Advanced Methodology of Structural Redundancy Analysis for Optimizing Passive Fire / Cryogenic Spill Protection

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Abstract: An advanced methodology for structural redundancy analysis against pool fire and cryogenic spill hazards was established to optimize the application area of Passive Fire Protection (PFP) and Cryogenic Spill Protection (CSP) on structural steels for onshore Oil and Gas plants.

PFP and CSP on structural steels are widely applied to reduce the risk of escalation from fire or cryogenic spill hazards in the oil and gas industry. However, PFP and CSP not only require initial material and application cost but also introduce additional risk of corrosion under insulation (CUI), etc.; thus, optimization of the PFP/CSP is beneficial in many situations.

The structural redundancy analysis can optimize PFP/CSP application area by identifying which structural members are necessary to maintain the structure’s integrity. This analysis has been applied considering jet fire hazards in offshore projects up till the present; however, it has not been widely adopted for pool fire or cryogenic spill hazards in onshore projects. One major reason is that the structural redundancy analysis requires fire simulations by CFD and heat transfer analysis and structural analysis by FEM, thus the analysis consumes many resources and only a limited number of scenarios can be evaluated during the detailed engineering phase. To extend the analysis to all pool fire or cryogenic spill scenarios and affected structures in onshore projects, a new structural redundancy analysis methodology has been established by developing the methodology used in offshore projects.

The analysis is conducted using STAAD.Pro and Abaqus which are commonly used for linear and non-linear analysis of structures, respectively. This paper describes the analysis methodology, its effectiveness and benefits compared with the conventional design methodology in accordance with code and standard.

Keywords: Pool Fire, Cryogenic Spill, PFP/CSP, Structural Redundancy Analysis, STAAD.Pro, Abaqus

1. Introduction

Passive Fire Protection (PFP) and Cryogenic Spill Protection (CSP) are widely applied on structural steels to reduce the risk of escalation from fire or cryogenic spill hazards in the oil and gas industry. However, PFP and CSP are costly in terms of the material itself and cause corrosion under insulation (CUI) if inspection and maintenance are not properly implemented through the life of the plant. Thus, optimization of PFP/CSP is beneficial in any oil and gas projects.

One of the most effective methods to optimize PFP/CSP application is through structural redundancy analysis, by identifying which structural members are critical to maintain structure's integrity and should be applied with PFP/CSP. Figure 1 shows the concept of the structural redundancy analysis.

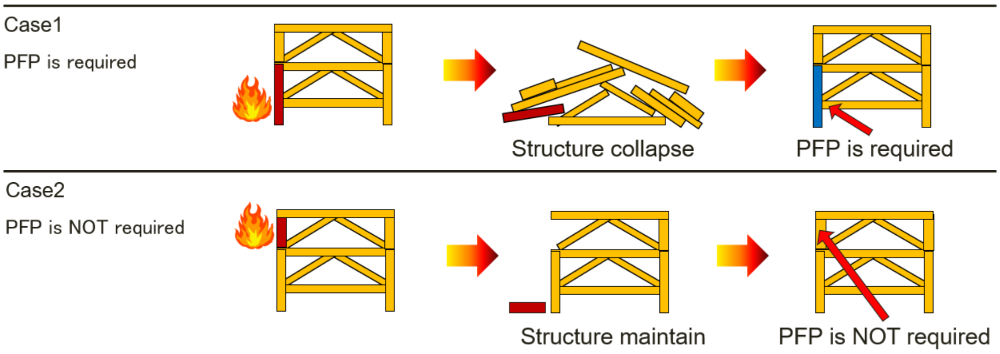

Figure 1. Simple Image of Structural Redundancy Analysis

This analysis has been widely applied against jet fire hazard in offshore projects; however, it has not been applied against pool fire and cryogenic spill hazard in onshore projects. This is because offshore installations are required to minimize the risk of CUI under harsh offshore environment and the topside weight and cost. On the contrary, onshore installations are relatively easier to provide inspection and maintenance for PFP/CSP, and are not subject to a stringent weight limit because many onshore installations have been constructed by stick built, as opposed to modular construction. Also, the typical material for PFP to protect against pool fire hazards is dense concrete or a lightweight cementitious material that are not so costly. However, onshore installations have come to apply modular construction and the projects request to apply CSP recently, especially for LNG production facilities. Thus, optimization of PFP/CSP is seen favorably as a means to reduce project cost. There is a challenge in the current structural redundancy analysis that it consumes a significant amount of computing time due to simulations by CFD, heat transfer analysis and structure analysis by FEM. This is why in practice only a limited number of scenarios can be evaluated during the detailed engineering phase of a project.

To conduct the analysis for a wider range of scenarios in large onshore projects, an advanced redundancy analysis methodology against pool fire and cryogenic spill hazards has been established based on the methodology applied in offshore projects.

2. Advanced Methodology for Structural Redundancy Analysis

Figure 2 shows the overall steps of the advanced methodology for structural redundancy analysis against pool fire and cryogenic spill hazards.

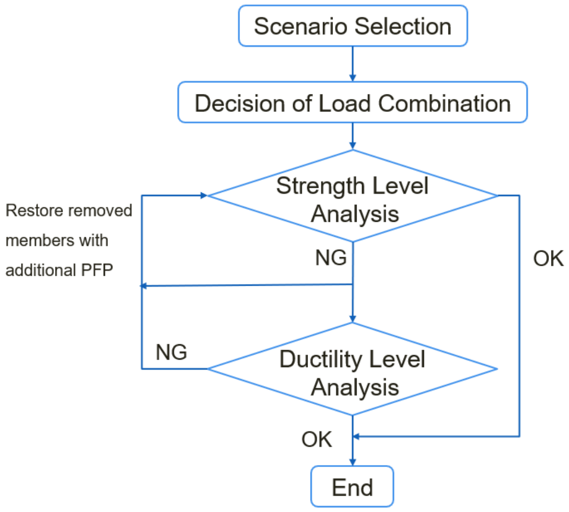

Figure 2. Overall Steps of Advanced Methodology

2.1. Scenario Selection

2.1.1. Pool Fire Scenario Selection

As the first step, the pool fire scenarios subjected to this analysis are selected.

Generally, the sources of pool fire and their PFP extents are determined by the project requirement and there are two design approaches, i.e., Risk-Based Approach and Prescriptive Approach. This paper details the explanation based on the prescriptive approach as per API RP 2218[1], because it is applied to most onshore projects. However, this method can be applied to pool fire scenarios identified according to the risk-based approach.

The first step is identifying equipment which has the potential for causing pool fire hazards, known as fire potential equipment. API RP 2218[1] can be referred to identify high, medium and low fire potential equipment based on the type of equipment, operating condition, fluid properties, etc. The fire scenario envelope is the three-dimensional cylindrical space showing the extent of thermal radiation intensity from the pool fire, which causes substantial property damage. In the case of hydrocarbon pool fires, the typical fire scenario envelope extends from a 6 m to a 12 m radius, and heights from a 6 m to a 12 m from the source of liquid fuel. These fire scenario envelopes are then represented in plot plan drawings and a 3D model according to the location of the fire potential equipment. Figure 3 shows an example of fire scenario envelopes and the affected structural members.

The structural members within the fire scenario envelope are identified by referring to the 3D model and are removed from the structural analysis model, since all the structural members within the fire scenario envelope are assumed to collapse. Although pool fire intensities are relatively lower than jet fires', the duration can be much longer, e.g., 2 hours, which is potentially long enough to damage structural members that are exposed to the pool fire. The temperature analysis in accordance with API RP 2FB[2], shows that the structural members reach their critical temperature regardless of the size of the structural members. Therefore, the temperature analysis does not need to be conducted unless the pool fire scenario duration is deemed short by the Fire Risk Analysis.

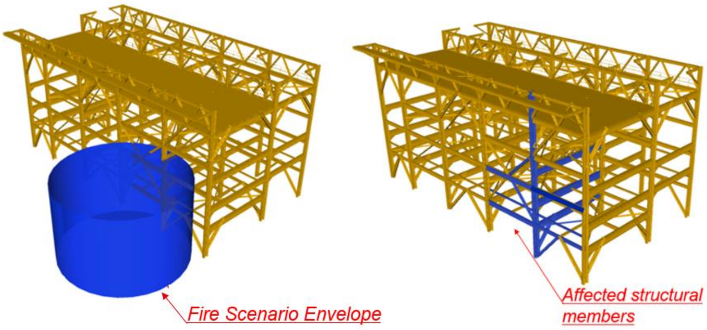

Figure 3. Fire Scenario Envelope and Affected Structural Members

2.1.2. Cryogenic Spill Scenario Selection

Currently, no standard or published engineering practice is available to determine the impact of cryogenic spill scenarios following the prescriptive approach. If the risk-based approach is applied, the extent of the cryogenic spill and duration can be obtained. When the extent is to be determined without the risk-based approach, it can be determined considering a leak frequency from a source of cryogenic spill, the direction of the spill, the equipment layout, and past project experiences which applied a risk-based approach, etc. Typically, a 5 mm to a 10 mm equivalent release hole size can be assumed depending on the degree of congestion and the extent of the cryogenic spill can be calculated by a consequence calculation software, e.g., PHAST by DNV. A pressurized cryogenic spill can spread in all directions, and therefore several discharge directions should be considered including the most severe scenarios in terms of the type and number of affected structural members. These should be selected for further analysis.

The temperature analysis does not need to be conducted, since the structural members exposed to the cryogenic spill will reach the ductile-brittle transition temperatures in a short period of time. All members exposed to the cryogenic spill should be removed from the structural analysis model. Cryogenic spill impinged on a structural member can drip down to the ground level along with the structural column, the impinged member and all lower members should be removed.

Figure 4 shows an example for selected cryogenic spill scenario and affected structural members.

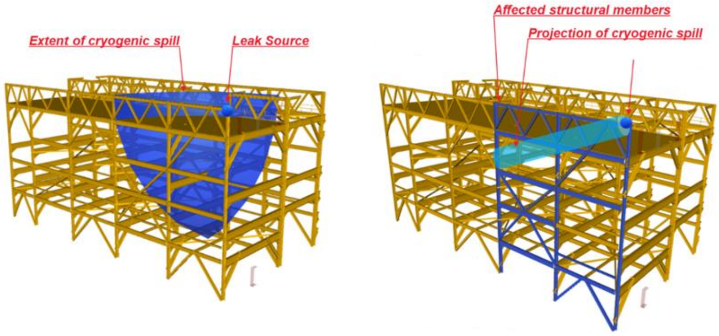

Figure 4. Selection of Cryogenic Spill Scenario and Affected Structural Members

(Leak from Air Cooled Heat Exchanger on the Top of Structure)

2.2. Decision of Load Combination

An important part in the structural model is setting the load combination to be considered. For example, one consideration could be that gravity loads are included exclusively, and low frequency loads such as wave, wind, or live loads are not included. This is an approach presented in the FABIG Technical Note 13[3]. Other approaches e.g. ASCE 7-10 [5] expect loads such as snow load or rain load to be included depending on the geographical location of the project site.

2.3. Strength Level Analysis

Strength Level analysis is a conventional linear elastic analysis using structural design software, e.g., STAAD.Pro by Bentley. The methodology of strength level analysis is the same for both pool fire and cryogenic spill scenarios.

The criterion for the strength level analysis is an utilization ratio of 1.5 in accordance with API RP 2FB[2]. Although the scope of this code and standard is for offshore facilities, the same criterion can be applied to the onshore facilities.

The strength level analysis is conducted according to the following steps:

1) Remove the structural members as per Subclause 2.1.1 and 2.1.2 from the structural analysis model.
2) Calculate the utilization ratio, the ratio of actual stress to allowable stress, based on the situation of the load combination in accordance with Clause 2.2.
3) If the calculated utilization ratio is lower than 1.5, then the redundancy analysis is completed, which means no PFP or CSP is required for the selected scenario.
4) If the calculated utilization ratio is higher than 1.5, then there are two options. One is to restore some of the removed members which contribute to the structure's integrity with addition of PFP/CSP, such as the large columns at the corner of the module structure. Another is to proceed with Ductility Level Analysis in accordance with Clause 2.4.
5) When some members are restored with addition of PFP/CSP, strength level analysis is to be conducted to confirm if the criterion of the utilization ratio is met, or to recalculate load distribution for the following ductility level analysis.

Figure 5 shows an example of strength level analysis results. Red portions show the members where the calculated utilization ratio is higher than 1.5 and green portions means the members where the ratio is less than 1.5.

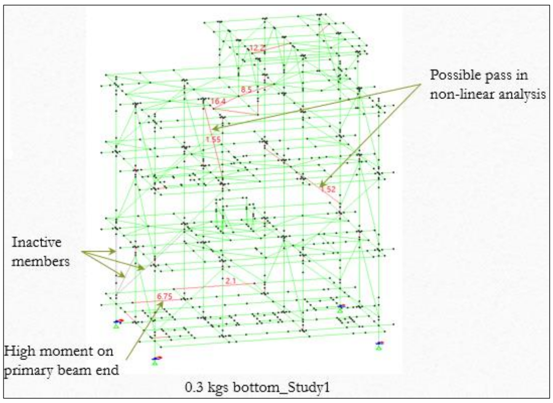

Figure 5. Example for Strength Level Analysis Result

2.4. Ductility Level Analysis

As shown in the overall steps in Figure 2, ductility level analysis follows the strength level analysis if the calculated utilization ratio is higher than 1.5. The structural model in the strength level analysis is used in the ductility level analysis to keep consistent analysis conditions, including the structure's configuration and load combination considerations.

Ductility level analysis is a nonlinear elastic-plastic analysis which is undertaken using structure analysis software, e.g., Abaqus by Dassault Systemes.

The ductility level analysis is conducted according to the following steps:

1) Import the structural model used in the strength level analysis into the non-linear elastic-plastic analysis software.
2) Confirm if the residual deformation is acceptable, for example, there is no progressive deformation.
3) If the result exceeds the tolerance, additional PFP/CSP should be applied to some structural members and re-run strength level analysis and ductility level analysis until the result is acceptable.

Figure 6 shows an example of the displacement result from the ductility level analysis. The red portion in Figure 6 shows the significant deformation. If such deformation happens, additional PFP/CSP should be considered for the members that are critical to the structure's integrity.

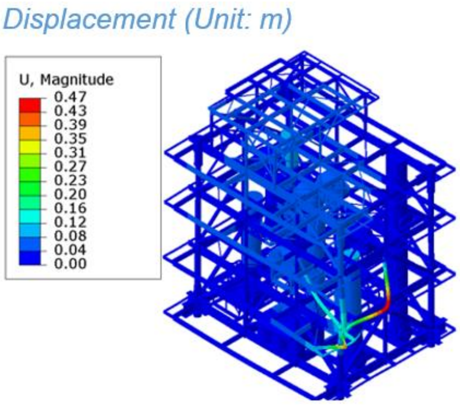

Figure 6. Example for Ductility Level Analysis Result

3. Case Study

3.1. Pool Fire Scenario

This section presents the structural redundancy analysis conducted using a pool fire case scenario.

As a first step, a pool fire with a horizontal radius of 9 m occurring under the pipe rack is assumed as the scenario that is subjected to structural redundancy analysis.

Three fire scenarios with different conditions are studied, namely Scenario 1, 2 and 3. Scenario 1 represents a pool fire scenario that originated from a pump near the pipe rack structure. The height of the fire scenario envelope for Scenario 1 is 12 m. Scenario 2 shows a pool fire scenario around the pump near a pipe rack structure supporting an air cooled heat exchanger (ACHE), resulting in part of the pipe rack being contained within the fire scenario envelope. Scenario 3 is a pool fire scenario that occurred due to leakage from ACHE, resulting in many members of the pipe rack being contained within the fire scenario envelope. For Scenario 2 and Scenario 3, the height of fire scenario envelope is considered to reach the highest structural members below ACHE, since it is commonly accepted that the pool fire hazard escalates vertically under ACHE due to an upward air current[6].

Figure 7 illustrates the three selected pool fire scenarios and Table 1 summarizes the condition of each pool fire scenario.

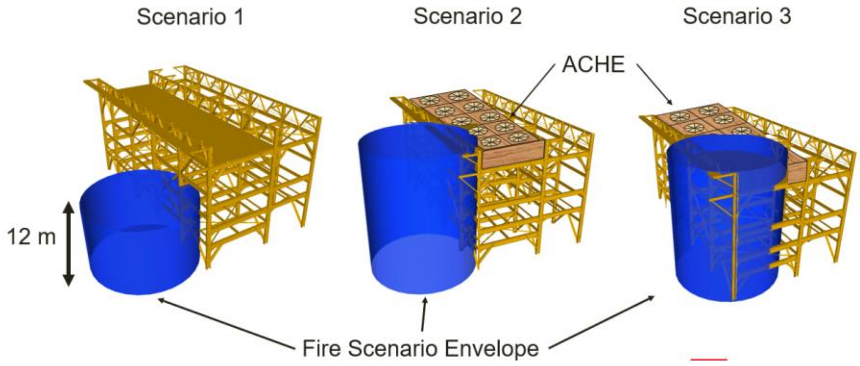

Figure 7. Selected Pool Fire Scenario

Table 1. Pool Fire Conditions for Each Scenario

	Pool Fire Conditions			Structure
	Source	Radius	Height	
Scenario 1	Pump	9 m	12 m	Piperack
Scenario 2	Pump	9 m	Up to Highest Member	Piperack with ACHE
Scenario 3	ACHE	9 m	Up to Highest Member	Piperack with ACHE

Next, load combination is decided to include gravity load with notional load based on ASCE 7-05 / 7-10[4, 5], which is applied to all scenarios.

3.1.1. Result of Redundancy Analysis for Scenario 1

In the strength level analysis for Scenario 1, the red highlighted structural members in Figure 8 were affected by heat radiation and removed from the structural analysis model, STAAD Pro. In this scenario, no member is expected to fail (maximum utilization ratio: 0.99), which means the structure's integrity can be maintained without PFP for the given pool fire scenario and no further assessment is required.

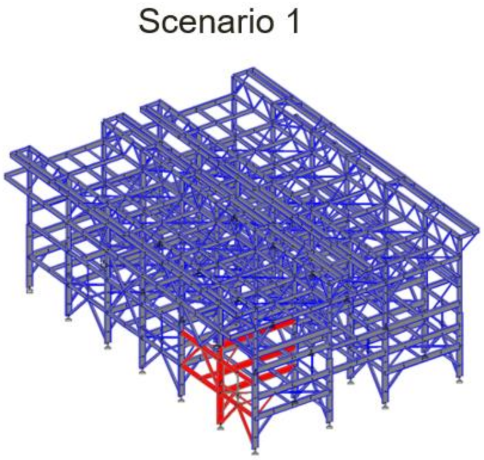

Figure 8. Affected and removed members for Pool Fire Scenario 1

Table 2. Maximum Utilization Ratio among the Structural Members for Scenario 1

Member No.	Type	Utilization Ratio	Result
1791	Dia-Beam	0.99	Not Failed

3.1.2. Result of Redundancy Analysis for Scenario 2

In the strength level analysis for Scenario 2, the red highlighted structural members in Figure 9 were removed from the structural analysis model. The members dedicated to support ACHE are not removed in this case because it is clear that collapse of those members cause escalation of pool fire and PFP is required to be applied for those members. As a result of strength level analysis, column members in Figure 10 are expected to fail because the load and actual stress of the member increase.

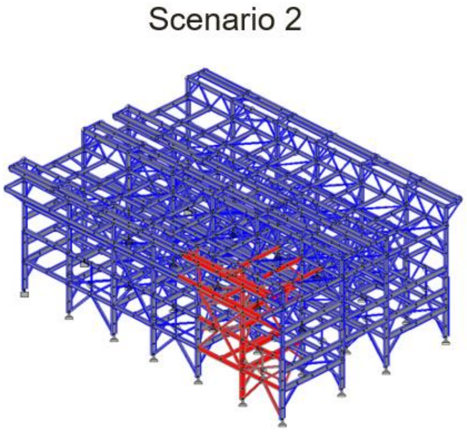

Figure 9. Affected and Removed Members for Pool Fire Scenario 2

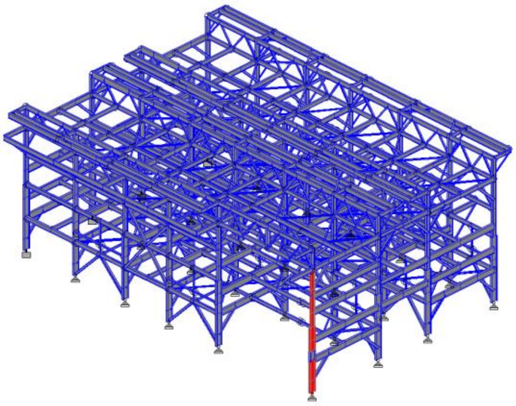

Figure 10. Failed Members for Pool Fire Scenario 2

Table 3. Utilization Ratio of the Failed Members for Scenario 2

Member No. (Highlighted Portion)	Type	Utilization Ratio	Result
7	Column	2.048	Failed
384	Column	1.715	Failed
402	Column	1.622	Failed
464	Column	2.027	Failed
582	Column	1.782	Failed
712	Column	1.306	-
1248	Column	1.974	Failed
1538	Column	1.158	-

Since failed members are necessary to maintain the structure's integrity, the result of the strength level analysis cannot be accepted. Thus, ductility level analysis is conducted using Abaqus without addition of PFP on the members. Figure 11 shows the result of ductility level analysis. Since deformation occurs for only a minor portion of the structure as shown in red in Figure 11, no further analysis is required and additional PFP is not required to be applied.

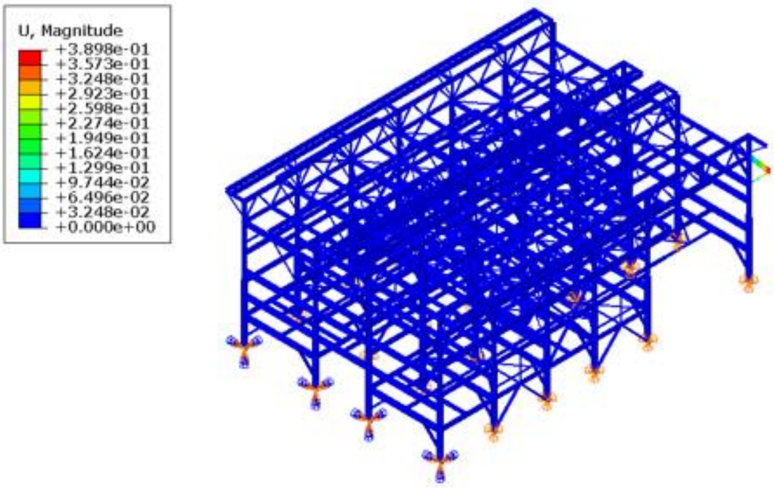

Figure 11. Ductility Level Analysis for Pool Fire Scenario 2

3.1.3. Result of Redundancy Analysis for Scenario 3

In the strength level analysis for Scenario 3, the red highlighted structural members in Figure 12 are removed from the structural analysis model. This Scenario 3 is the most severe scenario out of the three scenarios since many numbers of the structure will be removed. The result of the strength level analysis shows that the red highlighted members in Figure 13 are expected to fail due to compression/tension from cantilevered ACHE support.

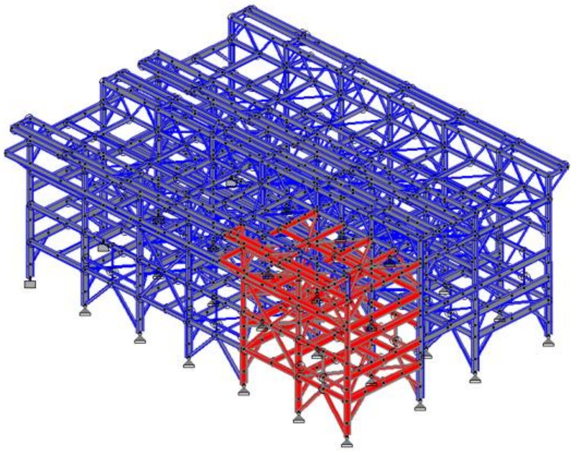

Figure 12. Affected and Removed Members for Pool Fire Scenario 3

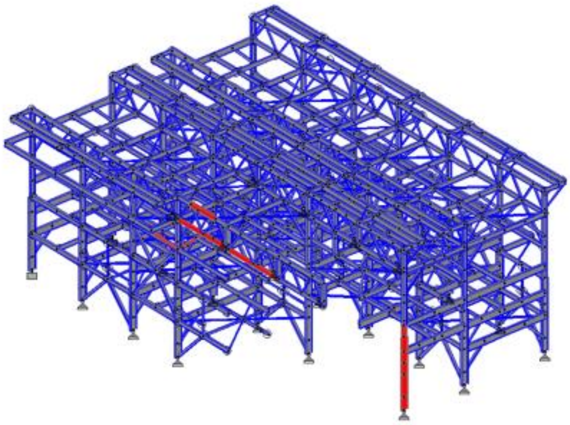

Figure 13. Failed members for Pool Fire Scenario 3

Table 4. Utilization Ratio of the Failed Members for Scenario 3

Member No. (Highlighted Portion)	Type	Utilization Ratio	Result	Member No. (Highlighted Portion)	Type	Utilization Ratio	Result
13	Column	1.824	Failed	798	Column	1.794	Failed
14	Column	1.249	-	799	Column	1.914	Failed
41	Column	1.826	Failed	840	Z-Beam	3.644	Failed
42	Column	1.248	-	841	Z-Beam	1.308	-
355	Column	1.721	Failed	1025	Z-Beam	1.278	-
356	Column	1.17	-	1163	Z-Beam	1.514	Failed
381	Column	1.833	Failed	1254	Z-Beam	1.825	Failed
399	Column	1.703	Failed	1255	Column	1.249	-
470	Column	1.816	Failed	1529	Column	1.547	Failed

471	Column	1.248	-	1693	Column	1.671	Failed
560	Column	1.832	Failed				
561	Column	1.342	-				
709	Column	1.693	Failed				

Following the strength level analysis, ductility level analysis is conducted without addition of PFP on any failed members, and Figure 14 shows the result. As shown in Figure 14, ACHE cantilever members are expected to fail due to displacement from horizontal load. In accordance with overall steps shown in Figure 2, the strength level analysis needs be conducted again after some removed members are restored with PFP.

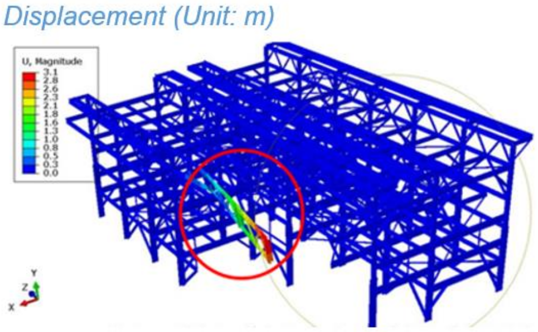

Figure 14. Result of Ductility Level Analysis for Scenario 3

Figure 15 shows the updated strength level analysis model with the restored members and additional PFP. The restored members are selected taking into account the result of the ductility level analysis in Figure 14. As a result of the strength level analysis after addition of PFP, the calculated utilization ratio of the restored members is still higher than 1.5 and Figure 16 shows the failed members highlighted in red.

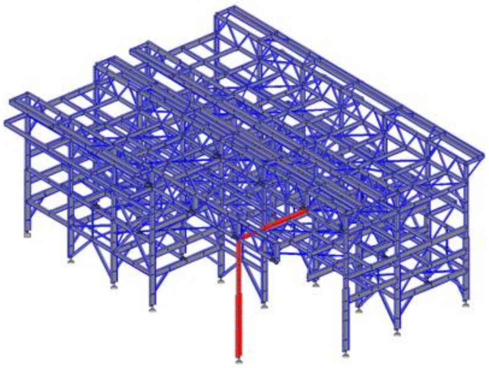

Figure 15. Restored Members with PFP

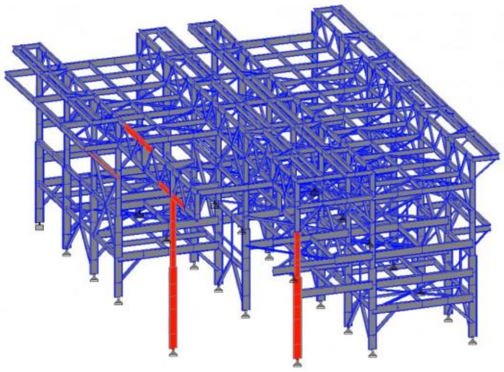

Figure 16. Failed Members for Pool Fire Scenario 3 after Addition of PFP

Table 5. Utilization Ratio of the Failed Members for Scenario 3 after Addition of PFP

Member No. (Highlighted Portion)	Type	Utilization Ratio	Result	Member No. (Highlighted Portion)	Type	Utilization Ratio	Result
6	Column	1.935	Failed	711	Column	1.695	Failed
14	Column	1.907	Failed	798	Z-Beam	2.068	Failed
42	Column	1.924	Failed	839	Z-Beam	1.344	-
356	Column	1.912	Failed	992	Z-Beam	1.853	Failed
382	Column	1.902	Failed	1025	Z-Beam	1.73	Failed
383	Column	1.828	Failed	1040	Z-Beam	1.31	-
400	Column	1.917	Failed	1247	Column	1.726	Failed
401	Column	1.706	Failed	1255	Column	1.931	Failed
463	Column	2.068	Failed	1523	Column	1.91	Failed
471	Column	1.921	Failed	1693	X-VBrace	1.658	Failed
561	Column	1.914	Failed				
581	Column	2.036	Failed				
710	Column	2.066	Failed				

Ductility level analysis is conducted again for the structure model with added PFP. The structure model which is used for the strength level analysis is imported into Abaqus. Figure 17 shows the result of ductility level analysis after addition of PFP. The displacement of members is not significant (maximum 0.04 m) and it is concluded that the result is acceptable and no further PFP is required for Scenario 3. Figure 18 shows the final result with the PFP applied members.

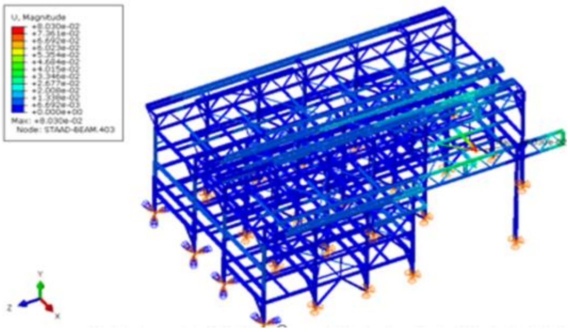

Figure 17. Result of Ductility Level Analysis after Addition of PFP

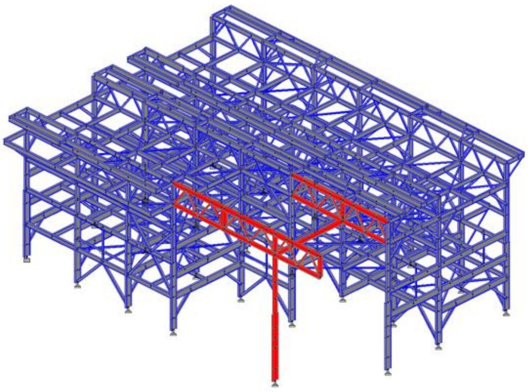

Figure 18. Final Result of PFP applied Members

3.2. Result for Cryogenic Spill Scenario

In the same way as pool fire case, a cryogenic spill scenario and the affected structural members are selected first.

A cryogenic spill release from an air-cooled heat exchanger is considered since a pressurized release from an elevated location has the potential to impact many members of the structure. The extent is calculated by consequence analysis software, PHAST by DNV. The shape of the cryogenic release is a cone with the apex at the release point and it is treated as a cylinder shape with the calculated extent of 18.0 m and the base diameter of 1.0 m for the analysis model.

As described in Subclause 2.1.2, the cryogenic spill direction shown in Figure 19 is selected as the most severe scenario considering the type and number of affected structural members. Structural members shown in Figure 20 are then removed from the strength level analysis model as those are expected to be affected by this cryogenic spill scenario. This removal process also considers the possibility of the cryogenic leaking downwards along the structure.

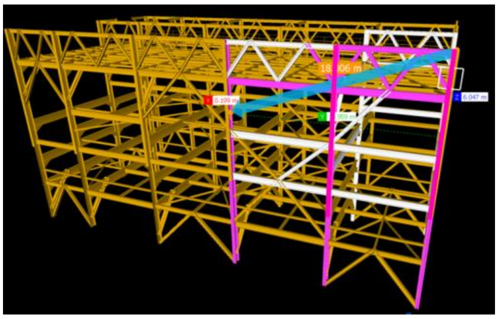

Figure 19. Cryogenic Spill Scenario from Air Cooled Heat Exchanger

(Light Blue: Cryogenic Spill, Pink: Affected Members)

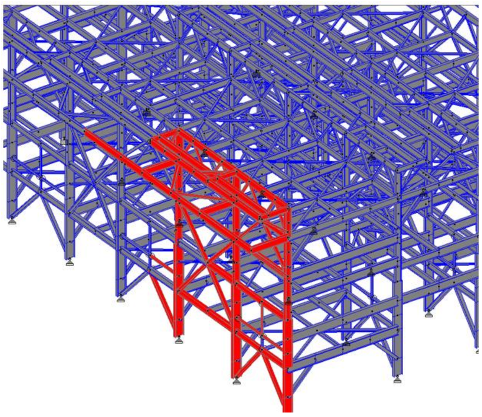

Figure 20. Affected and Removed Members for Cryogenic Spill Scenario

For the load combination, the same load combinations as the pool fire scenarios described in Clause 3.1 were applied.

The result of the strength level analysis shows that one vertical brace in Figure 21 is expected to fail in compression where utilization ratio is 1.66 over 1.5. Although this utilization ratio is not so high, ductility level analysis is conducted to confirm whether additional CSP is required.

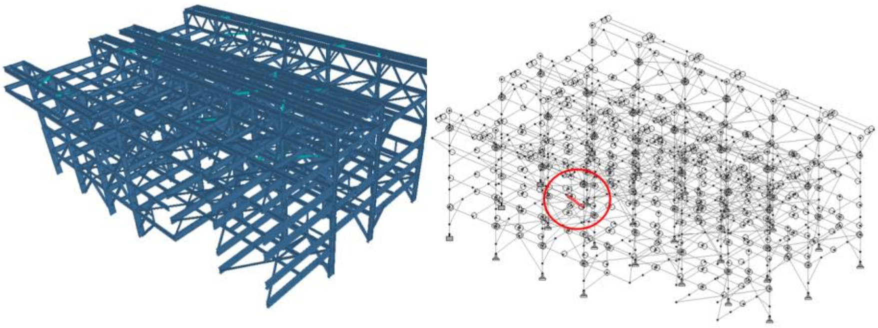

Figure 21. Failed Member in Strength Level Analysis

Figure 22 shows the result of ductility level analysis. There is no significant progressive deformation which the maximum vertical displacement is only 0.095 m in the cantilever beam and the stress level is still lower than the yield stress.

In conclusion, no CSP is required for this cryogenic spill scenario.

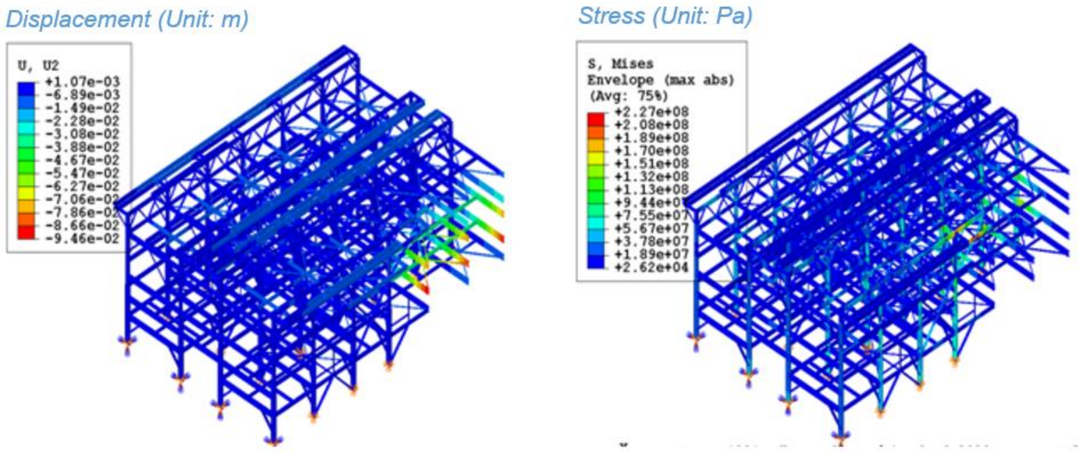

Figure 22. Result of Ductility Level Analysis for Cryogenic Spill Scenario

4. Conclusion

An advanced methodology for structural redundancy analysis has been established for pool fire and cryogenic spill hazards at onshore facilities based on the methodology applied to offshore facilities. By conducting case studies using linear and non-linear structural analysis software, the established methodology has been demonstrated. The application of this methodology allows the optimization of PFP and CSP applied areas by identifying the members which are critical for the structure's integrity. The advanced methodology can save time, compared with the conventional methodology, since fire and cryogenic spill simulation by CFD and heat transfer analysis by FEM are not required.

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