Thermal and Structural Behaviour of Offshore Structures with Passive Fire Protection

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Abstract: In offshore structures, hydrocarbon fires cause the structure to loose its rigidity rapidly and this leads to structural integrity and stability problems. The Passive Fire Protection (PFP) system slows the transfer rate of fire heat and helps to prevent the collapse of structures and human losses. The vital design factors are decided in the detailed design stage. The determined design thickness must be accurately applied in the fabrication yard. However, there are many cases that the PFP is overused because of various reasons. This excessive application of the PFP is an unavoidable problem. Several studies have been conducted on the efficient application and optimal design of the PFP. However, the strength of the PFP has not been considered. In addition, research studies on the correlation between the thickness of the PFP and the structural behaviour are not widely available. Therefore, this study attempts to analyse the thermal and mechanical effects of the PFP on the structure when it is applied to the structural member. In particular, it is intended to determine the change in the behaviour of the structural member as the thickness of the PFP increases.

Keywords: passive fire protection; thermal; structural; beam; finite element method

1. Introduction

The Passive Fire Protection (PFP) coating system is widely used in offshore topside structures to protect structures from hydrocarbon fires in both oil and gas industries. In particular, epoxy intumescent passive fire protection material has been used for the past 30 years. When a fire breaks out, the epoxy intumescent coating thickness increases and the coefficient of heat conduction of the coating decreases thereby slowing down heat transfer. The reduction in heat transfer prevents the protected structure from experiencing elevated temperatures from the fire. Epoxy passive fire protection materials are expensive and construction takes a lot of time and money. The weight is not negligible either. In order to solve these problems, various studies were conducted on the efficient application of passive fire protection and analytical techniques and procedures were developed for optimal design.

Amongst these, Kim et. al. [1,2] performed nonlinear finite element analysis to analyse Floating Production Storage and Offloading (FPSO) topside structures subjected to fire load. Friebe et. al. [3] presented different case studies to demonstrate the effect of different applications of PFP on collapse time of an FPSO module structure. Sari et. al. [4] used a risk-based method and compared against a conventional PFP optimisation method based on API RP 2FB and concluded that a risk-based approach can provide significant reduction of required PFP material. Lim et. al. [5] presented a PFP material selection and optimisation process to reduce the impact of fire by considering different PFP material thicknesses. They indicated that cementituous material and cellular glass showed better fire prorection performance. Garaniya et. al. [6] proposed a methodology to assess the effectiveness of passive fire protection by using Fire Dynamics Simulator. Paik et. al. [7,8] performed full-scale fire testing to investigate the collapse of steel

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stiffened plate structures subjected to lateral patch loading with and without passive fire protection. In another study, Ryu et. al. [9] presented new computational models to study fire-induced progressive collapse behaviour of steel stiffened plate structures with and without PFP. They developed transient thermal elastic-plastic large-deformation finite element models for this purpose.

The PFP coating system is designed based on fire risk analysis of the offshore structure. The effect of fire is assessed through sophisticated fire load assessments and CFD-based fire simulations. Based on these, the duration of each structural member's exposure to high temperatures can be calculated. Depending on its duration, the type and thickness of passive fire protection coating for each area is designed. Ambient conditions, materials, and structural composition of each structural member are also considered in the passive fire protection design.

However, there is one big issue in the application of passive fire protection; it is often applied more excessively than the design requirement. This is due to the geometric shape of the structural members, the surrounding fittings, and the skill of the workers. For example, about 20 to 30 mm of PFP is installed in the angle type beam to which 11 mm of PFP should be applied. It is one of the inevitable problems in the structural production process. This kind of thick passive fire protection causes unexpected interference with surrounding outfittings. In addition to that, the weight increase of the structure cannot be ignored due to its vast area of coverage. Significant additional cost of materials should also be considered.

Therefore, it is essential to determine the effect of the thick PFP itself on the structure. Moreover, it is important to investigate whether the PFP attached to steel has a positive effect on the thermal and mechanical behaviour of the steel structural members. To the best of authors' knowledge, the effect of PFP material properties on structural behaviour was not taken into account in earlier studies. Hence, this study aims to evaluate how the application of passive fire protection affects the thermal and mechanical behaviour of structural members. The effect of the change in the thickness of passive fire protection on the structure is examined. Possible positive effects besides the original function of the PFP applied to offshore structures are considered. For structural members with passive fire protection, finite element analysis is conducted for each condition before and during a fire.

2. Passive Fire Protection Systems

When a fire occurs and the temperature reaches 260-470ºC, the Young's modulus of the steel is reduced by 40% [11]. In the case of a fire caused by flammable gas or liquid, it takes less than one second for the structure to reach this temperature. This can cause collapse of the structure.

The Passive Fire Protection (PFP) is one of the means used to prevent the premature destruction of steel structures in the event of a fire. The proper amount level of PFP is determined by the following factors: the size of the individual elements of the steel structure, the size of the member section, and the purpose of use. This study considers the characteristics of epoxy PFP materials based on the Chartek 7 product, which is a widely used product in the offshore industry. The ingredients, which cause fire protection, are very similar across a broad spectrum of products [10].

2.1. Material Characteristics of Epoxy PFP

In the event of a fire, epoxy PFP material swells or intumesces. A layer of durable insulated char slows the rate of temperature rise on the steel substrates. The PFP materials protect the steel structure from reaching the critical core temperature within a certain period of time. The critical core temperature is the temperature at which the steel begins to loose its load capacity and it depends on the grade of the steel and the internal load requirements [12].

The PFP material is generally highly impervious to water ingress. It can also provide additional anti-corrosion features for the iron. Adhesion and strength are effectively improved by using flexible mesh together. It is tough, durable and resistant to impact and vibration damage. It does not require much maintenance [13].

Table 1 shows the material characteristics of Chartek 7 which is a representative product of passive fire protection materials. The density of 1.0 t/m^3 is much smaller than normal cement of 2.8 t/m^3 and similar to that of rubber of 0.93 t/m^3. The thermal conductivity of 0.213 W/m°C is superior to the concrete of 0.92 W/m°C and as small as the thermal conductivity of the wood of 0.2 W/m°C. The thermal properties such as the thermal conductivity and specific heat can be found in detail in Section 3.

Table 1. Material Characteristics of Epoxy PFP

Property	Value	Units
Density	1000	kg/m^3
Thermal Conductivity	0.213 (1.45)	W/m°C (Btu·in/hr ft^2°F)
Coefficient of Thermal Expansion	68×10^{-6} (38×10^{-6})	cm/cm°C (in/in°F)
Specific Heat	1.17 (0.28)	J/g°C (Btu/lb°F)
Moisture Absorption	3.3% non top-coated 1.4% top-coated	
Flame Spread	25.0	
Smoke Generation	130.9	
Toxicity Index	1.3	
Hardness	Typically 70	
Impact Strength / Inch of Notch	0.69 (0.10)	J/cm (ft·lb/inch)

2.2. Mechanical Properties of Epoxy PFP

Table 2 indicates the mechanical properties of Chartek 7. Its lap shear strength is 10MPa and compressive strength is above 18MPa. It is flexible and not affected by the deflection of the steel substrate for pre-erection applications. This material has a fully fire rated capability such as H-rated and J-rated for offshore platform applications [13].

Table 2. Mechanical Properties of Epoxy PFP

Property	Value	Units
Spray Applied Density	1000 (62.4)	kg/m^3(lb/ft^3)
Tensile Strength	12.8 (1850)	MPa (psi)
Tensile Modulus	1786 (259,000)	MPa (psi)
Compressive Strength	18.6 (2700)	MPa (psi)
Compressive Modulus	1172 (170,000)	MPa (psi)
Flexural Strength	22.8 (3300)	MPa (psi)
Flexural Modulus	1586 (230,000)	MPa (psi)

Property	Value	Units
Lap Shear Strength	10.0 (1450)	MPa (psi)

3. Methodology

Primary and secondary members are subjected to passive fire protection because they can possibly be affected by fire loads in offshore topside structures. As mentioned earlier, PFP's main purpose is to help the structural member maintaining its function even at extreme temperatures of the rapidly rising hydrocarbon fire. The type and thickness of the passive fire protection system suitable for each component are finally determined in the process of the detailed design phase. Its thickness is usually determined from a minimum of about 3 mm to a maximum of about 18 mm. It is possible that it can be applied thicker in some different cases.

This study considers three types of PFP systems. Based on these, 44 case studies are considered to examine the thermal and mechanical characteristics of structural members with the PFP as the thickness of passive fire protection increases. The first analysis study explores the temperature distribution and thermal characteristics under different PFP coverage and thermal load conditions. This is done through transient analysis by applying the standard hydrocarbon fire curve. The second study is to perform linear static structural analysis for structural members with PFP in the absence of fire. In the third study, the behaviour of the PFP-applied structural members under both thermal and structural loads during the outbreak of fire is investigated. Finally, time-dependent thermal loads are applied to the columns subjected to compression in order to examine deformation and buckling characteristics.

3.1. Selection of Target Structures

Structures as shown in Figure 1 were considered to determine the application of passive fire protection and its impact on the behaviour of the structural members. The structural steel I-section beam is mainly used as a primary structural member to support various decks, gratings, pipes, and equipment in offshore platforms. Numerical analysis is carried out by dividing the state into no fire (i.e., no thermal load) and under fire conditions as:

A. The I-beam supports the steel deck as a primary structure. The underside of the steel deck is directly subjected to the heat of the fire. Therefore, the underside is covered with PFP. The top face of the I-beam is not covered with the PFP since it does not directly contact with fire heat.

B. The I-beam supports steel grating (or large equipment) as a primary structure. The I-beam does not have the PFP on the upper surface. In the event of a fire, the heat affects directly to all sides of the I-beam.

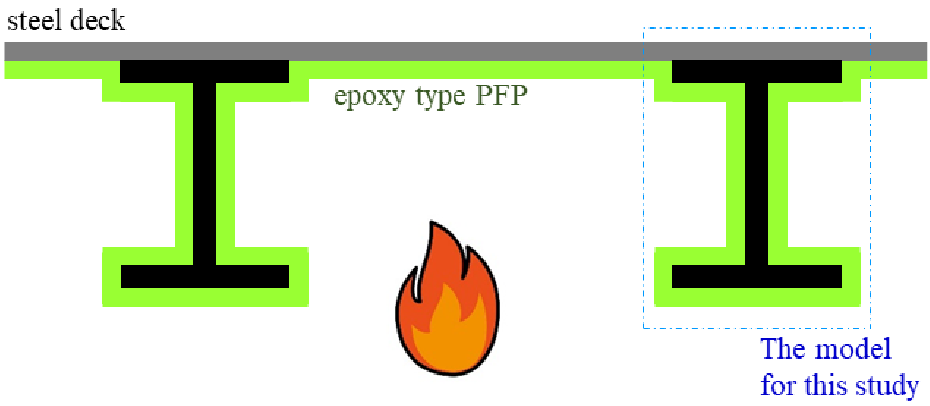
C. As a primary structure, the I-beam acts as a column. Thus, the compression force is applied to the top of the I-beam. Passive fire protection applies to all aspects. The thermal load from the fire is also applied to all sides of the I-beam.

3.2. Definition of Analysis Conditions

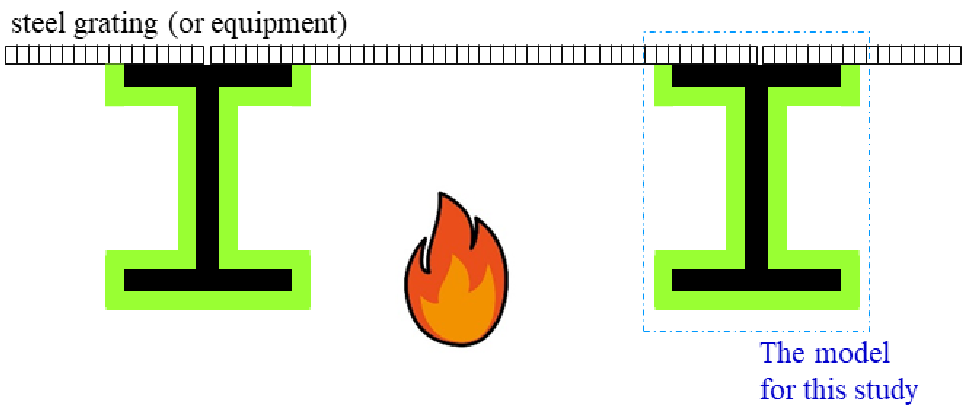
As given in Table 3, the analysis cases are set in groups of three and 44 different cases are considered. Transient thermal and structural analyses were performed using ANSYS, a commercially available finite element analysis software [14]. The temperature distribution obtained as a result of heat transfer analysis was used as an input for the structural analysis.

Group A uses the plane element type to accurately identify the thermal distribution and characteristics of the I-beam section for hydrocarbon fire. Transient thermal analysis was performed with 200 time steps. Group

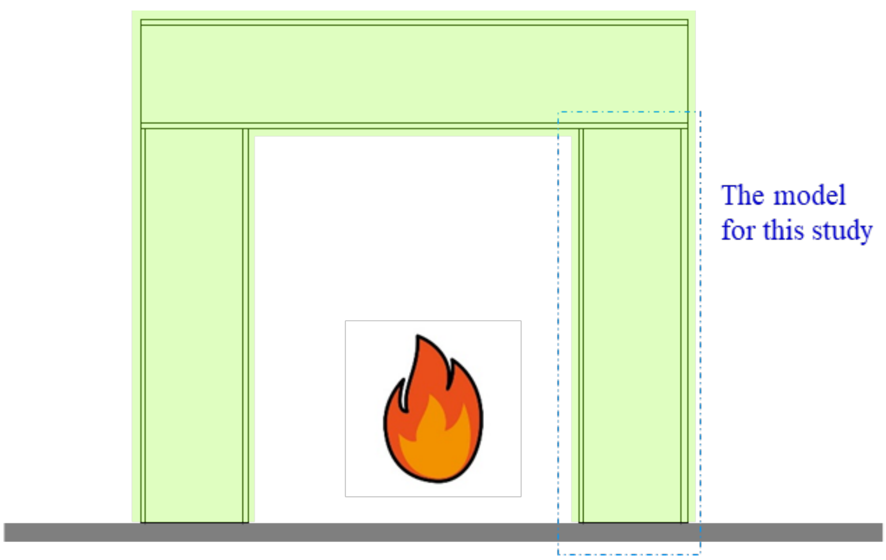
B is a setting to identify the structural behaviour of the PFP-applied beam with the data obtained by thermal analysis. This coupled analysis was performed on the PFP-applied beams with six types of PFP thickness. Group C aims to examine the buckling behaviour of the columns subjected to compression. The vertical displacement caused by the compressive force can also be calculated. The buckling analysis considers “prestress effects” in the structural analysis process of a beam subjected to compressive force. Then, the characteristics of buckling can be evaluated by performing "Eigen Buckling" analysis.



(a) I-beam Supporting the Steel Deck



(b) I-beam Supporting the Grating (or Large Equipment)



(c) I-beam as a Column

Figure 1. I-beam Frame with PFP

Table 3. Cases of the Numerical Analysis

Group	No.	PFP Thickness (mm)	Structural Load	Thermal Load	Numerical Analysis		Boundary Condition
					Type	Element	
A	TH3-00	0	Not applicable	Standard hydrocarbon fire	Transient/ thermal	Plane55	Not applicable
	TH3-01	1					
	TH3-03	3					
	TH3-06	6					
	TH3-10	10					
	TH3-15	15					
	TH4-00	0	Not applicable	Standard hydrocarbon fire	Transient/ thermal	Plane55	Not applicable
	TH4-01	1					
	TH4-03	3					
	TH4-06	6					
	TH4-10	10					
	TH4-15	15					
B	NFS-00	0	30kPa	Not applicable	Static structure	Solid185	Fixed at both ends
	NFS-01	1					
	NFS-03	3					
	NFS-06	6					
	NFS-10	10					
	NFS-15	15					
	DF3-00	0	30kPa	Standard hydrocarbon fire	Transient/ Structural thermal coupled	Solid70 Solid185	Fixed at both ends
	DF3-01	1					
	DF3-03	3					
	DF3-06	6					
	DF3-10	10					
	DF3-15	15					
	DF4-00	0	30kPa	Standard hydrocarbon fire	Transient/ Structural thermal coupled	Solid70 Solid185	Fixed at both ends
	DF4-01	1					
	DF4-03	3					
	DF4-06	6					
	DF4-10	10					
	DF4-15	15					
C	NFB-00	0	Compression load 350MPa	Not applicable	Static structure	Solid185	One end fixed Other free
	NFB-01	1					
	NFB-03	3					
	NFB-06	6					
	NFB-10	10					

	NFB-15	15					
	DFB-00	0	Compression load 350MPa	Standard hydrocarbon fire	Transient/ Structural thermal coupled	Solid70 Solid185	One end fixed Other free
	DFB-01	1					
	DFB-02	2					
	DFB-03	3					
	DFB-04	4					
	DFB-06	6					
	DFB-10	10					
	DFB-15	15					

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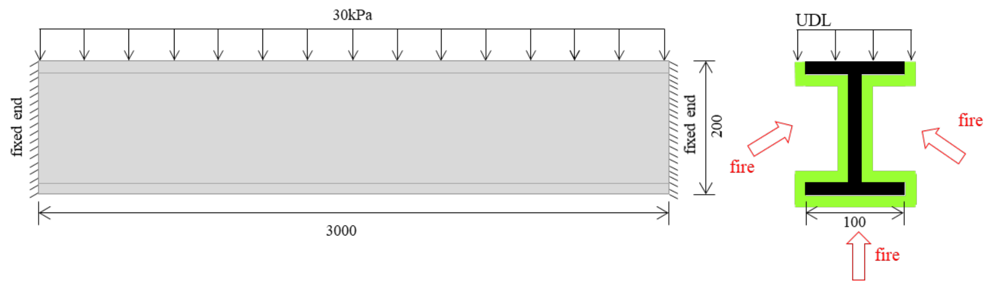
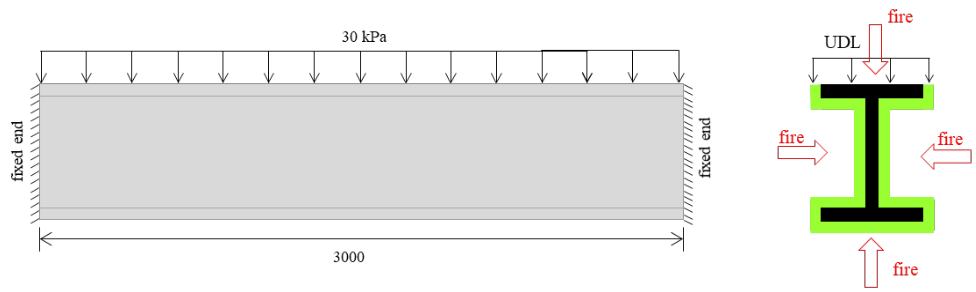
3.3. Application of Structural and Thermal Loading, and Boundary Conditions

Figure 2 shows the dimensions, structural loads, thermal loads, and boundary conditions based on the model demonstrated in Figure 1. In Figures 2 (a) and (b), 30 kPa of uniformly distributed load is applied to the upper surface of the I-beam over the entire length. The two ends of the member are assumed to be fully fixed. In case of Figure 2 (a), the fire heat on the top surface of the I-beam section is not taken into account in the numerical calculation. Figure 2 (b) is the setting in which fire heat is applied to all sides. The numerical analysis was performed by considering the symmetry condition. For Figure 2 (c), a compressive load of 350 MPa was applied to one side of the cantilever beam. The other side is fully fixed.

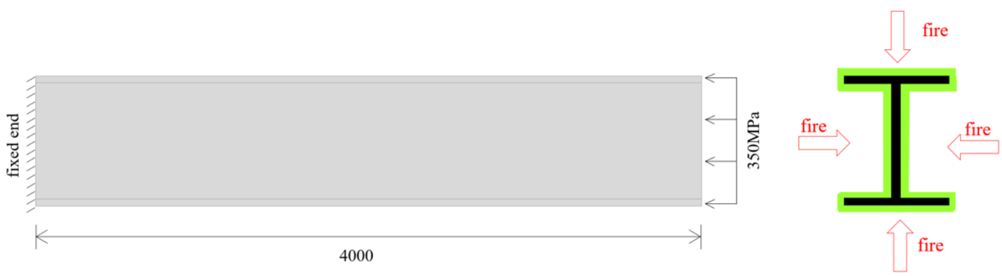
The size of the member section used for all analyses is 200×100×10 (mm). The temperature by the standard hydrocarbon fire curve, indicated in Figure 3, was applied for 200 minutes under the conditions of each structural model [15].



(a) I-beam with No fire on the Top Surface (DF3 analysis cases)



(b) I-beam with Fire on All Sides (DF4 analysis cases)



(c) I-beam as a Column with Fire on All sides (DFB analysis cases)

Figure 2. Configurations of the Steel Member for Analysis

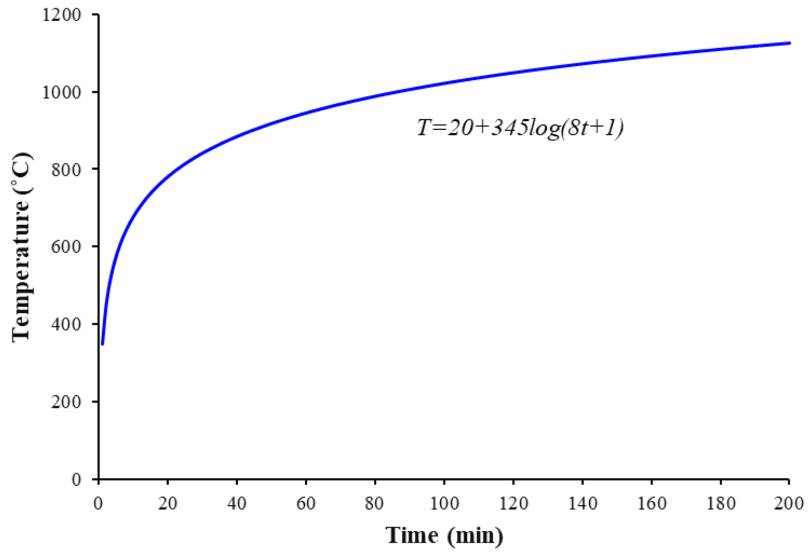


Figure 3. Standard Hydrocarbon Fire Curve

Figures 4 and 5 show the finite element models for the coupled analysis which are based on Figure 2. First, The SOLID70 elements were used for the transient thermal analysis and then SOLID185 was utilized for the structural calculation.

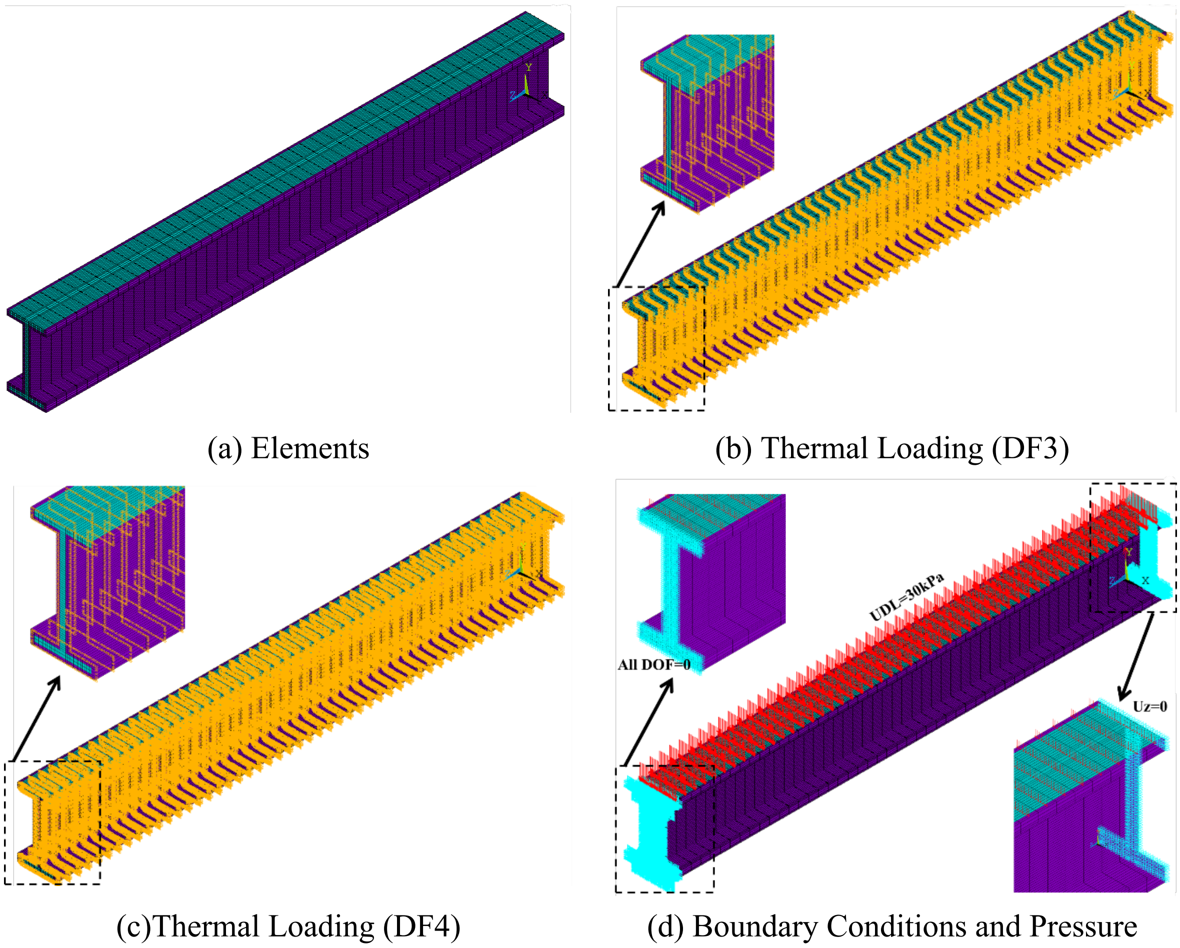
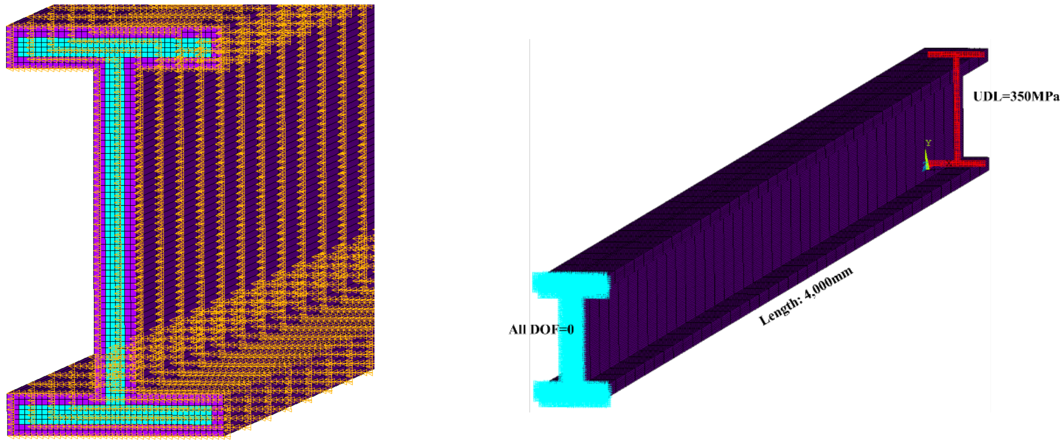


Figure 4. Finite Element models for DF3 and DF4 analysis cases



(a) Thermal Loading (all sides) (b) Boundary Conditions and Pressure

Figure 5. Finite Element model for DFB analysis cases

3.4. Material Properties

To examine the behaviour of the offshore structure subjected to fire heat load, the dependency of materials on the temperature change must be defined [2]. In this study, specific heat, thermal conductivity, and elastic modulus values of each material were used for the numerical analysis.

3.4.1. Properties of Steel

The variation of specific heat (C_a, J/kg·K) of steel with temperature is given below and is represented in Figure 6 (a) as [11]

$$\text{for } 20^\circ\text{C} \le \theta_a \le 600^\circ\text{C}; C_a = 425 + 7.73\times10^{-1}\theta_a - 1.69\times10^{-3}\theta_a^2 + 2.22\times10^{-6}\theta_a^3 \quad (1a)$$

$$\text{for } 600^\circ\text{C} \le \theta_a \le 735^\circ\text{C}; C_a = 666 + \frac{13002}{738-\theta_a} \quad (1b)$$

$$\text{for } 735^\circ\text{C} \le \theta_a \le 900^\circ\text{C}; C_a = 545 + \frac{17820}{\theta_a - 731} \quad (1c)$$

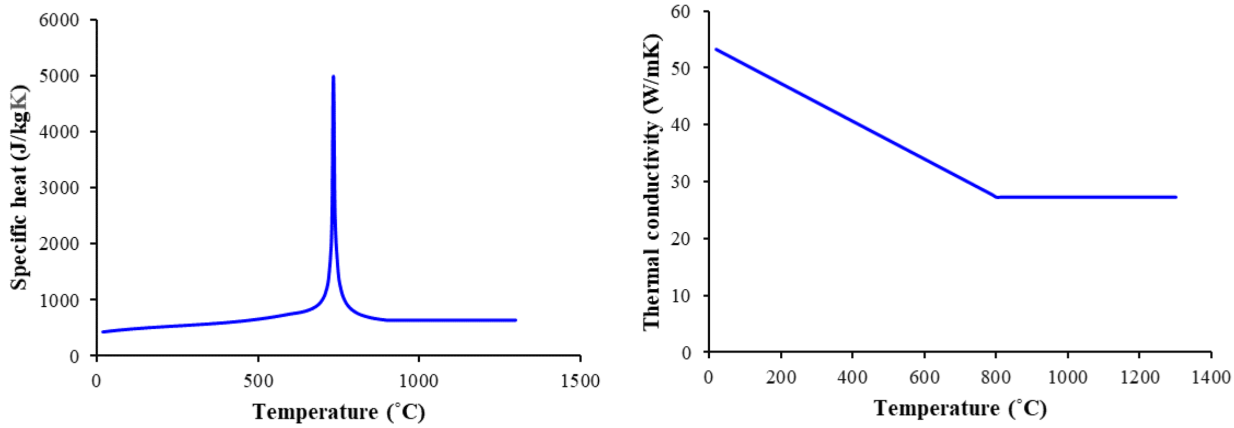
$$\text{for } 900^\circ\text{C} \le \theta_a \le 1200^\circ\text{C}; C_a = 650 \quad (1d)$$

where, θ_a is the steel temperature [°C].

The variation of the thermal conductivity of steel (λ_a, W/m·K) with temperature is given below and is shown in Figure 6 (b) as [11]

$$\text{for } 20^\circ\text{C} \le \theta_a \le 800^\circ\text{C}; \lambda_a = 54 - 3.33\times10^{-2}\theta_a \quad (2a)$$

$$\text{for } 800^\circ\text{C} \le \theta_a \le 1200^\circ\text{C}; \lambda_a = 27.3 \quad (2b)$$



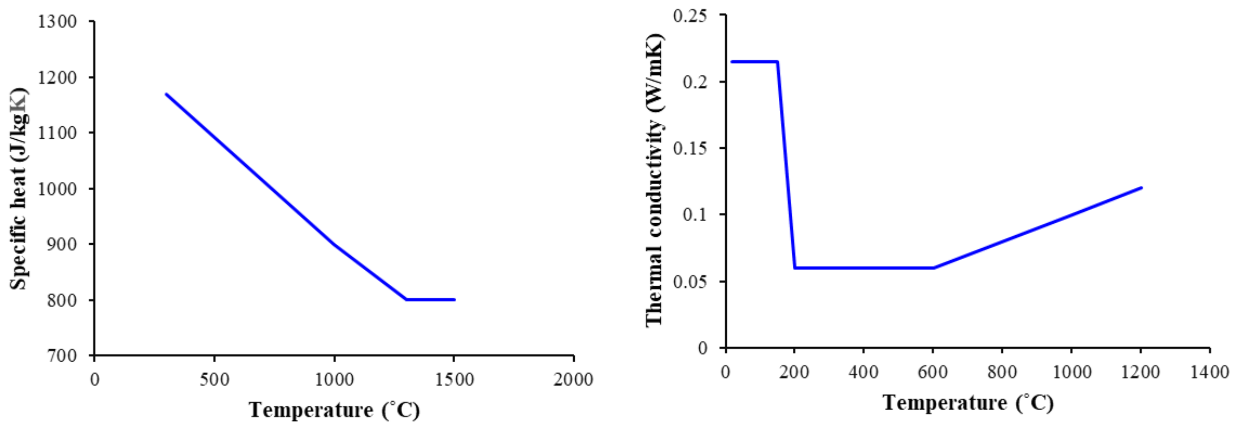
(a) Specific Heat (b) Thermal Conductivity of Steel

Figure 6. Variation of steel properties with temperature

The change in Young's modulus of steel is shown in given in [11]. The modulus of elasticity of the steel does not change until the temperature reaches 100°C, but it starts to decrease after that temperature. It is shown that it decreases by 40% at 500°C and decreases by more than 90% at 800°C.

3.4.2. Properties of the PFP Material

The specific heat of the epoxy type PFP material changes depending on the temperature as shown in Figure 7(a) [16]. This value decreases linearly as the temperature increases to around 1300°C. Above 1300°C, the rise of the temperature has no impact on the value. Figure 7(b) shows the change in thermal conductivity with increase in temperature of the PFP material. The thermal conductivity rapidly decreases at 150°C. The change in both density and elastic modulus with the increase in temperature of the PFP material was not considered in numerical analysis due to the lack of information.



(a) Specific Heat (b) Thermal Conductivity

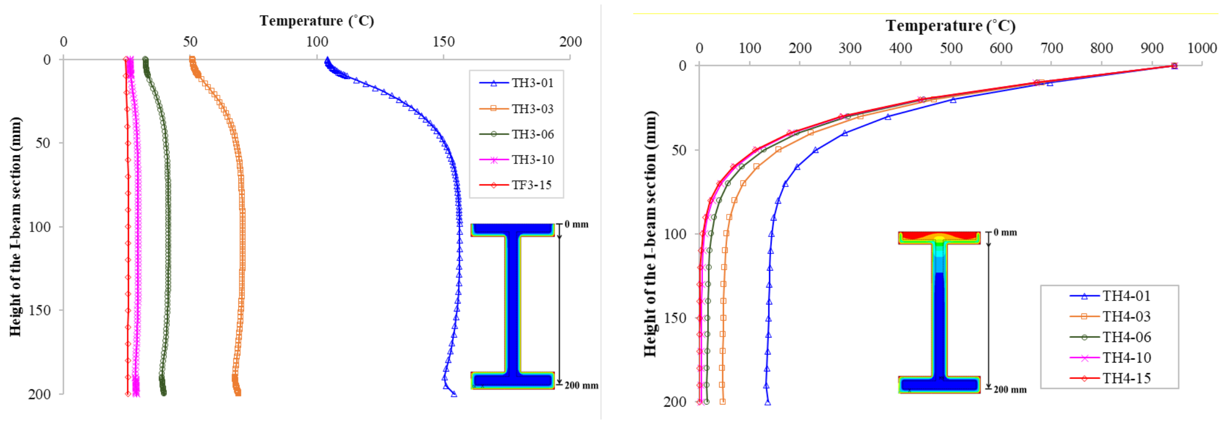
Figure 7. Variation of properties of the epoxy type PFP material with temperature

4. Numerical Results

4.1. Analysis Group A

Generally, the conditions of fire protection for offshore structures are mainly applied for 60 minutes and 120 minutes. Therefore, Figure 8 shows the temperature distribution results of the I-beam section after 60 minutes of fire. Looking at the results of the TH3 cases, it can be seen that as the thickness of the PFP increases, temperature change in the beam section decreases significantly. In particular, when the PFP thickness is 15 mm, the heat of the fire hardly reaches the steel. Hence, it is determined that the PFP is completely slowing the heat transfer.

This trend can also be seen in the interpretation of TH4 cases on the top surface of the I-beam section without the PFP. The temperature rises rapidly. From the height of 100 mm to 200 mm of the section, it shows a constant temperature distribution due to the effect of the PFP.

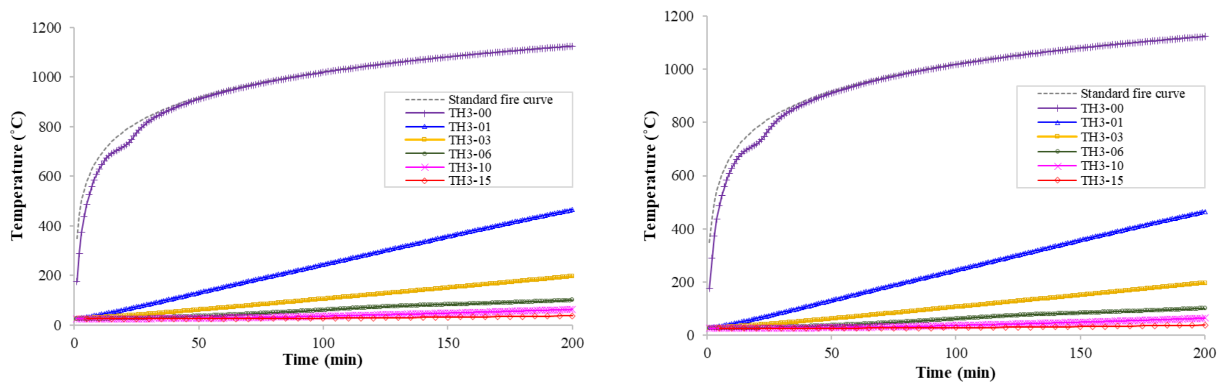


(a) TH3 analysis cases (b) TH4 analysis cases

Figure 8. Temperature distribution in the I-beam section after 60 minutes of fire

Figure 9 shows the temperature change over time at the midpoint of the I-beam. By comparing the two graphs when the PFP is not applied and when 1 mm thick PFP material is applied to the steel, it can be seen that the application of the PFP causes a significant delay in heat transfer even at very small thickness of PFP. Furthermore, it is confirmed that the rate of temperature change over time gradually decreases as the PFP becomes thicker.

In cases where the applied PFP is over 6 mm thick, the temperature increase over time is not much larger than the fire temperature. In particular, in the cases of TH3, the temperature does not exceed 100°C even at 200 minutes. The temperature tends to stay at an almost constant value. On the other hand, in TH4 cases, the rate of the temperature change with time is relatively large. Since 100°C is the starting point of the change in the elastic modulus of the steel, this result is important.



(a) TH3 analysis cases (b) TH4 analysis cases

Figure 9. Change in temperature over time (Center point of I-beam)

Based on the results above, the temperature of the steel was analysed 60 and 120 minutes after the fire occurred. As mentioned earlier, in the fire protection design for offshore structures, the conditions of 60 and 120 minutes defence time are the critical design criteria.

Figure 10 shows the temperature difference between the TH3 and TH4 analyses at the same PFP thickness after 60 and 120 minutes of fire. The average difference at 60 minutes is less than 10°C. After 120 minutes, the difference is about 40°C. If the structural member should be protected from the fire heat up to 60 minutes, the behaviour of the condition of the I-beam is not that dangerous even if the PFP is not applied on the top surface of it. It can also be seen that the thicker the layer of the PFP is, the smaller the difference is.

This result is very meaningful for the following reason. In terms of heat transfer under the design conditions of H60 or J60 fire rated, it can be seen that it is not important whether PFP is applied or not to the flange side of the I-beam section even when heat is applied to the steel from all directions.

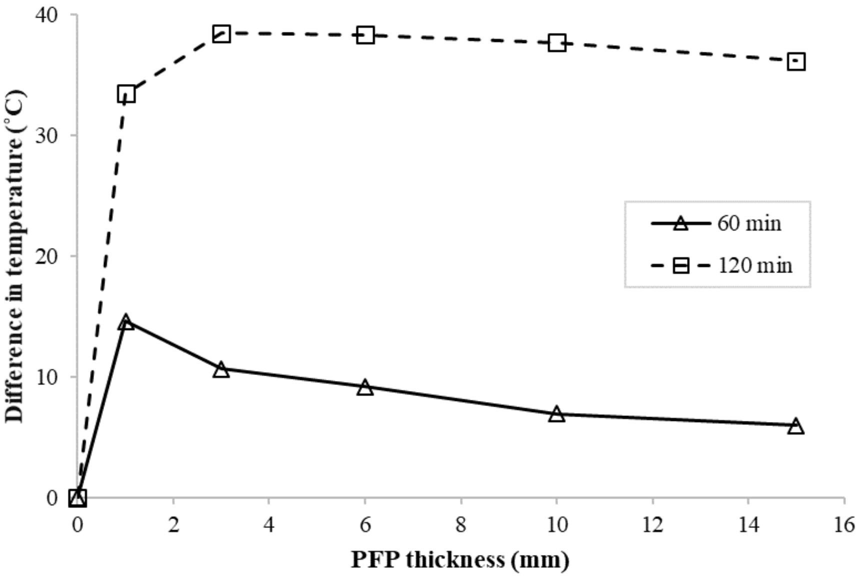


Figure 10. Temperature difference between TH3 case and TH4 case after 60/120 minutes of fire

Figure 11 shows the relationship between the temperature after 200 minutes of fire and the PFP thickness at the center point of the I-beam. It can be seen in Figure 11 that in both cases of TH3 and TH4, the temperature of the steel decreases as the PFP thickness increases. As the PFP thickness increases, the temperature change rate becomes smaller. Therefore, if the PFP is applied thicker than the appropriate thickness (which is judged to be 6 mm in this study), it is confirmed that increase of the PFP thickness does not significantly affect the reduction of the heat transfer.

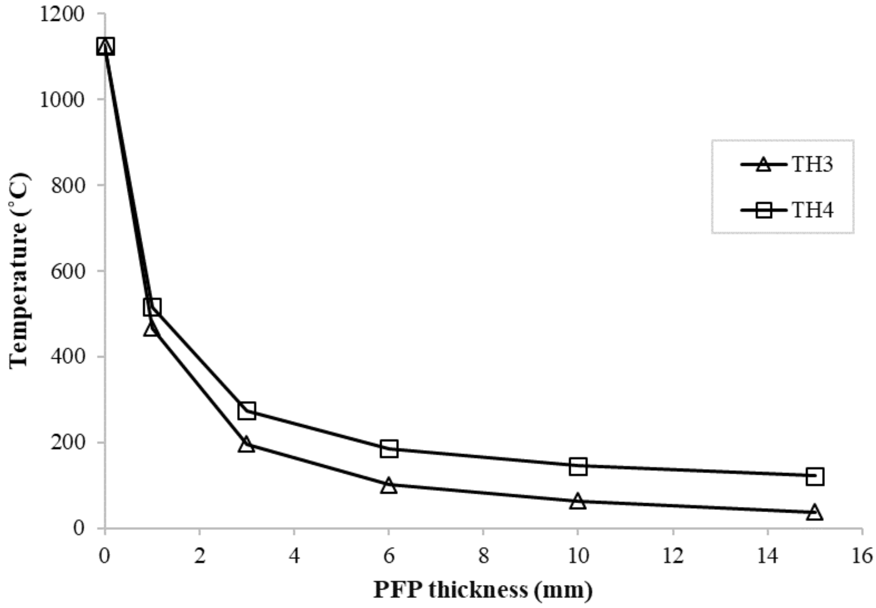


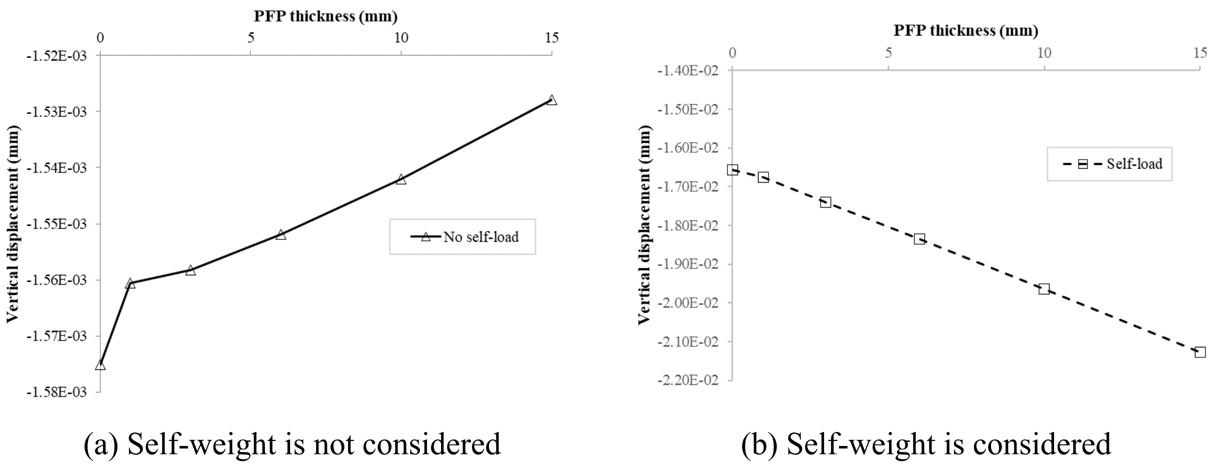
Figure11. Change in temperature with increase in PFP thickness (Center point of I-beam)

4.2. Analysis Group B

Regarding the behaviour of the PFP-applied beam during normal fire-free conditions, Figure 12 shows the change in vertical displacement at the center of the beam. When the PFP is applied, it appears that the deformation is increased by its weight. If self-weight is not taken into account, the application of a thicker PFP reduces the deformation of the beam. Therefore, the application of the PFP can increase the strength of the beam, but its weight causes the deflection of the beam.

Figure 13 shows the change in the vertical displacement value depending on the thickness of the PFP after 200 minutes of fire. In the range of 0 to 1 mm, the PFP layer plays a significant role regarding vertical displacement. There is a big difference between if the PFP layer exists or not. Even 1mm of the PFP material significantly lowers the heat conduction.

Although the displacement at the midpoint of the beam decreases in proportion to the increase in the PFP thickness, the reduction rate is not large. The main reason is that the PFP's own weight has a great influence on the beam behaviour. If the effect of self-weight of the PFP is limited, the increase in the thickness of the PFP layer can be interpreted in the sense that it reduces the deformation and increases the stiffness of the beam.



(a) Self-weight is not considered (b) Self-weight is considered

Figure 12. Beam deflection change in case of no fire

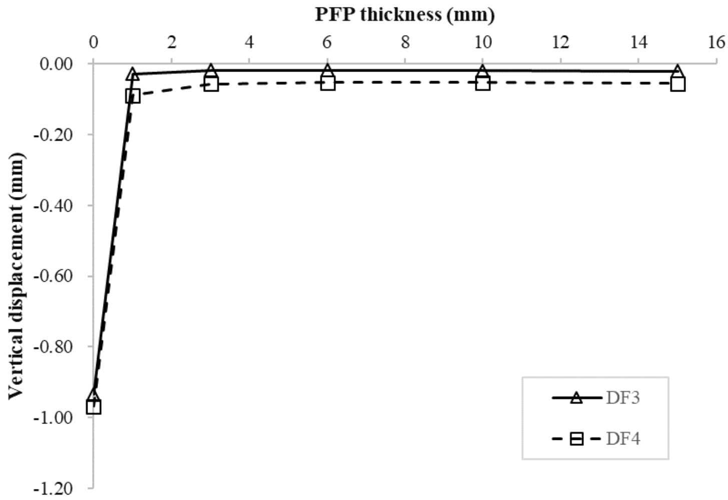
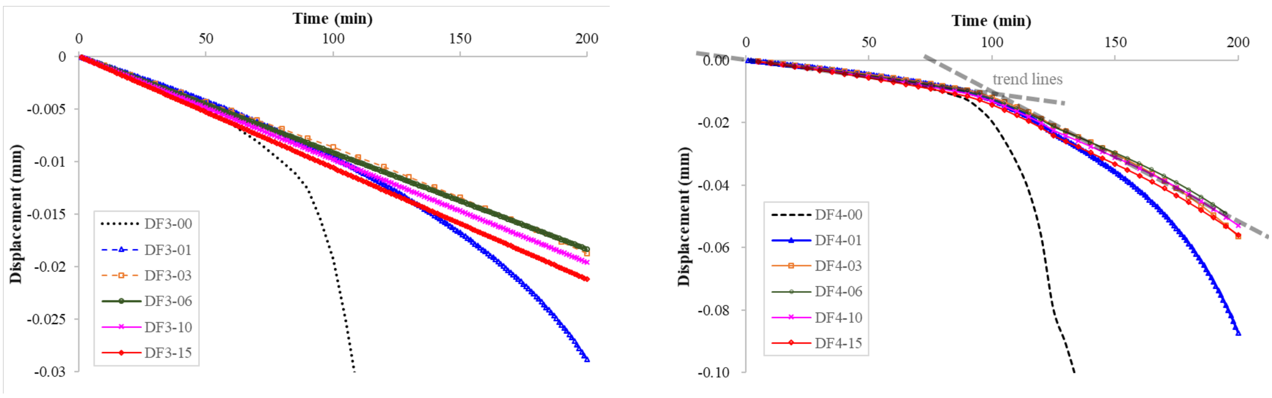


Figure 13. Comparison of the vertical displacement results after 200 Minutes of fire (Self-weight is considered)

Figure 14 shows the change in displacement over time. Here, it can be seen that the deflection of the beam is significantly reduced by applying the PFP. Also, the displacement tends to slightly increase as the PFP thickness increases. This is due to the self-weight of the PFP, as described above. In the case of DF3 analysis, the time-displacement is linear in most analysis cases because the PFP protects the beam from the thermal loads. In the analysis of DF4, the heat is transferred directly from the top of the I-beam where the PFP is not applied, so the deflection has a non-linear characteristic. In particular, looking at the DF4 analysis case, it can be seen that the rate of the time-displacement change increases at the point for about 100 minutes. The slope of the graph increases. After this point, the rate of the displacement change starts to increase and doubles at the end.



(a) DF3 Analysis Cases (b) DF4 Analysis Cases

Figure 14. Time-displacement curve by PFP thickness during fire (Center of I-beam)

4.3. Analysis Group C

When the PFP was applied to a column subjected to axial compressive force, the deformation behaviour and buckling load of the column structural member were examined. This type of structure is commonly used in real offshore structures.

As shown in Figure 15, it is confirmed that the temperature of the steel does not exceed 100°C since the PFP thickness is over 6 mm. Figure 16 (a) shows the magnitude of displacement due to a compressive force according to the thickness of the PFP. In a fire-free situation (NFB), there is little change in deformation depending on the thickness of the PFP. However, the role of the PFP is obvious in the event of fire and heat.

When the thickness of the PFP is less than 6 mm, the thickness of the PFP has a positive effect on the deformation of the beam. From the point where the PFP is 6 mm thick or more, the displacement is very similar to the case when there is no thermal load.

Similar trends can be seen in the BLF (Buckling Load Factor) values in Figure 16(b). The BLF is an index for evaluating the strength against the buckling of structures under compression. This coefficient is defined as the relative ratio of the critical load causing buckling divided by the compressive force exerted on the real object. In other words, a large buckling load factor indicates that the object is safe from buckling. The BLF value is significantly improved due to the application of the PFP. When a 6 mm thick PFP layer is applied to the beam, the buckling critical load increases by about 60 times compared to the case when there is no PFP layer.

For the PFP 6 mm thickness case, it shows a very similar value of the BLF value in case of no thermal load. In addition, as more PFPs are applied, it can be seen that the BLF value gradually increases. It can be seen that the PFP layer contributes to the increase in stability against buckling.

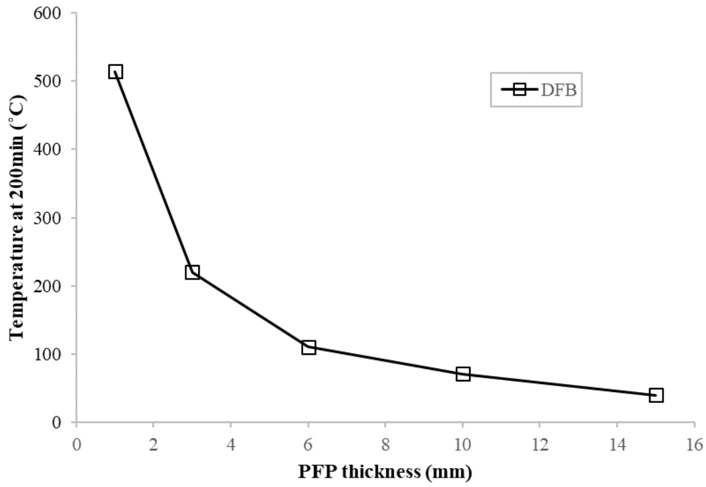
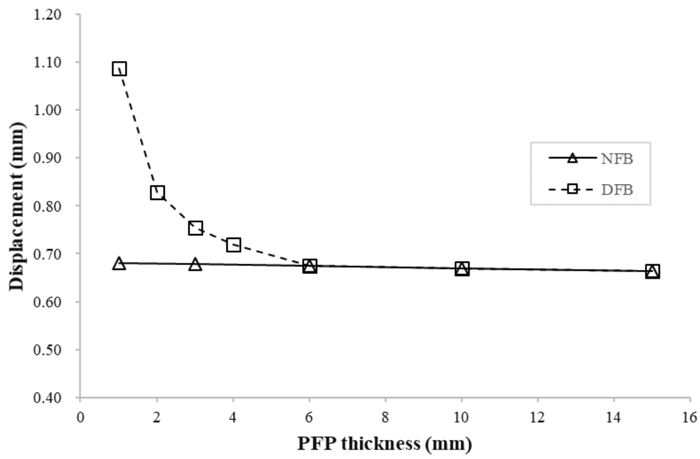
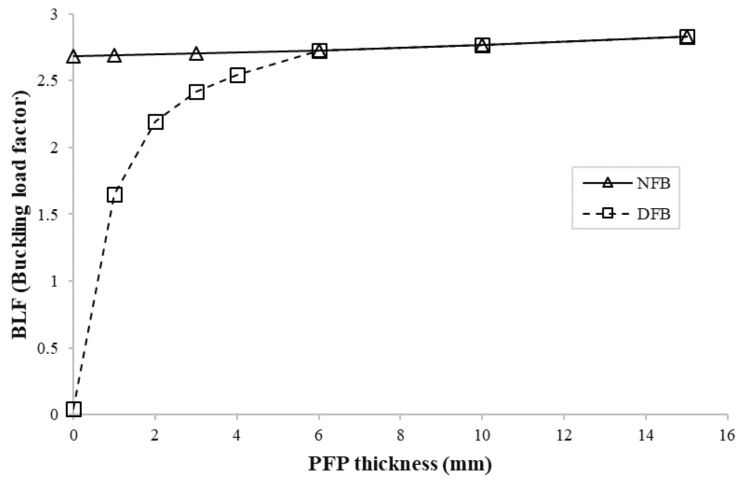


Figure 15. Temperature by PFP thickness in DFB Analysis (After 200 Minutes)



(a) Displacement



(b) BLF value

Figure 16. Displacement and BLF for each PFP thickness (Self-weight is considered)

Figure 17 shows the amount of compression displacement over time. The effect of applying the PFP to the four sides of the I-beam can be clearly seen by comparing DFB-00 and DFB-01. Even a very small amount of the PFP has a clear effect on reducing the heat transfer. In addition, as the PFP is applied thicker, the amount of heat transmitted to the steel is getting smaller. Therefore, there is no significant change in displacement.

Here, it can also be seen that when the thickness is greater than a particular thickness, the effect of the increase in the amount of PFP on the deformation of the beam is reduced. The particular thickness value in this study can be determined as 6 mm and a larger amount of PFP than 6mm can be considered as overused. However, it is clear that even though the amount of reduction in deformation is small compared to the amount of the increased PFP, it contributes to the reduction in the deformation of the structural member.

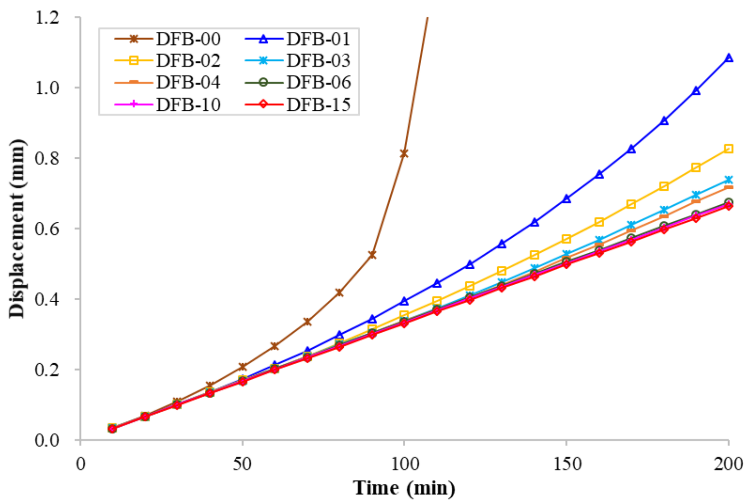


Figure 17. Displacement change by compression over time by changing PFP thickness

5. Discussions

Various types of numerical analysis cases were considered for the PFP-applied beam. The research findings offer a new perspective on designing PFP for offshore structures.

According to the current study, the following points can be emphasized:

1) Large number of research studies have been conducted on the efficient use of the PFP and the optimized design of the PFP-applied structures. However, the strength of the PFP itself has not been considered. In this study, the structural behavior of the PFP-applied beam was analysed using the PFP tensile strength value. This is the beginning of a new perspective in the field of the PFP research.

The structural members which were analysed in this study is an I-beam. It is the most widely used primary member in offshore structures. Numerical analysis of 44 cases were considered by combining the PFP application condition, application thickness, and fire load application condition for this beam.

Coupled analysis was performed to simulate the actual structural member situation and includes thermal and structural analyses. Firstly, the thermal analysis was performed by inputting the time-dependent standard hydrocarbon fire temperature and the result was used for structural analysis. The temperature changes for 200 minutes and the structural behavior of the beam were analysed.

When performing the thermal analysis, the quality of the analysis result was improved by considering the temperature dependent properties such as specific heat and thermal conductivity. In structural analysis, the relationship between the safety of buckling and the application of the PFP layer was analysed by using the BLF value.

2) This study offers a new perspective. Efforts were made to find the positive effects of the PFP material which has no function on structures unless a fire breaks out. This attempt can contribute to the cost reduction of offshore structures fabrication. The PFP is very widely applied to structures and it is often overused. If the technical data on the structural rigidity is inputted in the structural design, the effect of reducing the size of structural members can be expected. In addition, it would be possible to solve the problem of the excessive PFP application in the field. This study is the first step towards those goals.

3) This study considered the inclusion of the temperature-dependent material properties as much as possible. However, there is lack of information about temperature-dependency of some of the PFP properties such as the density and elastic modulus. For more accurate simulation of the PFP and beam behavior during a fire, studies on these two properties are definitely needed.

4) A mesh made by steel or fiber is one of the components of the PFP system. However, since the information on the mesh properties is not clear, the effect of it was not considered in this study. It will be necessary to study the mechanical properties of the mesh and include it in numerical analysis and experiments in the future.

6. Conclusions

PFP is widely used to help maintaining the integrity and stability of offshore structures for a certain period from hydrocarbon fires. In this study, the thermal and structural behaviour of PFP-applied beams before and during the fire was analysed using ANSYS.

The research findings can be summarised as:

1) From the results of heat transfer analysis, it was confirmed that in all cases, the application of PFP, even for a very small amount, significantly delayed the rate of heat transfer from the fire to the steel. The thicker the PFP, the greater reduction of the heat transfer takes place. However, when the thickness of PFP is greater than a certain value (6 mm), the effectiveness decreases.

2) A condition in which the PFP was not applied on the top surface of the I-beam was considered. Coupled analysis was performed on the cases where fire heat was directly transmitted to the top surface (DF4 analysis cases) and the case where it was not (DF3 analysis cases). As the thickness of the PFP increases, the deformation of the steel caused by heat decreases, but there is no significant change in the vertical

displacement of the beam. Looking at the DF4 cases' results of the displacement of the I-beam over time, the rate of the displacement change increased by about 2 times after about 100 minutes.

3) The buckling analysis was performed on the PFP-applied column structure. It was confirmed that both the displacement and the BLF value caused by the compressive force were sufficiently improved until the PFP reached a certain thickness. In particular, when the PFP layer is applied to the I-beam, the critical buckling load is improved by about 60 times compared to the case without the PFP layer. However, after reaching a certain thickness, the amount of thermal load had little impact on both the displacement and the BLF value. This is related to the point when the temperature of the steel remains below 100°C when the PFP is thicker than 6 mm.

4) This study will contribute to other further studies on the application of PFP as providing a new perspective to study structural analysis of PFP and beam composite.

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