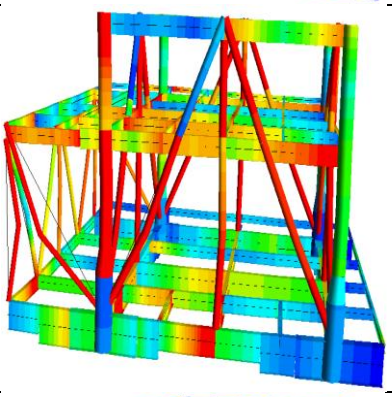
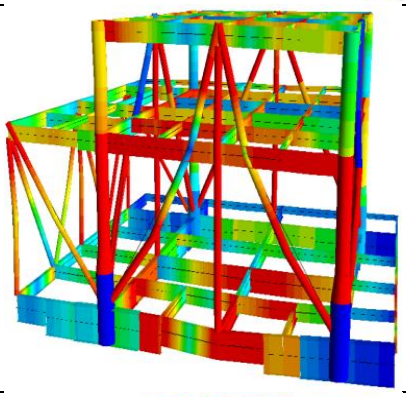
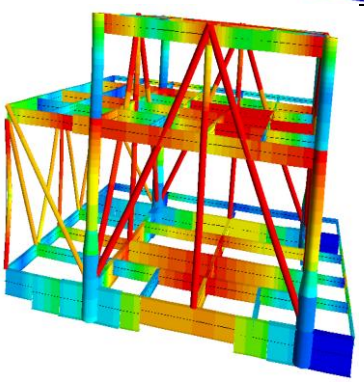
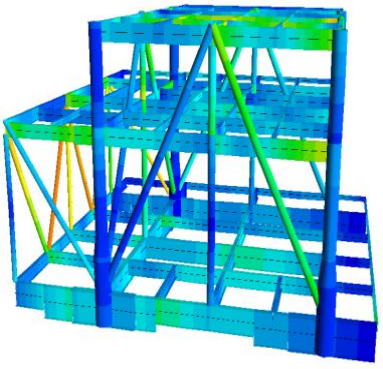
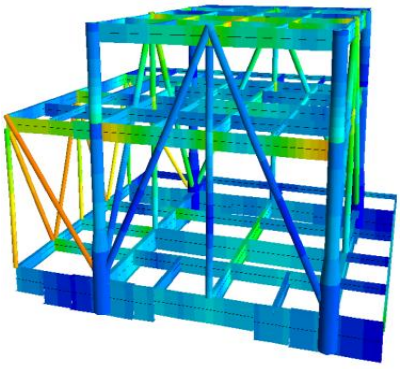
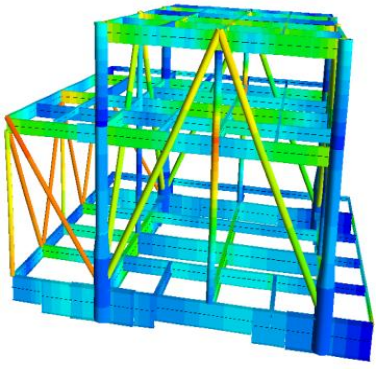


Figure 7-2 Amount of used PFP versus achieved collapse time

	Location #1 Plasticity distribution at 17min.	Location #2 Plasticity distribution at 15 min.	Location #3 Plasticity distribution at 13 min.
Case I			
Case II			
Case III			
Case IV			

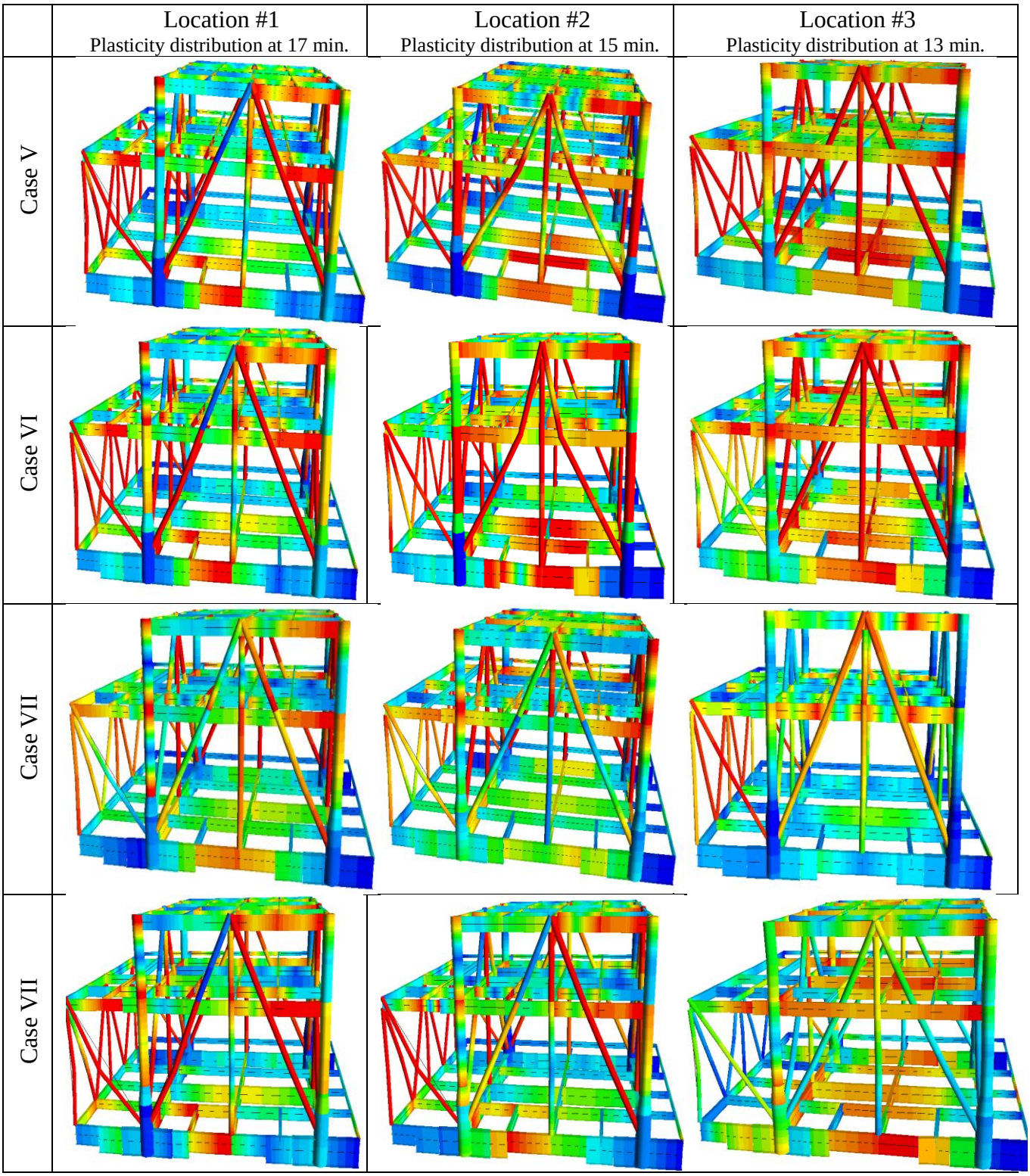
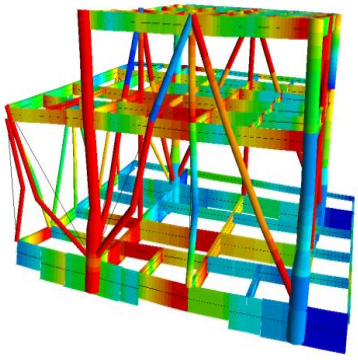
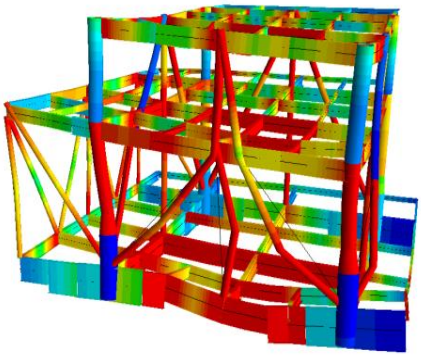
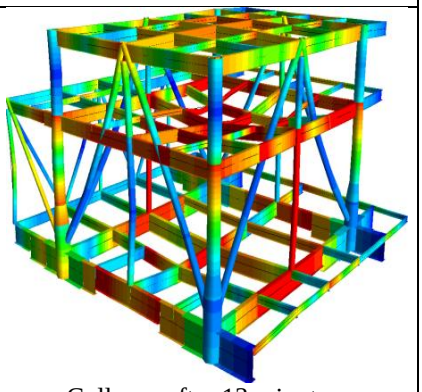
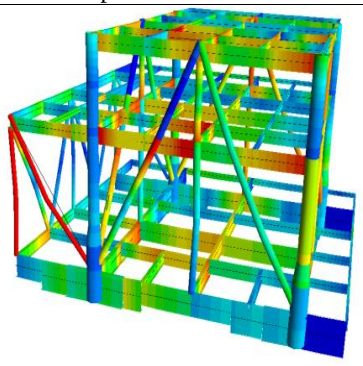
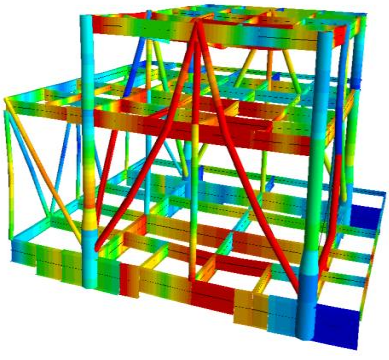
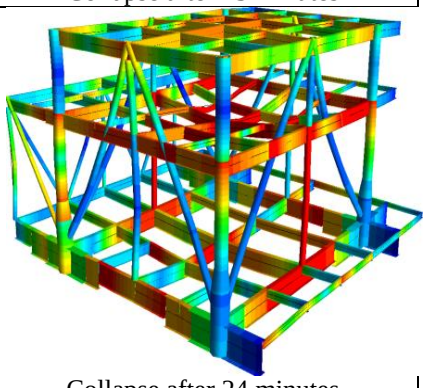
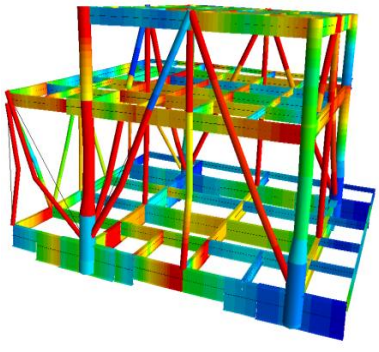
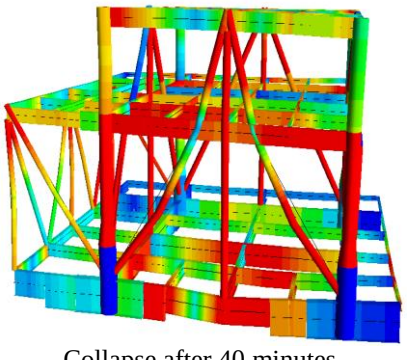
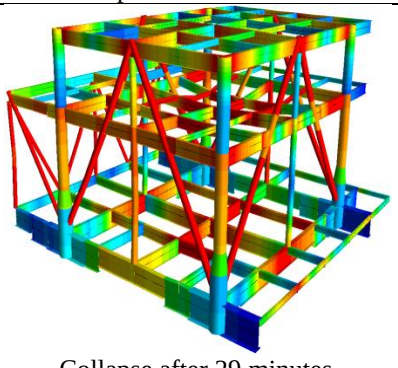
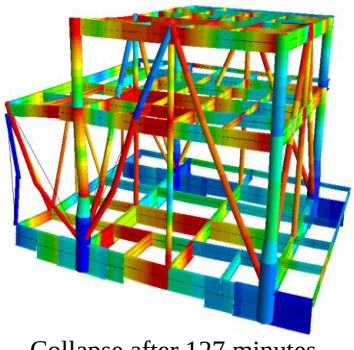
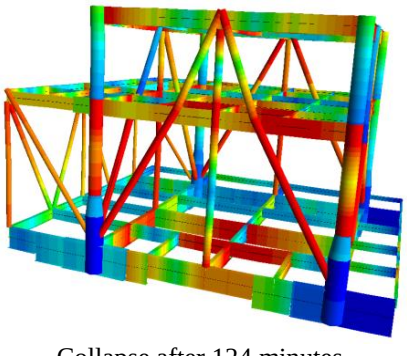
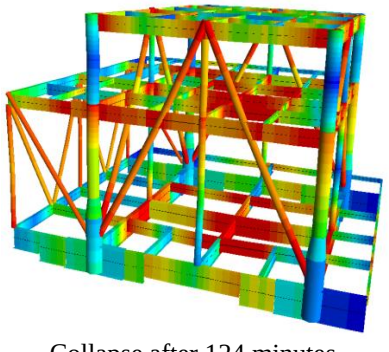


Figure 7-3 Comparison of plasticity distribution of all cases at the time of Case I's collapse

Approximate effect of the PFP reduction and Failure Mode

In Figure 7-4, the effect of coatback on the topside module is depicted at the moment of collapse time. Comparing Case I and Case II, it can be clearly seen that the module without any PFP has many areas and members with high plastic utilization, whereas in Case II, where PFP is applied on the primary vertical members, the plastic utilization is drastically reduced, especially around the areas where it is applied to. Comparing now Case II with Case III, it is clearly to see that PFP on the vertical primary members has a significant effect on them, whereas in Case III we can see a higher plastic utilization at the primary vertical member. For the case V to VII it is actually difficult to identify the significant differences, however, it can be easily seen that the horizontal PFP layout has a large effect on the plastic utilization for fire location 3.

	Location #1	Location #2	Location #3
Case I	 Collapse after 17 minutes	 Collapse after 15 minutes	 Collapse after 13 minutes
Case II	 Collapse after 28 minutes	 Collapse after 27 minutes	 Collapse after 24 minutes
Case III	 Collapse after 33 minutes	 Collapse after 40 minutes	 Collapse after 29 minutes
Case IV	 Collapse after 127 minutes	 Collapse after 124 minutes	 Collapse after 124 minutes

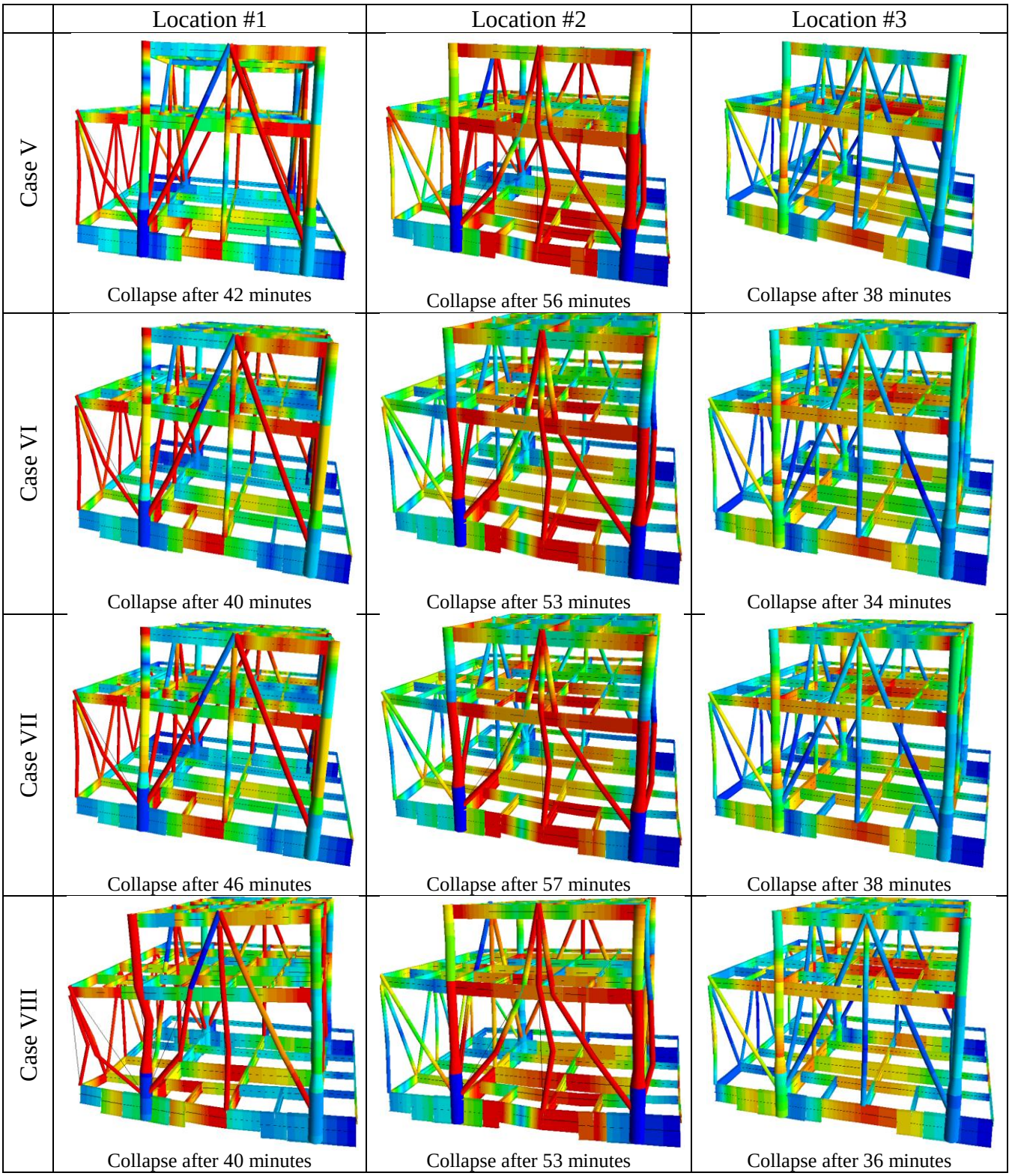


Figure 7-4 Comparison of plasticity distribution when each case collapses

7.2. Structural Integrity – Second Set

The figure 7-5 summarizes collapse time for eight cases for each fire location. Figure 7-6 shows the plasticity distribution and the resulting structural consequences at the moment of collapse in case of no PFP. During the fires some part of structure reaches plastic utilization of 1.0, full plastic condition, but, the deformation of module does not seem striking for structure integrity. On the whole, it can be seen that the fire at location # 6 is the most critical to the collapse time.

The overall tendency between the eight cases is nearly the same as of that one in the first set. However, the collapse time increased on the whole is generally higher. The shortest collapse time is achieved by not applying PFP in Case I, which is also reflected by the highest plastic utilization compared to any other case. The longest duration of the structure is achieved by fully applying PFP on the entire structure as shown in Case IV. It drastically increases the collapse time to more than two hours and it also prevents all members from becoming plastic. However, full PFP is not a practical solution since the cost for the PFP is too high. When applying the PFP on the vertical members Case II, the collapse time rises significantly for fire location # 5 and # 6 by preventing the primary vertical members from high plastic utilization. The required collapse time of at least 30 minutes is satisfied for all cases. Whereas applying the horizontal PFP as in Case III leads to substantial increase of collapse time for locations #4 and #6, however, relatively small change for location #5.

The use of coatback Case V on all secondary members connected to the primary members has a considerable influence on collapse time as identified in Figure 7-5. When the coatback is limited to the members connected to the load, the reduction of collapse time is negligible. It is because the plasticity near the load area is larger than any other area and the application of coatback is more effective to other area. Therefore, a selective application of coatback is an efficient way to save PFP coating while not deteriorating structural strength significantly. Case VII however does not improve the collapse time of the structure, even considerably more PFP is used. This can be explained by the previous case study, which showed that coatback length of more than 450mm have almost no effect on the structure.

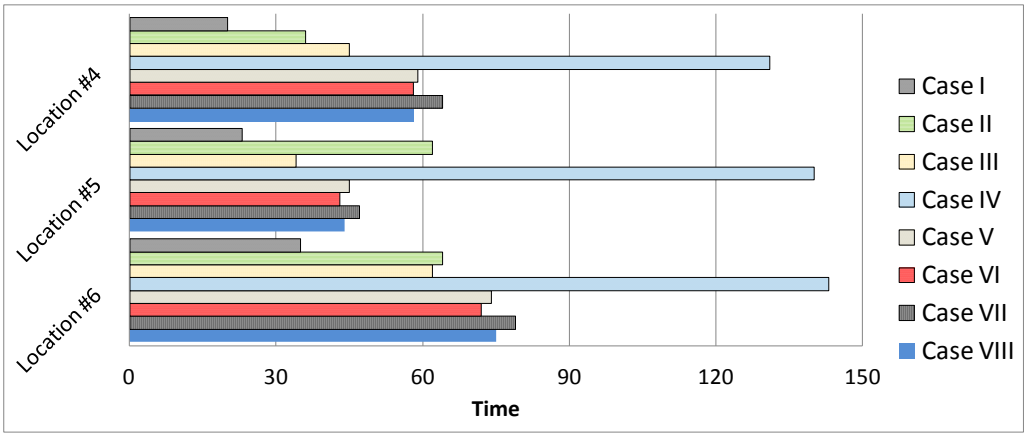
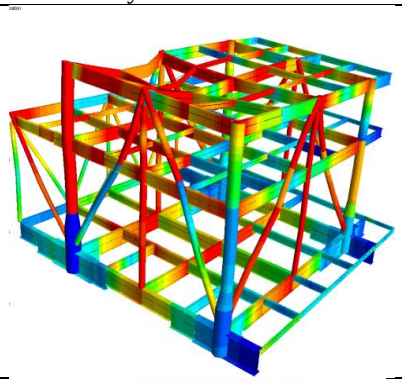
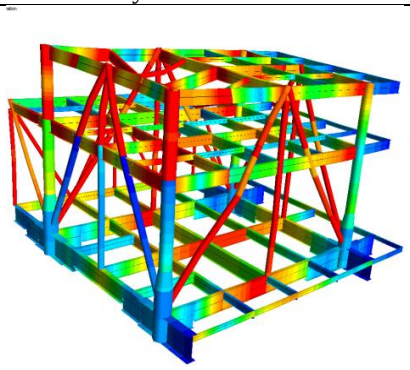
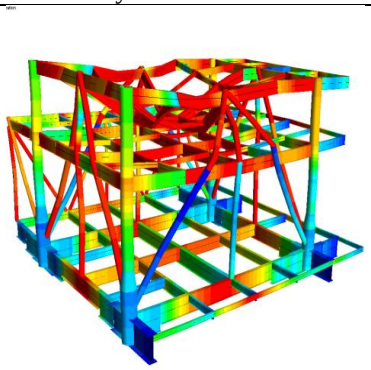
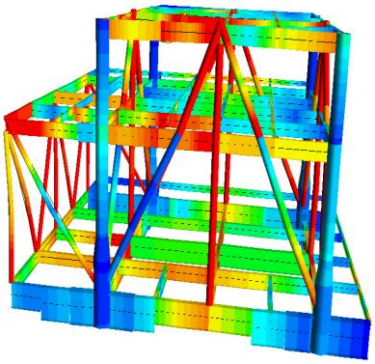
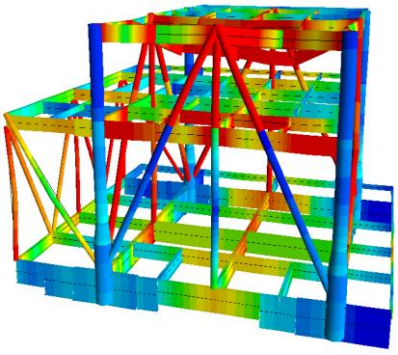
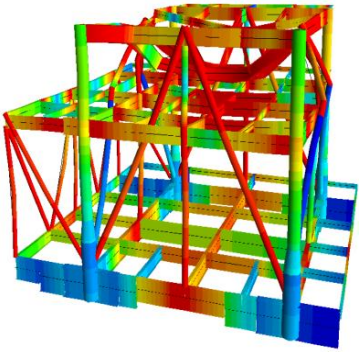
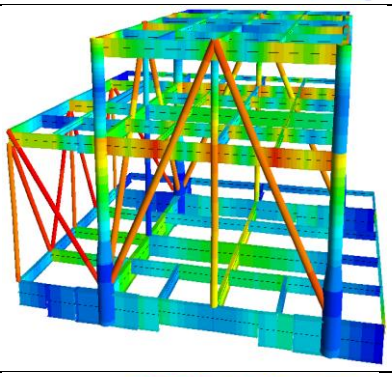
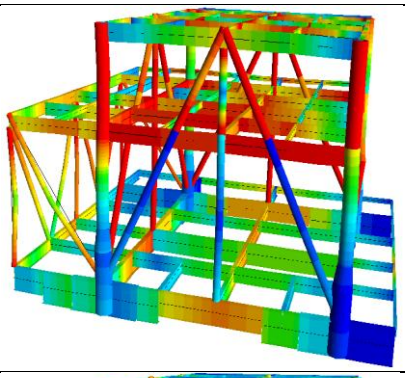
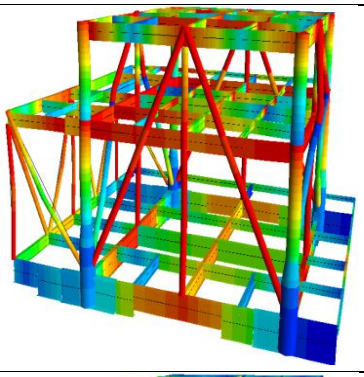
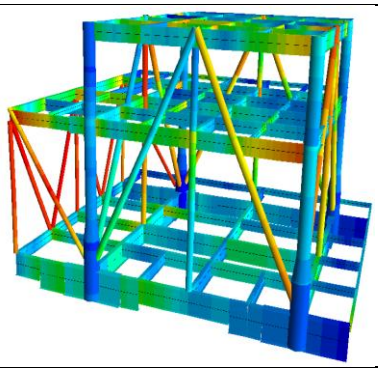
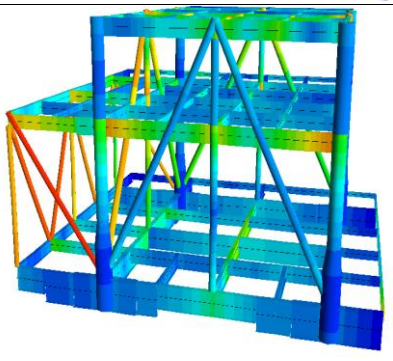
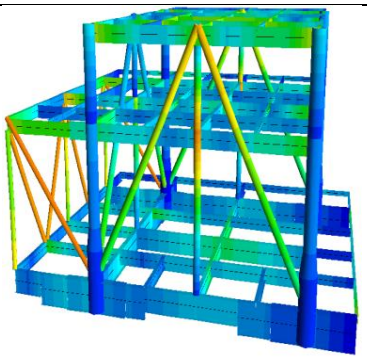


Figure 7-5 Comparison of collapse time for different PFP

	Location #4 Plasticity distribution at 35 min.	Location #5 Plasticity distribution at 20 min.	Location #6 Plasticity distribution at 15min.
Case I			
Case II			
Case III			
Case IV			

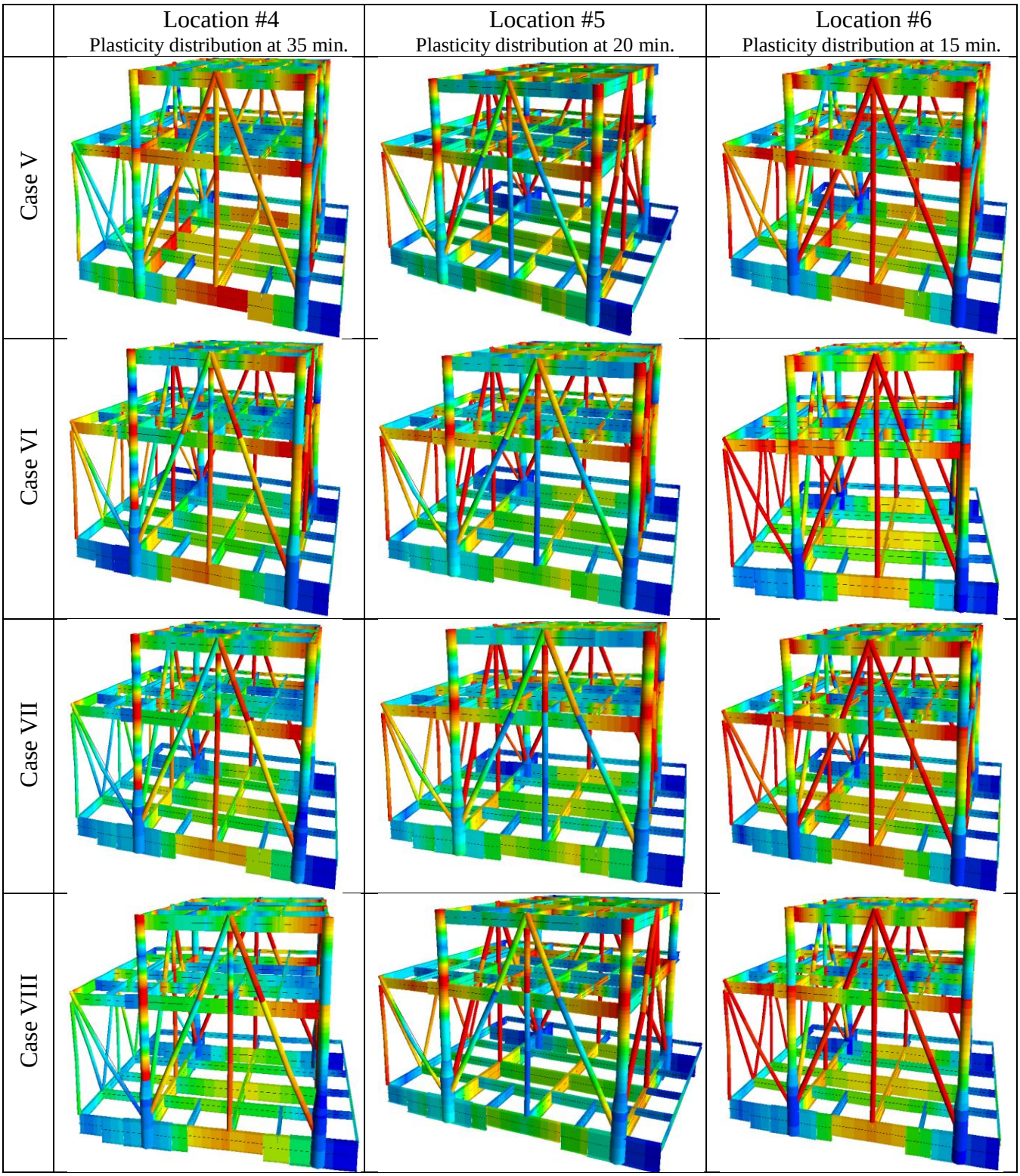
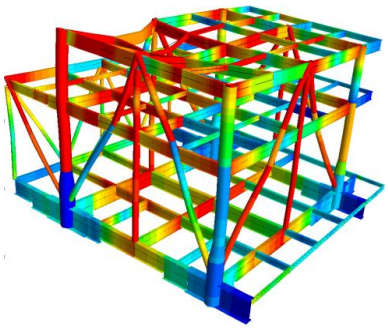
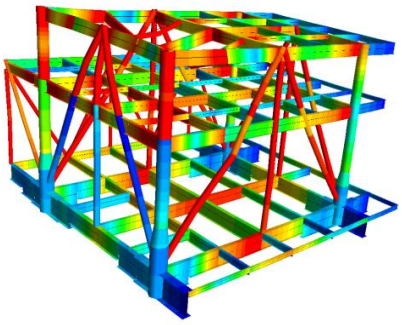
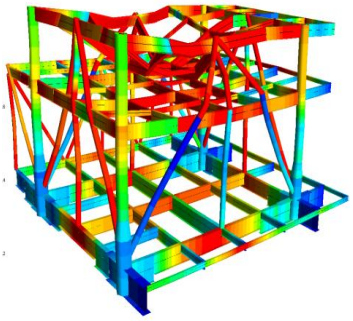
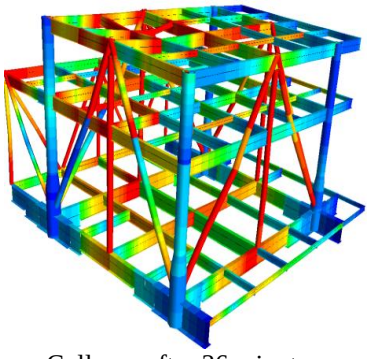
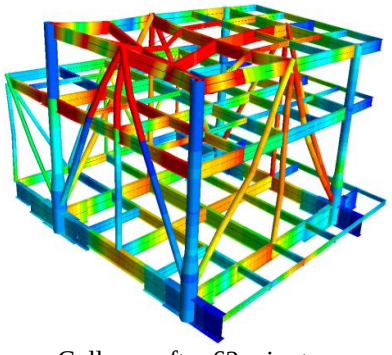
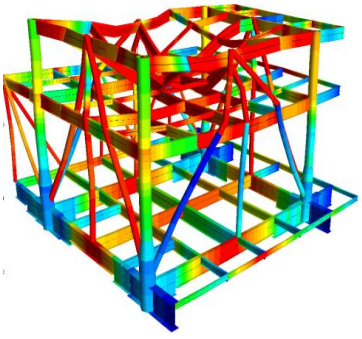
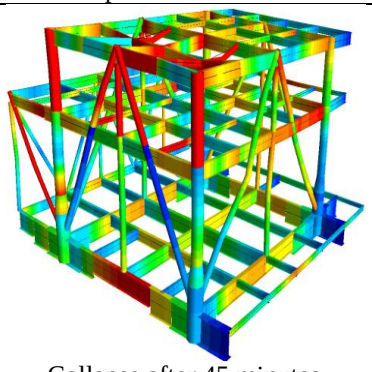
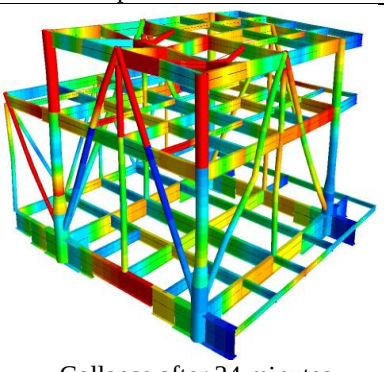
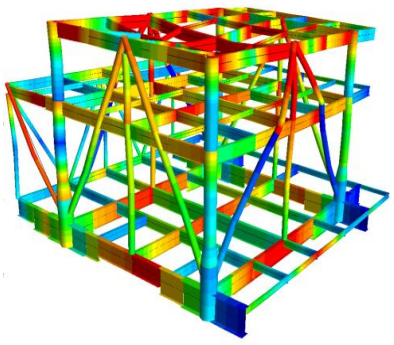
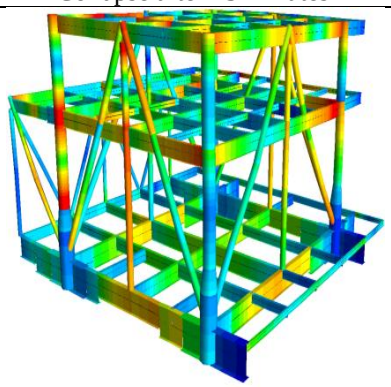
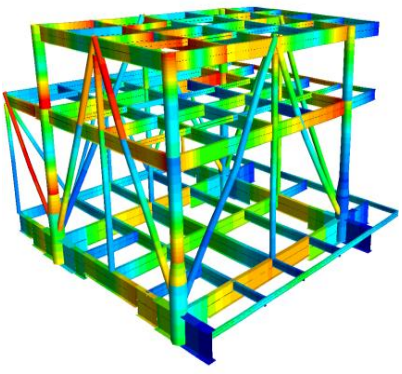
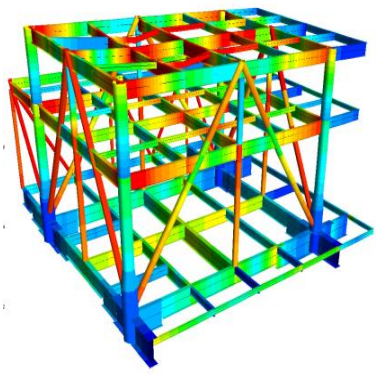


Figure 7-6 Comparison of plasticity distribution of all cases at the time of Case I's collapse

Approximate effect of the PFP reduction and Failure Mode

In following figures the effect of coatback on the topside module is examined. In the first line, the horizontal PFP has been applied. As can be seen from the following page, fracture at high plastic utilization spots appears at various points and in one case the module even collapse due to the high heating of the structure. However, with the coatback applied on the horizontal members, the spots with high plastic utilization area reduced at all three fire scenarios. It even could prevent collapse. The largest effect of the PFP we can observe for fire location 6. In case I and case II, where no PPF is applied on horizontal members, the structure fully collapses in the middle. Whereas, in those cases with horizontal PFP applied, the structure withstands a total failure. Comparing the fire locations for each case, it is easy to see that that the failure mode differs quite significantly for each fire location. In case I for instance, the deflection of the deck gets stronger as the fire location comes closer to the center. The same also holds for all other cases. In case IV, V and VI it is hard to spot any deflection for fire location 4 and 5, but fire location 6 shows quite large deflections and high plastic utilization.

	Location #4	Location #5	Location #6
Case I	 Collapse after 35 minutes	 Collapse after 23 minutes	 Collapse after 20 minutes
Case II	 Collapse after 36 minutes	 Collapse after 62 minutes	 Collapse after 64 minutes
Case III	 Collapse after 45 minutes	 Collapse after 34 minutes	 Collapse after 62 minutes
Case IV	 Collapse after 131 minutes	 Collapse after 140 minutes	 Collapse after 143 minutes

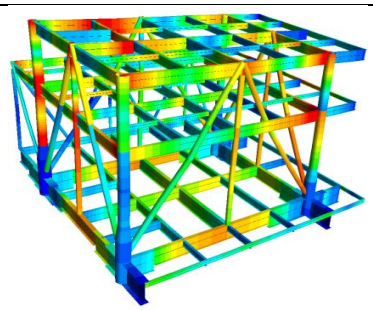
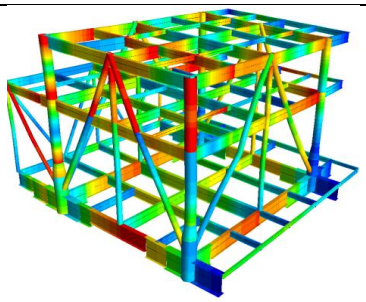
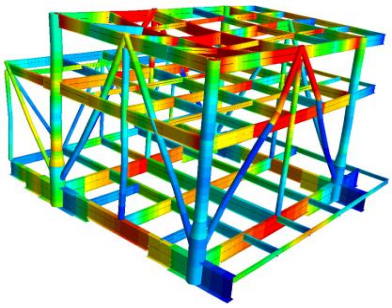
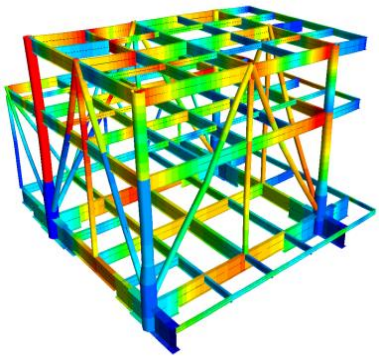
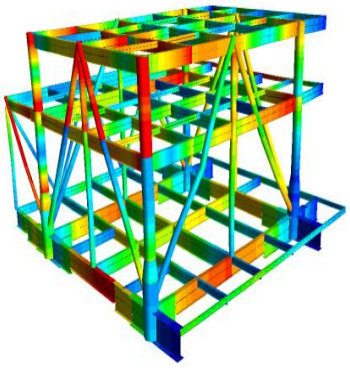
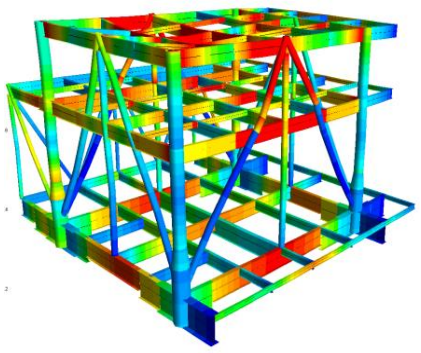
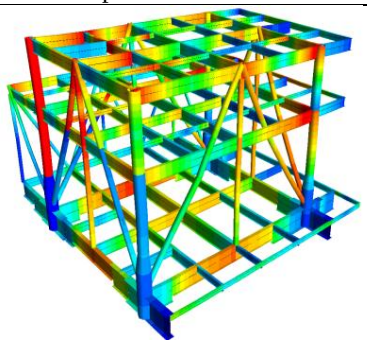
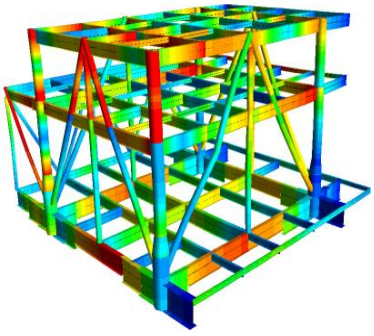
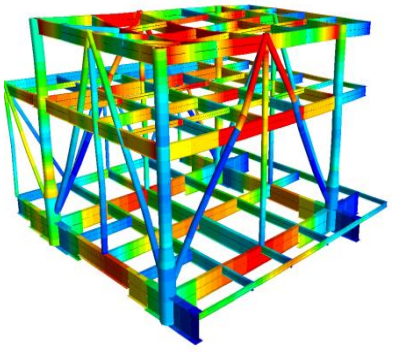
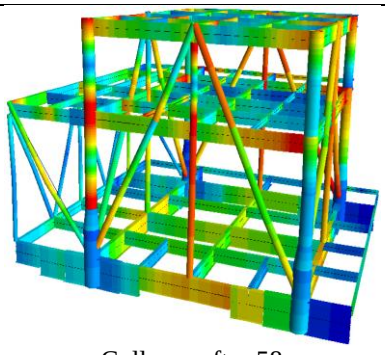
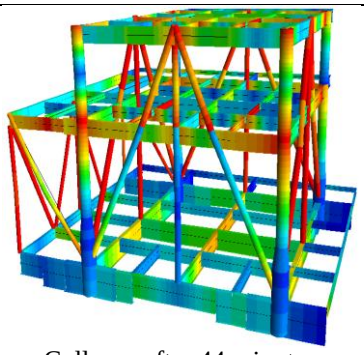
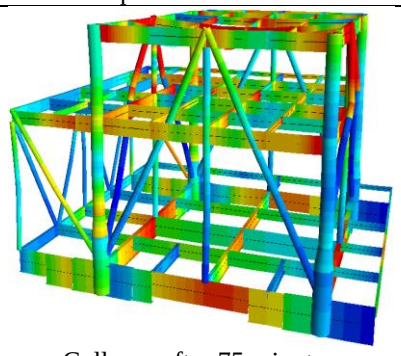
	Location #4	Location #5	Location #6
Case V	 Collapse after 59 minutes	 Collapse after 45 minutes	 Collapse after 74 minutes
Case VI	 Collapse after 58 minutes	 Collapse after 43 minutes	 Collapse after 72 minutes
Case VII	 Collapse after 64 minutes	 Collapse after 47 minutes	 Collapse after 79 minutes
Case VIII	 Collapse after 58	 Collapse after 44 minutes	 Collapse after 75 minutes

Figure 7-7 Comparison of plasticity distribution when each case collapses

8. Conclusion

In the first case study in this paper, the conventional application of 450 mm coatback length is justified. Longer coatback doesn't result in substantial increase in the structural integrity under fire load. The difference between structural behavior using beam element model and shell element model in USFOS is identified to be negligible. Also, should the loading carrying members be reinforced, since they were identified in the first case study to be most crucial to the structural integrity.

In the second case study, the effect of coatback for secondary members on the collapse time is identified to be significant. Especially, its effect is maximized when it is applied to the members under high equipment load. It is because those members experience high stress and the coatback slows down further plastic progress caused by heat load. It is shown that the systematic reduction of PFP can lead to significant savings on material cost. The PFP layout with the highest efficiency is found to be the case VIII, the PFP layout, which protects the load bearing structure. Overall, there is much space for improving already existing PFP layouts in order to achieve maximum safety and minimum cost.

9. Future work

As the future work we are going to implement the fire simulations computed by the fire and gas dispersion simulator Kameleon FireEX in order to capture the detailed temperature development in structures due to the heat load from. The results of fire scenarios of Kameleon FireEx KFX will be directly imported for USFOS simulations and allow a more clear and detailed picture on the temperature field.

10. Bibliography

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3) Amdahl, USFOS Norway, "USFOS User's Manual, release 8-5"
4) Amdahl, (2010), "Ultimate Strength Members of Members With Attachments During Accidental Fires"
5) DNV-RP-C204, (1999), "A Guide to Quantitative Risk Analysis on Offshore Structures"

6) EN 1993-1-2: Eurocode 3: Design of steel structures - Part 1-2: General rules - Structural fire design (2005)
7) Fabig UK, “Fire Loading and Structural Response”, 2009
8) Jord Baer, SHI, (2012), “Passive Fire Protection Study Report”
9) Kinsella Emmett, (2011), “Tools For Thermal Analysis Of Intumescent Materials”
10) Ptil, Petroleum Safety Authority Norway (2010), “Thermal properties of PFP material”

11. Appendix

11.1. Material Properties PFP

In the following Figure 11-1 and Figure 11-2 are two different materials for PFP which are commonly used as the passive fire protection. In analysis often used as an effective heat transfer is 5 kW/s, which is considered to be good, or sometimes values around 18, which is known as to be quite poor. The simulation of this paper has been conducted with the material from following Figure 11-1,

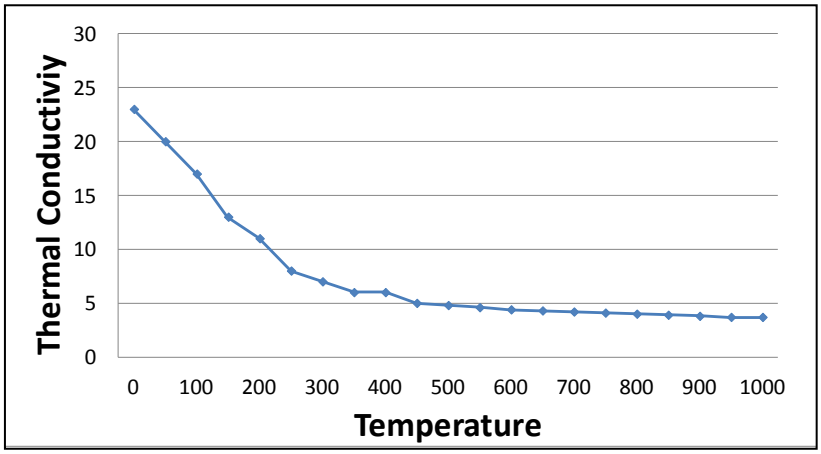

Figure 11-1 Effective heat conductivity of a PFP rated H-30

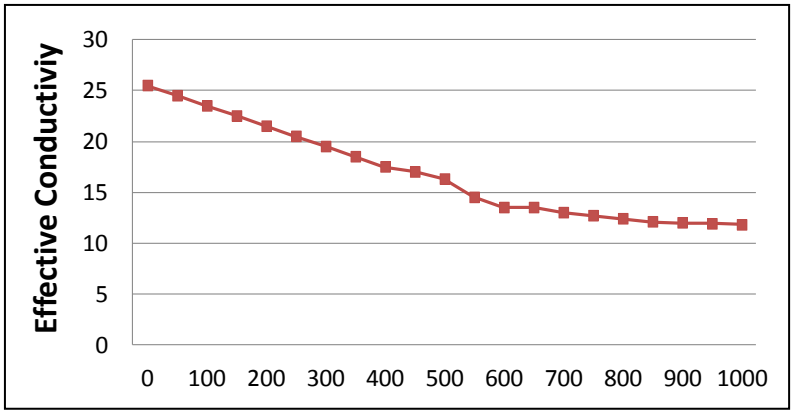

Figure 11-2 Effective heat conductivity of a PFP rated H-60

11.2. Material Properties Steel

The mechanical properties are strongly non-linearly dependent on the temperature and are assumed to follow the Eurocode 3 curves. The effective yield stress and for temperature below 400C, the ultimate stress is assumed unaffected. The properties with the major impact on the structural behavior are as follows [6]:

- Young's Modulus
- Specific Heat
- Poisson Ratio
- Expansion Coefficient
- Conductivity
- Yield Stress

Their values are input in a tabular format respectively to temperature. Values in between are interpolated and values outside the range are extrapolated.

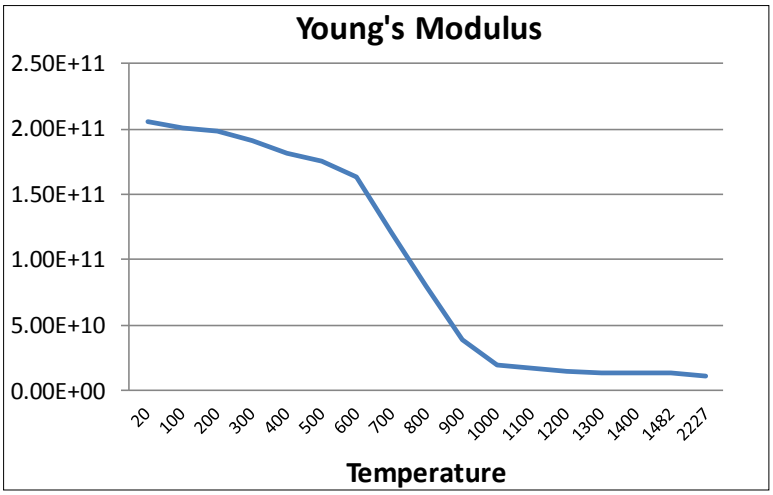

Figure 11-3: Young's Modulus of steel member

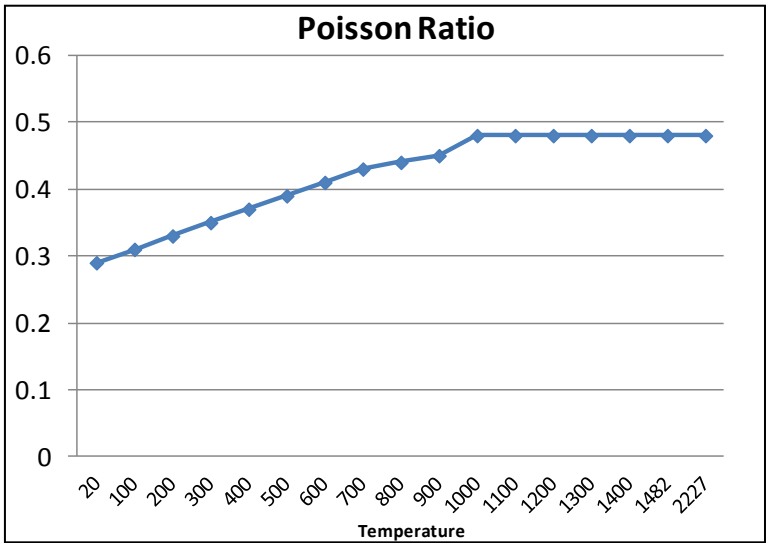

Figure 11-4: Poisson Ratio of steel member

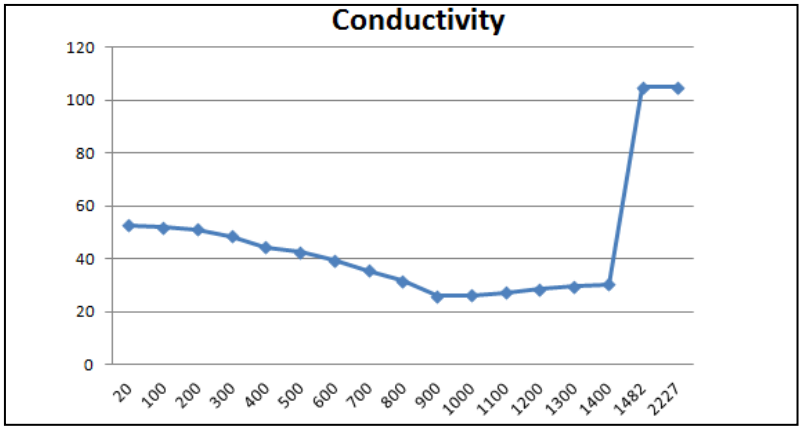

Figure 11-5: Conductivity of steel member

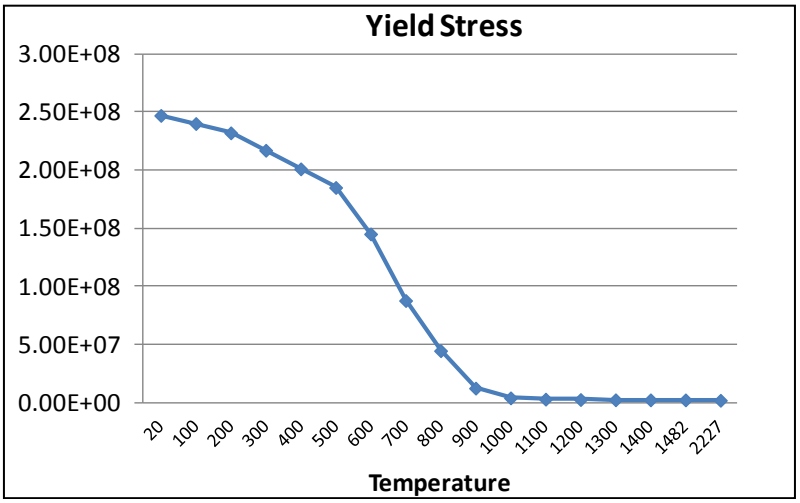

Figure 11-6: Yield Stress of steel member

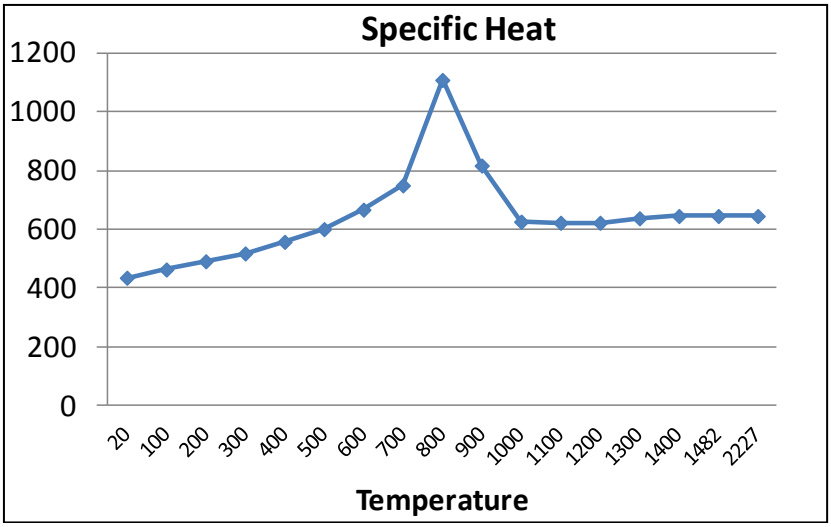

Figure 11-7: Heat Capacity of steel member

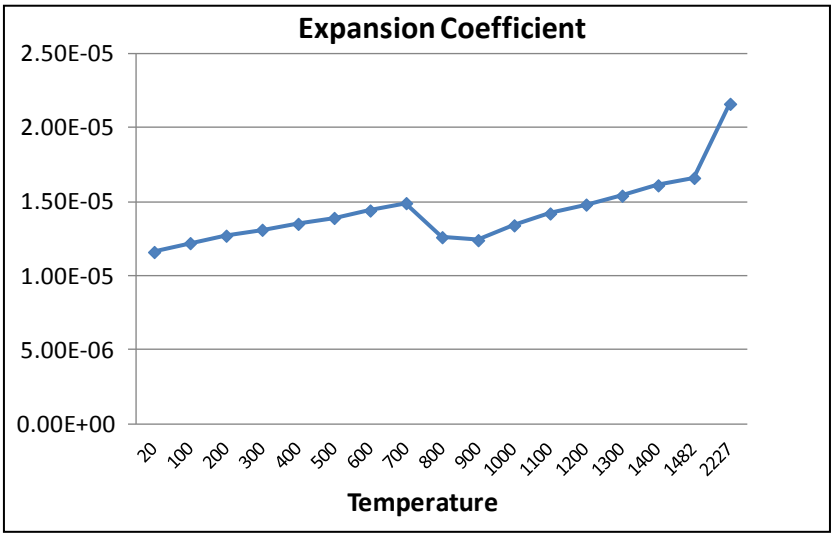

Figure 11-8: Expansion coefficient of steel member

12. 초　　록

FPSO Topside 모듈은 많은 양의 오일과 가스를 처리하기 때문에 항상 화재와 폭발에 대한 많은 위험을 안고 있다. 화재 발생시 구조물의 붕괴를 지연시키기 위한 일반적인 방법으로서 Passive Fire Protection가 주요 구조 부재에 널리 사용되고 있다. 하지만 PFP를 지나치게 많이 사용할 경우, 그 구입 비용 및 설치, 검사 유지 보수를 위해 과도한 비용이 소요될 수 있다. 특히, PFP의 설치는 제작 공정의 마지막 단계에서 이루어지기 때문에 자칫 FPSO 인도에 지연을 초래할 수 있다. 따라서 최소한의 PFP의 적용이 결국 제작 비용과 납기 지연의 위험을 감소시킬 수 있다. 본 논문은 일련의 열탄소성 유한요소 해석을 통해 어떻게 하면 최소한의 PFP로 충분한 안전성을 달성할 수 있을지에 대한 연구를 보여주고 있다. 또한 이 연구를 통해 적절한 화재 상태에서 서로 다른 PFF를 적용한 구조물의 거동을 잘 이해할 수 있다.

주요어: Passive Fire Protection (수동화재방호), 비선형 구조 해석, 열 전달 해석, 붕괴시간

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