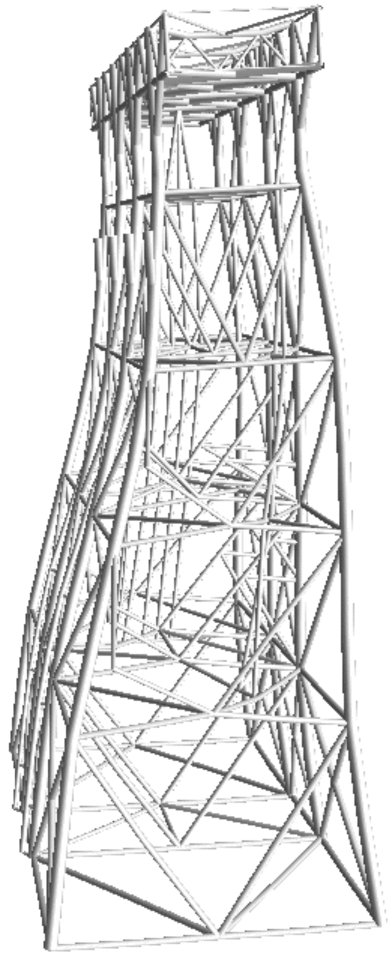
Fire Analysis

using

KFX, FAHTS and USFOS.



CONTENTS

1 Summary

The "Integrated Fire Assessment" is a method utilizing the following three inter-linked software tools:

- KFX : Simulation of the fire process
- FAHTS Computing the steel temperature based on KFX result
- USFOS Estimating the ultimate strength of the temperature-degraded structure

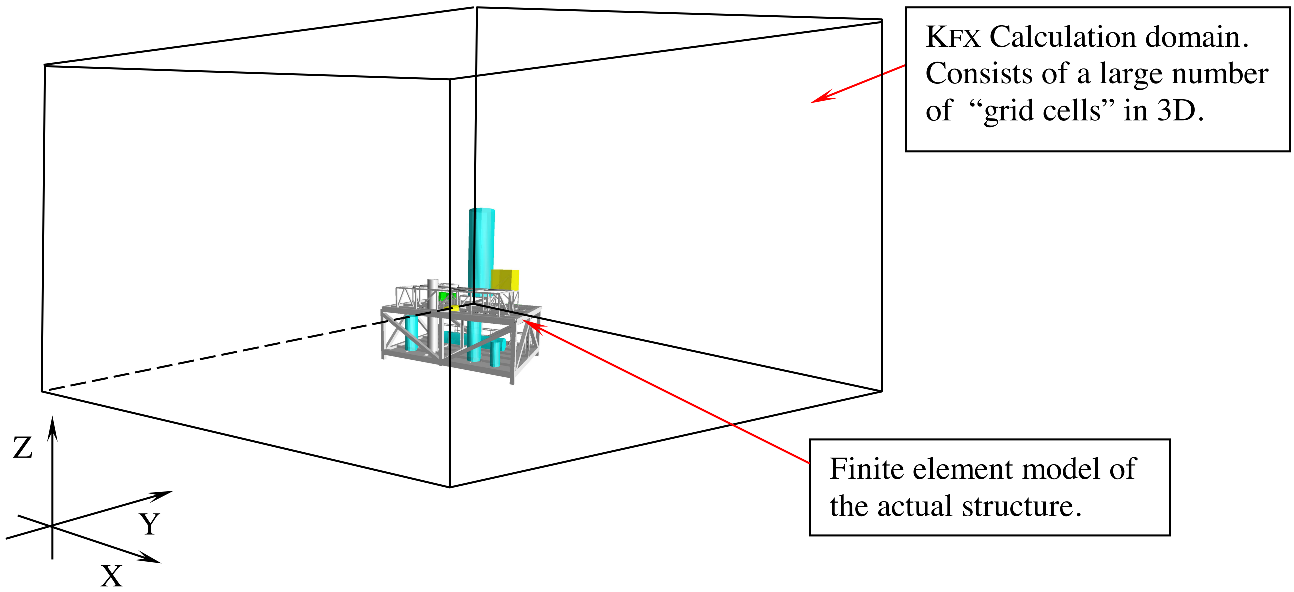
Key words:

- Gas- and Oil fires with different release rates, leak location, wind speed and direction.
- Presence of PFP, completely or partly, is accounted for
- Temperature dependent material properties, both thermal and mechanical
- Yielding of the steel and load re-distribution
- The ultimate resistance (strength) of the structure for different fire times and fire scenarios is identified.
- This ultimate resistance divided by the functional load gives the "Reserve Strength Ratio", RSR, at different fire times. RSR < 1.0 means that the structure will collapse.
- Depending on the wanted safety level, a minimum RSR is defined. This will be the basis for choice of amount of passive fire protection, PFP, to achieve this safety level.

2 Concept

The first version of the "Integrated Fire Assessment" tool was developed in the early 90's and consists of the following three "building blocks":

1. *"Kameleon FireEx"*, KFX:
   CFD based simulator for computing the combustion process of oil- and gas fires.
2. *"Fire And Heat Transfer Simulations"*, FAHTS:
   Finite element tool for simulation of the temperature rise in the steel structure based on results from KFX.
3. *"Ultimate Strength of Framed Offshore Structures"*, USFOS:
   Finite element tool for computing the ultimate strength of the degraded (by temperature) structure based on the temperatures computed by FAHTS.



The system works as follows:

1. The coordinate systems for KFX and the structure are identical.
2. This makes it possible for FAHTS to get the actual heat flux in every point of the structure by utilizing the data from KFX.
3. Two-dimensional elements (beams) are expanded to a 3D surface model in order to compute the surface heat flux, where the orientation of the surface is accounted for. (E.g.: a surface of a cross section facing away from the intense fire will receive less heat than a surface "looking at" the fire.)
4. The temperature fields from the 3D FAHTS element model is linearized and exported to USFOS. The temperature of a beam element in USFOS uses the mean cross section temperature and the temperature gradients to compute the mechanical degradation.
5. USFOS computes the ultimate strength of the degraded (by temperature) structure.
6. FAHTS and USFOS use the same structural model.

3 Methodology and Tools

3.1 Methodology

Several design/analysis methods exist, from simple temperature checks (e.g. 400°C) based on simplified "standardized" fires (e.g. NORSOK / HC), to *advanced* methods, which are tracing the accidental events from the actual hydrocarbon leak, ignition and combustion, heating of structural components up to material softening/weakening.

In scenario and performance based analyses, (which are the most advanced), real process information, probabilistic data for leakage frequencies /ignition and physical knowledge about leakage flows are used to identify the:

- Location of the hydrocarbon leaks
- Amount of gas and oil to be released
- Duration of the leak (valves shut, amount of fluid, etc).

This information is utilized in 3D dynamic fire simulators (KFX) in order to calculate realistic heat flux towards the structural components.

An offshore structure is designed to withstand a large number of different (mechanical) loads, from carrying its own weight including equipment, to extreme winds, acceleration from waves, transportation, etc.

In connection with the accidental fire condition, (Accidental Limit State, ALS), operational weight is the only loads considered, while direct environmental loads are normally small and neglected. However, modules on FPSO accounts for a certain roll acceleration in addition. This is the "functional load" to be carried in a fire.

As a minimum, the structure shall have a resistance corresponding to the actual functional load. In the simulation terms, this is denoted "load level = 1.0". A load level < 1.0 means that the structure will collapse.

In order to identify the structure's margins, the load level is increased beyond 1.0 until the structure becomes either unstable or get unacceptable large deformations.

If for example, the structure is able to carry 1.5 times its weight (functional load), the "Reserve Strength Ratio", RSR becomes 1.5.

RSR < 1.0 means that the structure will collapse, (or get unacceptable large deformations).

See section 3.5 on page 9 and /1/ for more information.

3.2 Temperature simulation utilizing KFX and FAHTS

The thermal response analyses are performed using the finite element tool FAHTS, together with the results from **KAMELEON FireEx ® KFX**, where detailed ray tracing gives the heat flux at the individual structural component surfaces, see Figure 3-1.

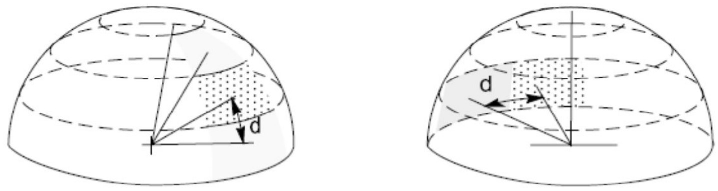


Figure 3-1 Ray-Tracing according to Shah and Lockwood.

The structural model is automatically transferred to surface shell elements in order to receive the correct heat flux and to capture thermal gradients over the cross section, caused by uneven fire exposure and/or partly protected members, see Figure 3-2. The heat exposure, (radiation heat flux and convective heat flux), is then varying from point to point on the structure depending on the actual point's coordinates and surface orientation (e.g. if the surface is facing against or away from the fire, etc.). Presence of PFP is accounted for.

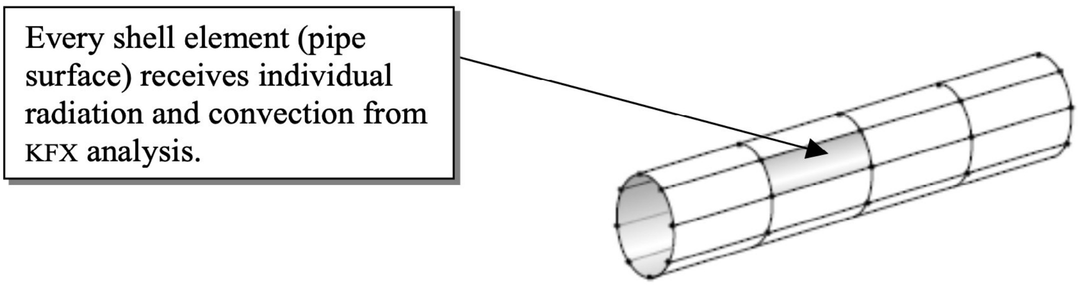


Figure 3-2 Heat flux input to the finite element model.

Different surfaces receive individual heat flux, and for the closed profiles (pipe, box), only the outer side will experience the fire. Internally, radiation between the inner surfaces will transfer heat from the most exposed side to colder parts, see Figure 3-3.

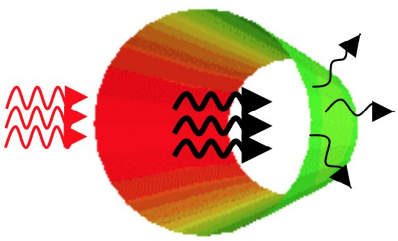


Figure 3-3 Internal radiation inside a pipe.

3.3 Mechanical Response of the degraded structure.

The mechanical response analysis is performed using the non-linear finite element program USFOS.

The program includes non-linear geometry effects, material yielding and thermal effects, (material degradation as function of temperature, see section 3.4 on next page).

USFOS calculates instability of individual components as well as system collapse.

The structural model used by USFOS is the same as that used by FAHTS. (It is possible for FAHTS to use a sub-set of this model to reduce the computation time for cases with localized fires).

This structural model has identical coordinate system as that used in the KFX simulations, and heat exposure on the different components is exported from KFX to USFOS automatically (via FAHTS).

The structure is accepted provided that:

- Global stability is preserved
- Deformations should not lead to escalations

In general, member yielding and buckling causing load shedding is allowed.

3.4 Temperature Degradation of mechanical material properties

The mechanical properties of metal are strongly dependent on the temperature. Depending on material type, different degradation curves are used. The curves are either predefined in USFOS (for steel and aluminium) or could be user-defined using commands: USERTDEP and TEMPDEPY.

USFOS is based on resultant plasticity, and the cross section parameters, (such as plastic bending capacity and axial), are degraded according to the curves. The transition from linear to plastic follows a smooth curve, which ensures numerical stability.

Figure 3-4 shows the degradation of the effective yield stress and E-modulus according to Eurocode-3.

The upper curve (square markers) represents the degradation of the "effective" yield stress, (ε = 2%), and for temperature below 400°C, the ultimate stress is unaffected.

The blue curve represents the E-mod.

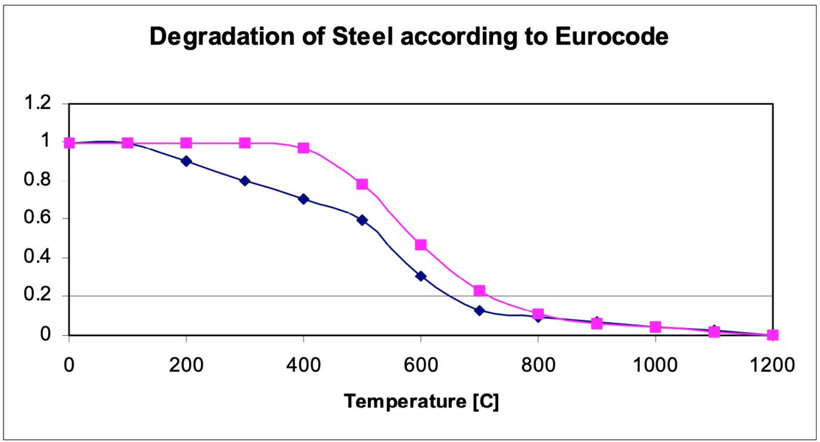


Figure 3-4 – Temperature degradation of steel according to Eurocode *)

**) Eurocode-EN 1993-1-2*

The USFOS command: "STEELTDEP " will assign the "Eurocode-3, 2%" curve to all material in the model.

The STEELTDEP combined with other default parameters in USFOS has shown good agreement with fire laboratory test of steel structures.

3.5 PUSHDOWN Method

The fire redundancy analyses (USFOS) are based on the "push-down" method. This means that the ***ultimate resistance*** of the degraded (by temperature) structure is computed.

It is required that the structure is, at least, able to carry the functional loads, ("load level 1.0" or higher).

Resistance above this minimum level could be interpreted as "reserve" or "safety margin".

The ratio between the structural resistance and the functional load is defined as the "Reserve Strength Ratio", RSR, (RSR ≥ 1 means that the structure is able to carry the functional loads. RSR < 1 means that the structure fails).

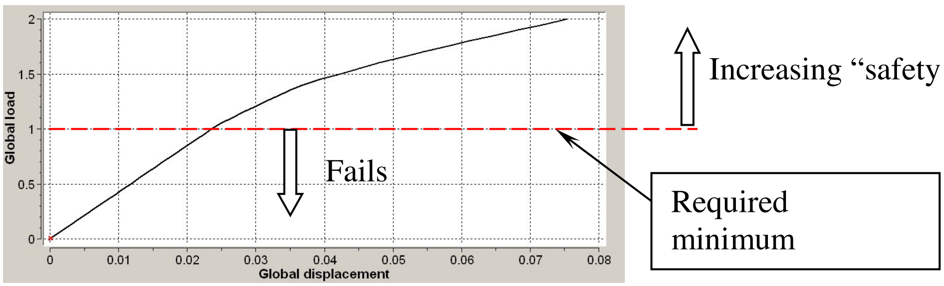


Figure 3-5 - Global Load vs. displacement. Load Level 1.0 corresponds to 100% load.

The general fire analysis procedure is described schematically in Figure 3-6. The inner loop uses the "PushDown" procedure, where the ultimate resistance for the functional loads of the degraded (by fire) structure is computed for every minute of the fire. Taking the peak from each pushdown simulation and placing it into the actual fire times create the structural degradation curve. Level 1.0 means 100% functional load.

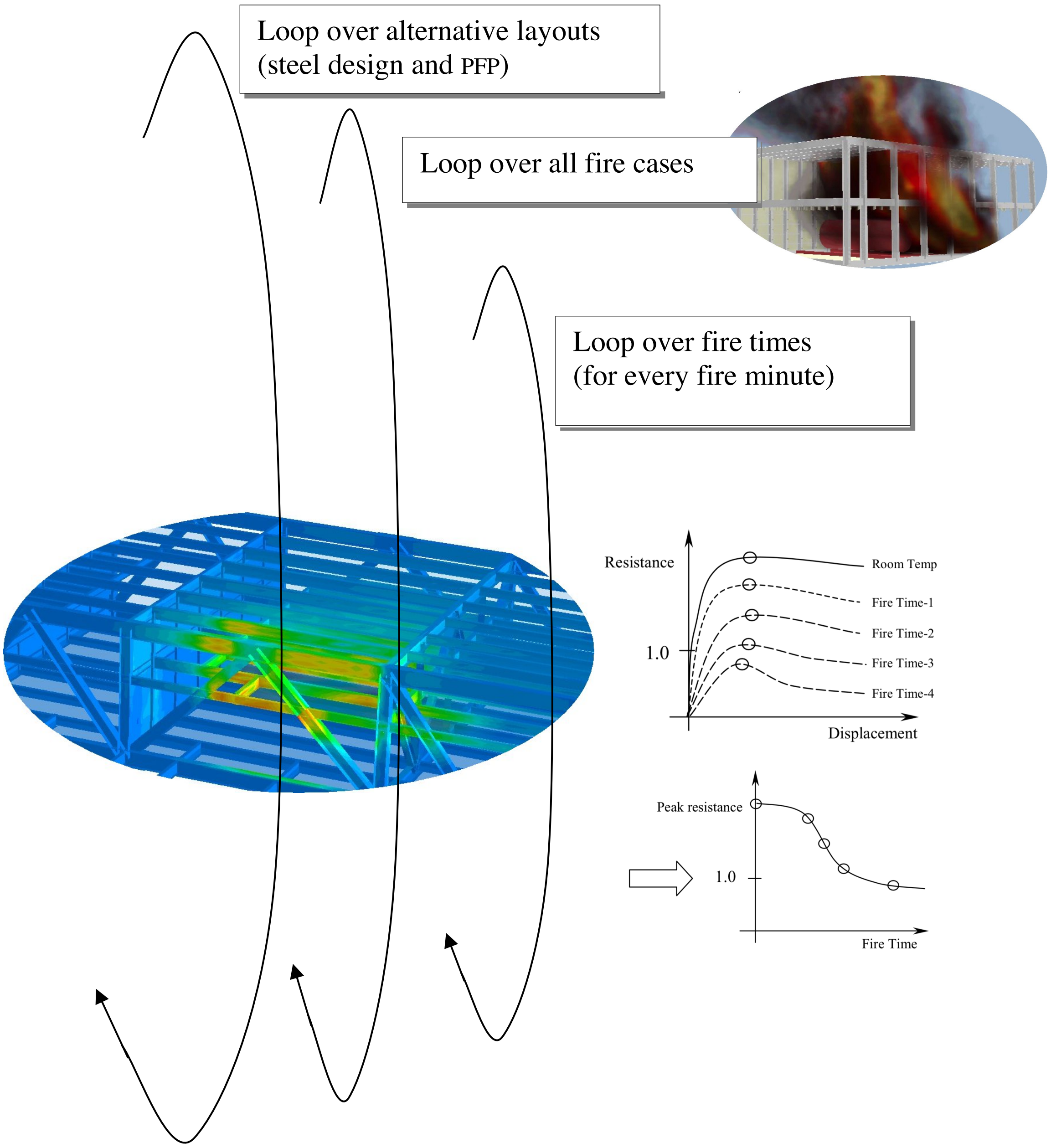


Figure 3-6 - General fire assessment simulation loop, (finding resistance vs. fire time).

See also /1/ for more information.

4 Fire Analysis Procedures

4.1 General

The main purpose of the fire analysis is to document how the structure could respond in fire. In practice to document that the structure, (with or without PFP), handles the actual fires with sufficient margin.

As for all engineering documentation it is normal to start with conservative models. If these conservative checks give sufficient margins, no further detailing is needed.

If the conservative fire analysis shows insufficient strength, and it would need PFP to meet the requirements, more refined simulations are normally recommended.

Below, some information is given regarding how to conduct the different kinds of fire simulations.

4.2 Alternative 1: Static Fire run to steady state temperatures.

One KFX simulation represents a given release location and rate, (e.g. 10 kg/s). The results from the simulation are stored in *one* “K2F” file. Typically will each release location start with simulations of different release rates “high”, “medium” and “low” (e.g. 30 kg/s, 10 kg/s and 5 kg/s).

As a first screening, do as follows for the structure *without* PFP:

1. Simulate (in FAHTS) each K2F file up to steady state is obtained. Normally, the steady state is found after 15-20 min. Simulate to 30min to get the steady state temperature field in the structure.

2. Perform PUSHDOWN check in USFOS for fire time =30min (i.e. at steady state).

3. If the structure survives all K2F files (i.e.: all release rates and locations) with a sufficient RSR margin, the simulations are completed. (It is normal to require a margin in the order of 1.5 on new platforms). I.e.: the structure does not need PFP.

4. If the structure does not handle all fires, proceed to the next alternative (next page).

4.3 Alternative 2: Fires with limited duration (single or transient)

There are several reasons and techniques to compute the fire response more accurately:

1. The hydrocarbon release is limited in time.
2. The required integrity time is limited. E.g.: Pipe supports have integrity requirements up to the time when the pipes are depressurised. (e.g. 10min).
3. The hydrocarbon release follows a certain release vs. time curve, and this transient is computed in KFX, resulting in several K2F files. (one per release).

4.3.1 Single fire, limited time

Alternatives 1 and 2 lead to same simulation procedure:

- Run the FAHTS simulation to the actual time (or longer)
- Perform PUSHDOWN at the actual limited time (e.g. 10min)

Ensure sufficient robustness, (depends on structure). Less critical structures such as pipe supports do not need large margins, e.g. > ~1.1. Supports of Valves (EV) need more robustness (> ~1.5).

4.3.2 Single fire, demonstrate structural resistance vs. time

Often it is of interest to check how the entire structure degrades vs. fire time. To obtain that information, the "PUSHDOWN" loop is used:

- Run FAHTS simulation to e.g. 1 hour. (steady state)
- Perform PUSHDOWN starting with time=0 (cold) and increment with e.g. 3min (or more dens).
- Record the RSR for the different fire times
- Plot the RSR vs. fire time as shown in Figure 4-1. This gives valuable information when need for PFP is considered.

Since only one K2F file is used, this plot gives an overview over how fast the structure heats.

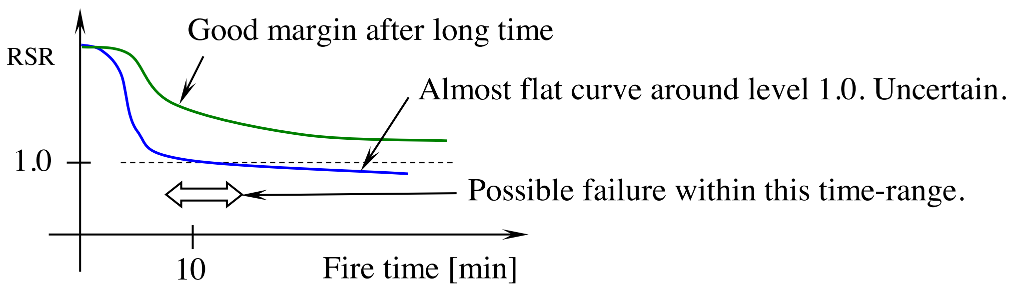


Figure 4-1 – RSR vs. time

4.3.3 Transient fire, demonstrate structural resistance vs. time

A transient release rate is simulated in KFX as "n" separate simulations with different rates. Figure 4-2 shows an example, where the real rate is approximated using three rates, 20, 15 and 10 kg/s.

The files are named e.g.: **`oil_001.k2f, oil_002.k2f`** and **`oil_003.k2f`**.

Each file contains a "Time" (very first number on the k2f file), and during the FAHTS simulation, the new k2f file is used when time is passed the average of the existing k2f file-time and the next.

FAHTS starts always with 001 file, and will keep the last file (here 003) if no more files are found. (The special case: single file has only one (001) file and use this throughout the entire simulation).

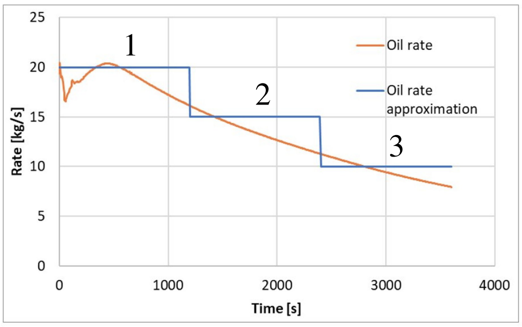


Figure 4-2 - Transient release approximated with 3 rates: 20, 15 and 10 kg/s

When a transient case is checked, two options exist in USFOS:

1. Use the option "**`UpToTime`**" under PUSHDOWN. The ""All-time-high" temperature per element up to the given time (e.g.: 60min) will be used to degrade the mechanical properties of the element. This is a quick check.

2. Use "**`AtTime`**" option and find the ultimate strength (RSR) for the different fire times. This is a more time consuming task, since USFOS need to be run "n" times, and the results need to be manually processed to create the RSR vs. fire time curve.

Option 2 is performed as described in section 4.3.2 on the previous page.

5 Simulation Failure criteria

Each fire redundancy simulation will demonstrate the structural resistance and the deformations.

In some cases the maximum accepted structural resistance (RSR) will be found from maximum deformation criterion. E.g.: the support of firewater pumps shall not deform more than a specified level.

In other cases, the maximum RSR is found from global instabilities, (e.g.: buckling of columns).

On top of such global criteria, limits have to be set on each component (beams and columns) regarding maximum plastic strain. Steel is a ductile material, but cannot be stretched "unlimited".

In design of steel, the fracture strain level is normally set to 15% for steel structures at room temperature (e.g. dropped object and explosion analysis).

However, in connection with fire, two points have to be considered:

1. Steel becomes more ductile for increasing temperature. (The fracture strain could be 30-50% for temperatures above 1,000°C. Just remember the blacksmith when he forms a curved object like the horseshoe. It is stretched far beyond 15% during that process).

2. The strength of the steel goes down with temperature. At 800°C more than 90% of the strength is "gone", and the member will in practice contribute little to the global strength.

It is ***not*** recommended to use 15% strain as a general criterion for all structural components.

Instead *disregard* strain checking for the following members:

- Small secondary members with no significance for the global safety of the structure (e.g. outer walk ways, stair tower, etc.)

- Members, which are almost "dead" structurally due to extreme temperature (e.g. > 800-900°).

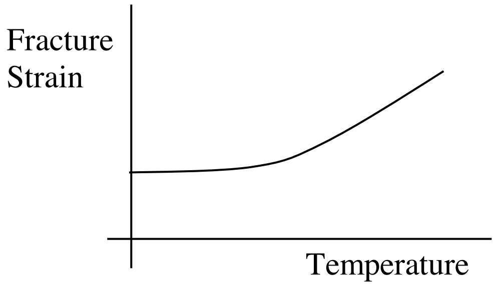


Figure 5-1 - Principle sketch of ductility vs. time for metal.

6 Safety Design Philosophy

6.1 General

In connection with design for handling of accidental events, certain criteria must be established. For accidental fires, the main issues are, *which fires to account for*, and *which consequences are acceptable (and which are not)*.

The first point means identification of the fire threats. Fire threats are identified by quantitative evaluation of possible leakages from available topside combustible reservoirs and leak frequencies and ignition probabilities for such events. Accidental fire scenarios with an annual probability above an agreed level of 10^{-4} are generally accounted for.

A selection of scenarios has been defined as a basis for the calculations. The size of the leakages (from ruptured pipes) used to identify dimensioning accidental heat loads is based on the probabilistic data. Leakage flow rates and leakage durations are calculated by solving standard fluid dynamic equations which account for real process parameters like the back pressure in the reservoirs, fluid temperatures and fluid viscosity as well as information about the plant construction geometry.

The second point is the *Acceptance Criteria* of a safe design, and this criterion is not straightforward to establish. Some points will be outlined in the next section.

6.2 Main Safety Functions

The overall safety design philosophy is based on fulfilling the main safety function requirements, which in brief are:

- Safe evacuation of personnel
- Controlled release of process pressure through the blow down and flaring system
- Avoid escalation (small events shall not lead to a catastrophe)

Even though the personnel evacuation process is not evaluated in detail as part of the discussed safety design philosophy, the requirement of safe evacuation of personnel limits the *time* of which all other safety systems must be kept intact. It is not wise to use the minimum time required for personnel evacuation as the main safety function time limit, because unexpected events may occur during the evacuation process.

In practice, this time limit is stated by the plant operator based on company policy and is a time limit quite a bit larger than the minimum evacuation time. Normally the time of which the main safety functions shall be kept intact, must also be approved by the authorities of the country where the plant shall operate.

Regarding safe evacuation on the Platform/FPSO, the time limit of keeping the main safety systems intact is *one (1) hour*. This time limit is generally used in the fire analysis and structure response analysis that form the basis of the safety assessment and recommendation for PFP application.

Figure 6-1 and Figure 6-2 describe the flare system and design philosophy in principle. The branches from the main flare go to different equipment items in the modules to each side of the central pipe rack. In order to avoid fracture of the flare line, extreme deformations have to be avoided. This is obtained by having limits on the deformations on the heavy items located on the main beams, and to avoid that the main columns collapse. In addition, a possible "collapse" of a module should be controlled, (gradually increasing deformations, "inwards").

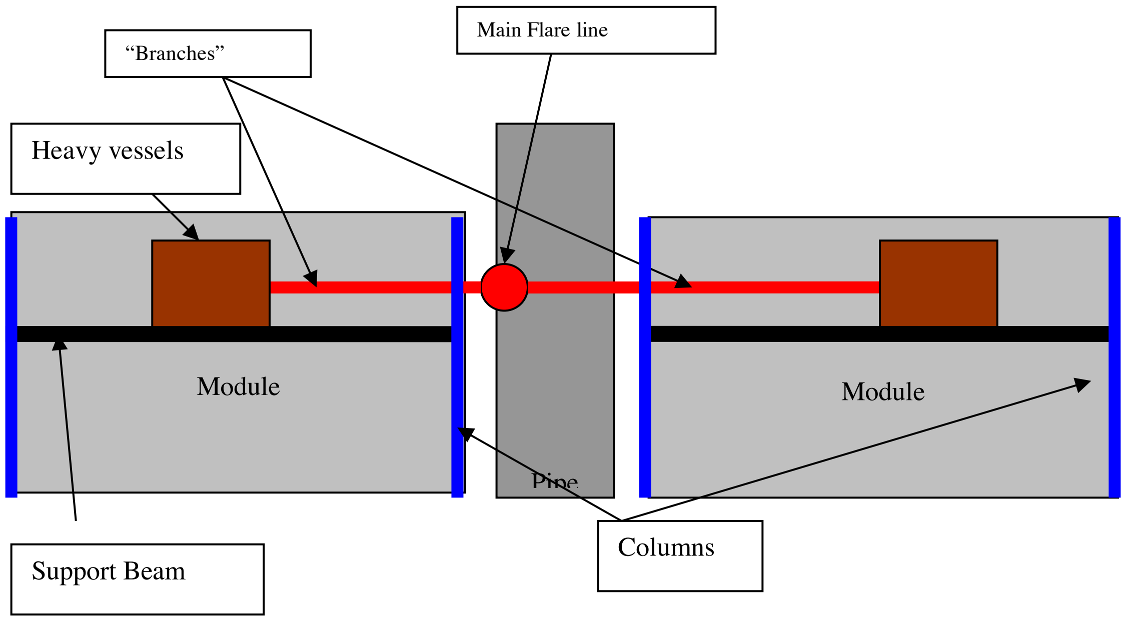


Figure 6-1 - Principle sketch of modules, pipe rack and flare pipes.

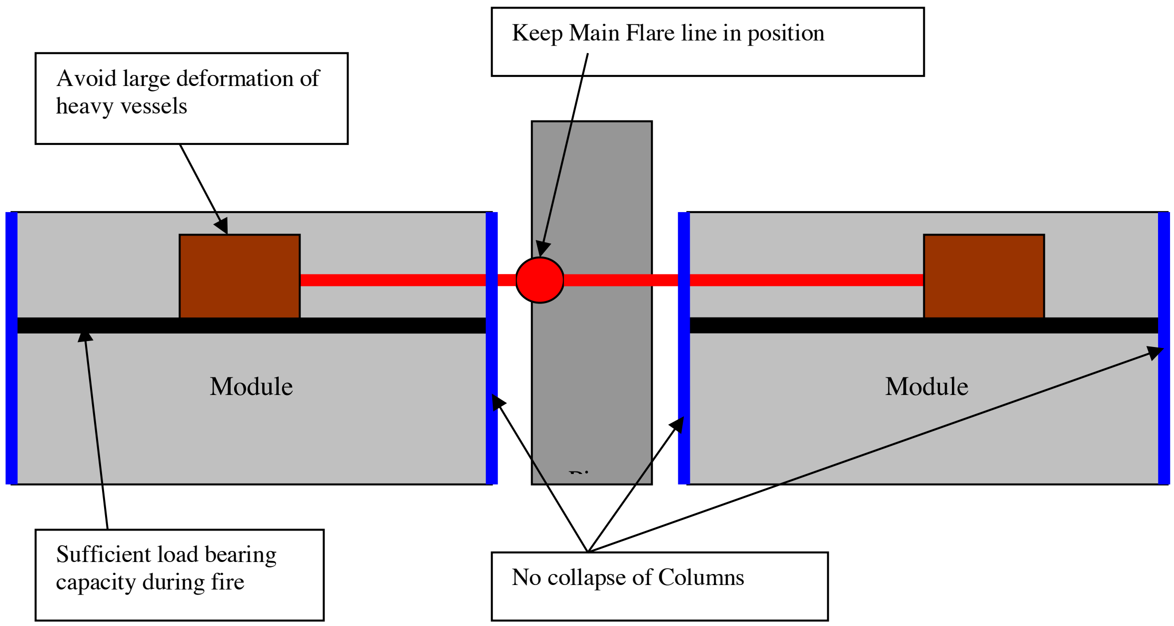


Figure 6-2 - Principle sketch of design philosophy

Support columns and beams behave very different when exposed to high heat loads, and this has to be described in more detail.

A column is designed for carrying axial compression forces. A perfect straight column has best performance, and the performance *decreases* for increasing imperfection ("banana" shape of the column). Columns are therefore more vulnerable for extreme loading than other components (see Figure 6-3).

An axially fixed beam behaves very differently. Here, the performance *improves* for increasing deformation (mid point), since the loads are increasingly carried by axial tension as the beam deforms, see Figure 6-4.

This fundamental difference in performance has impact on the use of PFP. Important columns with little or no redundancy (no load shedding opportunities) have to be fully protected, while beams with axially restrained ends could be left unprotected or partly protected. The actual need for PFP will be based on simulations where the function requirements must to be fulfilled.

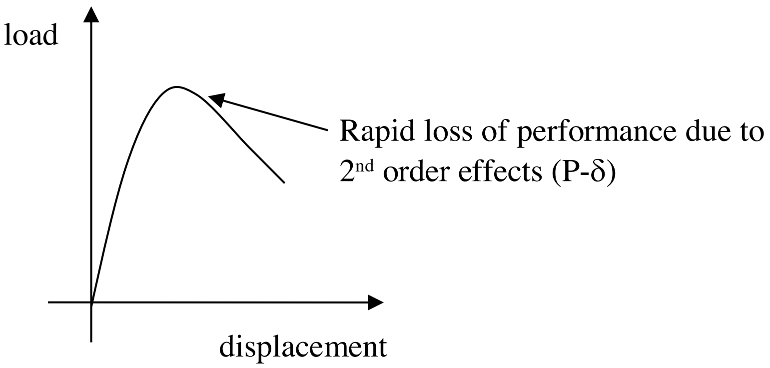


Figure 6-3 - Typical Column Behaviour

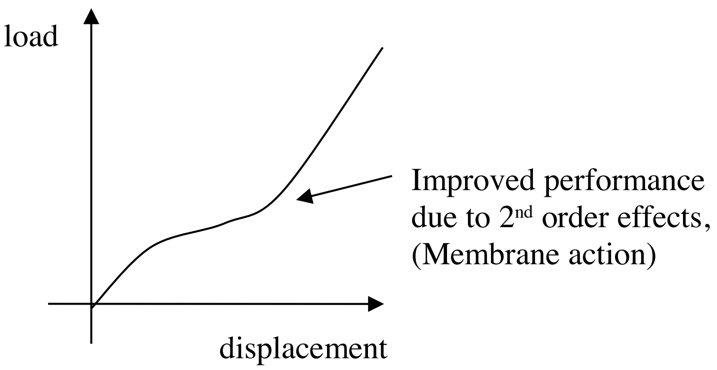


Figure 6-4 - Typical Beam Behaviour, (axial fixed).

6.3 Passive Fire Protection

PFP is provided on selected members based on the general temperature development and structural behaviour in the modules for the various fire scenarios. PFP is applied to preserve adequate strength and maintain the structural integrity of the modules, in particular the modules carrying substantial amount of hydrocarbon. Values for heat resistance representative of typical PFP products with a thickness of approximately 5mm are used throughout the analyses.

(An average “U-Value” of 10 [W/m^{2}K] is often used as a conservative assumption regarding insulation performance).

The trusses in the module are regarded as critical to maintain structural integrity. Typically, columns have a continuous collapse pattern and therefore most columns are protected.

The capacity of the deck beams on the other hand, tends to increase when they are deformed (membrane effect). I-sections are less efficient regarding PFP area versus protected length hence; an effort is made to reduce the number of protected deck beams.

For deck beams, the outside of the top flange could normally be left open as it will not be subjected to the most extreme radiation/convection, (see Figure 6-5). For all protected columns and diagonal braces, the whole cross section should be protected.

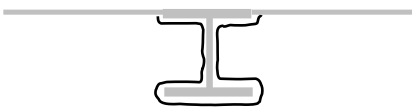


Figure 6-5 - Over side of top flange could be left open if documented sufficiently.

In addition, possible variations in the fire loads are taken into account, such as slightly different wind directions and locations for leakage. Therefore, some of the “cold” steel may be protected if small variations in the fire scenarios could cause high temperatures.

However, not all of the structure is protected even if heated significantly. The residual strength of the unprotected steel in combination with the protected system shall preserve global integrity.

The final proposed layout will be the result of an iterative process where several PFP layouts are analysed.

The results should not be sensitive to moderate changes in PFP performance and accuracy within ±20% is acceptable.

7 References

/ 1 / "PUSHDOWN analysis in USFOS." USFOS AS, 2014.
The document is available on www.usfos.com under manual/usfos/theory.