SYNTHESIS REPORT

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Germanischer Lloyd (GL - Germany)
Tecnomare (TM - Italy)
Snamprogetti (SP - Italy)
WS Atkins Safety& Technology Ltd. (AS&T - U.K.)
Computational Safety and Reliability (CSR - Denmark)
Instituto Superior Tecnico (IST - Portugal)
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OFSOS

Optimised Fire Safety of Offshore Structures

Brite-Euram Project 4359, 1992-1995

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2. Abstract

This paper summaries the work carried out within BRITE/EURAM Project 4359:" Optimised fire safety of offshore structures ", which started on 1st August 1992 and finished on 31st November 1995. The objectives of the project are here illustrated, focusing on the main technical results.

The main thrust of the project has been the application of probabilistic principles in all aspects of fire safety assessment and design, This is reflected in the main results of the project which include:
- a methodology for fire safety assessment combining Quantitative Risk analysis and Structural Reliability Analysis techniques,
- a comprehensive methodology for reliability based design optimisation of passive fire protection,
- a suite of software modules assembled into the OFSOS software system,
- comprehensive case studies on existing offshore platforms,
- guidelines for use of the developed methodology in the fire safety assessment of offshore topsides.

The extension of traditional QRA (Quantified Risk Assessment) techniques to incorporate the effects of fire on the structure may be considered, together with the development and testing of (research level) software to be used in carrying out this kind of additional analyses, as the main technological results of the project. Considerable advance was achieved also in the field of reliability based optimisation, which fact qualify the project results in terms of basic research.

3. Introduction

According to statistics of hazardous occurrences in oil and gas production offshore, fire is one of the major risks which could lead to serious damage or total loss of the installation (see e.g. Fig. 1). While this has been recognised since long time, practice for fire safety design of earlier generations of offshore platforms was principally based on regulations for ship design, according to the International Convention on Safety of Life at Sea (SOLAS 1974) [1] and IMO MODU Code [2].

It was not until the Piper Alpha accident that this issue was seriously addressed, In the 1990 the UK Department of Energy published a new document [3] including a number of recommendations, particularly in relation to fire protection, permanent and temporary accommodation, muster area and escape routes. Furthermore, Lord Cullen's enquiry into the Piper Alpha accident [4] led to several radical changes which were subsequently implemented by the UK Government.

This new thinking provided the background for the collaborative industrial research Project OFSOS, launched in 1992 under the CEC's BRITE/EURAM Framework. The principal objectives of the project were to propose a rationalisation of the fire safety management of offshore installations and to develop a methodology for the assessment and optimisation of fire safety.

The commencement of the project coincided with the completion of the Phase-i of the Fire and Blast project organised by SCI [5]. As far as possible relevant results from the Fire and Blast project were taken into account and efforts were concentrated on scientific and computational advancement of key ingredients of fire safety, namely:

- application of methods for the consequence analysis and risk assessment to topside structures and system layout to identify dominant hazard scenarios,
- probabilistic modelling of fire and blast scenarios,
- probabilistic modelling of temperature distribution inside structural components,
- probabilistic modelling of non-linear structural response under thermal loading,
- development of a probabilistic strategy for safety assessment of topside structures under time dependent fire and blast loading (system reliability approach using temperature or strength criteria),
- development of reliability based design optimisation for passive fire protection of topside structures (using temperature or strength criteria).

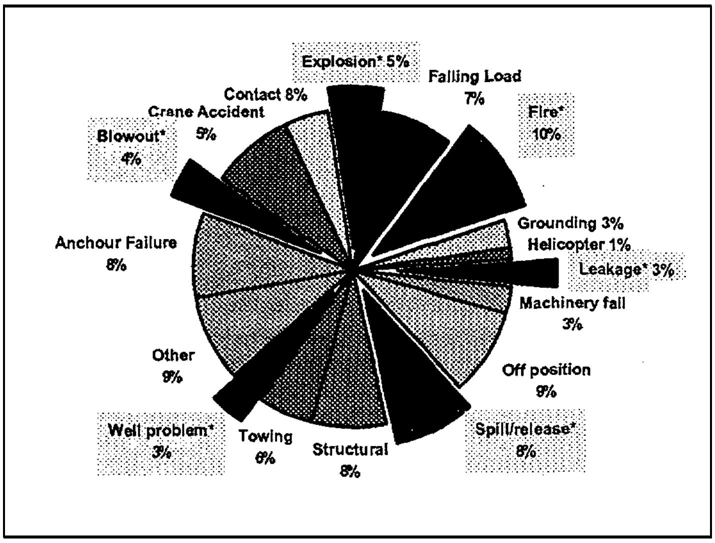

Figure 1: Accident frequency pie chart in the North Sea,

The theoretical developments have been implemented into individual software modules and subsequently integrated into the OFSOS software suite which has been used in some as far as possible realistic case studies, aiming to demonstrate the feasibility of the proposed approach and simultaneously providing testing opportunity. Some existing offshore structures have been studied, covering different type of layout and being subject to different fire scenarios.

The objectives of the project have been pursued by a multi-disciplinary Consortium (summarised in Table 1), which included not only experts in R&D, offshore topside designer and regulators, but also oil operators. These latter besides entering the project as sponsors, played a very active and important role by providing both data and advice.

229 man-months were employed in the project, they can be roughly subdivided in:

30% in analysis (regulations, previous results, theoretical studies)
35% for software development (including documentation)
25% for development of guidelines and execution of test cases
1 O% for management.

Organisation, Country	Activity	Function in the Project
Registro Italiano Navale - RINA (I)	Classification Society	Expert in risk and structural reliability analyses; expert of regulations on offshore and onshore fire safety, development of guidelines. Co-ordinator.
Germanischer Lloyd - GL - (D)	Classification Society	Expert in fire safety measures, emergency procedures and equipment. Partner.
Tecnomare S.p.A. - TM (I)	Research & Engineering Company	Expert of design of offshore installations and on use of advanced techniques and software . Partner.
Snam Progetti S.p.A.- SP (I)	Off-shore Platform Designer	Expert of design of offshore plants and of risk analysis. Associated partner..
WS Atkins Engineering Sciences Ltd. - AES (UK)	Research & Engineering Company	Expert of structural risk analysis, developer of RASOS software. Partner.
Computational Safety and Reliability - CSR (DK)	Consulting Engineering Company	Expert of structural reliability and of reliability based design optimisation.. Partner.
Instituto Superior Tecnico - IST (P)	University	Expert of structural reliability and of collapse modelling of structural components. Partner.
AEA Petroleum Services - APS (UK)	Contract Research Organisation	Expert of CFD modelling of fire and blast, expert of risk analysis. Associated partner.
AGIP - (I)	Oil Company	Sponsor
AMOCO UK.	Oil Company	Sponsor
British Gas	Oil Company	Sponsor
Chevron UK	Oil Company	Sponsor

Tab. 1: Role of the partners

4. Technical description and Results

4.1 Fire and blast modelling

One of the goals of the project was the development of a software package (research level) for the probabilistic analysis of structures under fire and blast loading. As it is well known, the algorithms adopted to solve structural reliability problems require the execution of thousands of evaluation loops which fact implies that complex and time-consuming models normally adopted when carrying out deterministic assessment can seldomly be used and simplified models must be adopted.

This is the case for the fire and blast modelling and for this reason, a review of methods of release calculation and escalation effects was carried out: as a result, the pool fire, jet fire and blast computer programs: POOL, TORCH, EXPL, and EXPRESS have been selected to be merged together in order to develop RASOS_B (Blast& Fire) software module.

POOL (code for calculating radiation from pool fires) is a flame surface model in which the flame is represented by a tilted cylinder with an elliptical horizontal base which enables the downwind flame spill-over to be represented; the programme has been validated against experimental data provided by Shell Research Ltd and by British Gas plc for hydrocarbon fuel mixtures.

TORCH is a surface emitter which treats the flame as uniformly radiating solid body with constant surface emissive power and shaped as the frustum of a cone; the flame dimensions orientation and radiated heat flux are described by empirical correlation.

EXPRESS predicts the pressure peak associated with the venting of the flame from the vessel where an estimated turbulent burning velocity is used in place of laminar burning velocity to **allow** for flame acceleration. Its predictions have been compared with those of the FLACS code and with experimental data taken from explosion tests in 1:5 scale offshore modules and in larger wedge-shaped enclosures.

EXPL combines simple theoretical relationships with relationships based on experimental data. The module is represented as a rectangular box with a vent at one end and an ignition point on the opposite wall, which is the easiest configuration to model and the most conservative in terms of overpressures. The model includes a series of obstacles between the vent and the ignition point..

These softwares have been compared with the results of the computational fluidodynamic codes FLOW 3D interfaced with RAD3D to model thermal radiation. Examination of simpler relevant fire scenarios suggests that the codes give good heat flux predictions in the conditions for which they have been developed; generally speaking this means open, unobstructed flames in a uniform cross-wind.

As a second step, the resulting RASOS_B (Blast&Fire) software has been fully interfaced with RASOS_T (Thermal analysis) and it has been enhanced considerably to model furnace effects which are very important in the case of **enclosed** fires within offshore topside modules.

As far as the modelling and prediction of heat transfer into skeletal structures, a specialised software, HOTPLATE, was produced, in addition to that, RASOS_T was given the capability to handle this problem.

4.2 Modelling emergency procedures

The objective was to assess safety, emergency systems and procedures of the selected platforms by analysing and classifying the currently applied Emergency, Evacuation and Rescue (EER) procedures and other important parameters for personal safety such as:

- location of escape routes,
- Temporary Safe Refuges (TSR),
- muster area
- automatic safety systems (shut-down, blow-down, fire fighting, emergency equipment).

From the know-how and experience of various different sources involved with safety on offshore installations (i.e. available safety studies, literature, practical experience from classification societies as well as from operators), a thorough overview of emergency procedures on various types of offshore platforms have been carried out focusing on the active fire protection system and in particular on:

a) location of equipment
b) reliability of equipment
c) effectiveness in mitigating those scenarios identified as' Design Accidental Events'
d) effects of fire or blast impingement on the equipment itself.

The following conclusions were reached:

current practice for (a)-to (c) is well developed;
item (d) tends to follow rules based on experience, with fairly conservatively set threshold for damage criteria.

To partially reduce this gap, a qualitative evaluation of all active equipment on board which is able either to reduce escalation of accidents or to at least limit their progress was provided mainly focused on:

emergency shut-down and blow-down systems
active fire protection systems
emergency alarm and controls
emergency ventilation systems.

The emergencies required to be covered by regulations was listed along with the typical contents of such procedures. The time to complete the platform abandonment has been estimated according to three scenarios (fastest, average and slowest evacuation time); large variations were observed as summarised in Table 2.

Task Step	Best Case	Average Time	Worst Case	Key Milestones (average time)
1. Detect Incident	O sec	10 sec	1 “rein	alarm raised 1 rein, 50 sec
2. Carry out Lo%'... ~.;;,::.	O sec	1 min	10 min	
3. Sound (Raise) Alarm	20 sec	40 sec	1 min	
4. Personnel Identify Alarm	20 sec	40 sec	1 min	muster complete 9 rein, 20 sec
5. Seek Additional Information	O sec	20 sec	3 min	
6. Make Safe Work Areas	O sec	30 sec	2 min	
7. Walk to Muster Point	O sec	10 sec	1 min	
8. Don Survival Suit and Life Jacket	0 sec	3 min	10 min	
9. Enter TEMPSC Fasten Seat Belt	2 min	3 min	8 min	
10. Move 'T' Card at Muster Point	20 sec	40 sec	2 min	
11. OIM Accounts for all Personnel	10 sec	1 min	10 min	
12. OIM Decides Best Available Method for Evacuating	1 min	5 min	15 min	boat loaded 7 min
13. Enter TEMPSC Fasten Seat Beit	1 min	2 min	6 min	
14. OIM informs SBV of Evacuation by TEMPSC	1 min	2 min	6 min	boat clear of installation 5 rein, 45 sec
15. Start Engine	5 sec	10 sec	1 min	
16. Lower Craft	20 sec	25 sec	2 min	
17. Slip the Falls	5 sec	10 sec	20 sec	
18. Drive Away	2 min	3 min	10 min	
TOTAL	8 rein, 40 sec	23 min, 55 sec	89 min, 20 sec	

Table 2: Estimated time to evacuate a typical platform by totally enclosed motor propelled survival craft

4.3 Identification of hazard scenarios

The final goal of the project being the development of a Risk Assessment procedure for offshore structures under fire and blast, it was appropriate to determine typical fire scenarios for offshore installation and to set up appropriate event trees which would enable the probability of structural impairment to be determined.

In order to meet these objectives and to identify fire events which could impair structural integrity, a range of platform types in a range of locations have to be considered. Four platforms were selected for this purpose (some details are provided in Table 3) and have been kept as guiding cases throughout the whole project.

Location	Type	Manning	Operation
North Sea	gas	manned	drilling & production
North Sea	oil	manned	drilling & production
Mediterranean Sea	gas	unmanned	production
Congo	gas	manned	production

Table 3: platforms considered in the study

For each platform hazard sources of ignition and release have been identified and categorised as "top event?; for the most relevant top events, event-trees have been developed for each platform in order to have a complete description of the hazard scenarios.

The event-trees obtained from the previous risk studies have been considerably enhanced to achieve integration of conventional risk analysis techniques with modem structural reliability analysis being developed in the project (cf. Figure 2).

Starting from the event trees, analysis of the consequences of accidental event scenarios has been carried out. The scope of this analysis was to evaluate the consequent effects on the platform safety functions, that is the aspects of the platform design which are necessary for full and safe evacuation during an emergency. This work identified a number of important key parameters for fire safety of offshore topsides; in particular the main items in order of importance were considered to be:

a) supporting structure
b) shelter area: may be any area where the crew will remain safe during an accident, until the platform evacuation is complete;
c) escape ways: is the safety function most impaired by consequences of accidental events;

b) and c) are considered affected by an accidental event or unserviceable if thick smoke, convective heat, intense radiation, blast or structural darnage intolerable to humans is experienced within the evacuation time from the beginning of the accidental event; while a) is considered affected by an accident if the load bearing members are so severely damaged that the structure containing b) cannot maintain the integrity for the time necessary to perform for platform evacuation.

On the basis of previous data and of the available Risk Analyses several events and/or scenarios have been identified as possibly hazardous involving tire; they are of representative variety with regard to the range of flammable materials, release sizes, rates and location, generic fire scenarios, possible impairment of vital platform safety functions and escalation potential.
The probabilities for each type of consequence following hydrocarbon release or explosion have been evaluated. By performing a detailed functional analysis, it has been possible to select a number (about 10) of top events from the OFSOS philosophy point of view, Le. such top events should:

lead to a fire or blast and be events whose consequences may be mitigated by proper layout and fire protection modifications

catastrophic top events likely to have fatal consequences, and for which no mitigation can be achieved by modification of layout or fire protection (e.g. collision by a ship, earthquake, etc.) have been excluded from the analysis.

The outcome of these scenarios is typically either a pool fire or a jet fire from hydrocarbon; these *fires* may **be** preceded by transient events such as cloud fires, fireballs, or explosion; two typical hazard scenarios are reported in Table 4.

In the case of serious gas release all safety functions are liable to damage through fire; it should be noted that the impairment frequencies are the highest for the escape ways.
Pool fires resulting from treated crude oil are considered to be of low probability due to the relatively high flash point of the treated oil.

Explosions from crude oil release are to be expected only in the case of untreated oil.

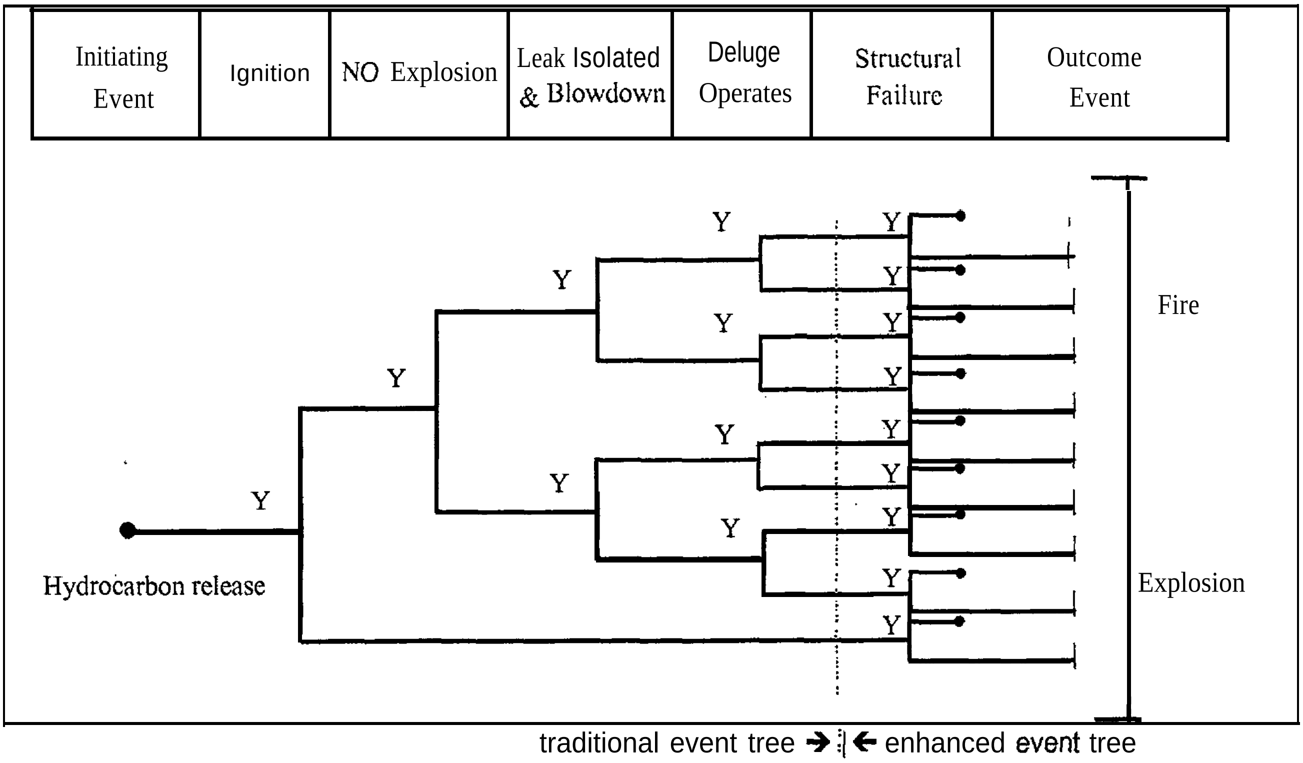

Figure 2: enhanced event tree.

Initial Event	Initial Parameter	I. Stage of Escalation	II. Stage of Escalation	Effect on platform Safety Functions
Jet fire at gas import riser above sea	Material released - gas Breach -50 mm Release Rate -35 kg/s Flame Length -31 m Duration ->90 min	Possible impingement on any of the centre platform legs and adjacent cross braces. Possible impingement and damage to topside floors	Escalation to further inventories on deck level due to high heat flux or damage to other risers could cause catastrophic release and derrick collapse	Depending on wind direction, some escape ways could be seriously damage, possible structural yielding,
Pool fire at oil import riser at sea level	Material released - oil Breach -50 mm Release Rate -58 kg/s Pool Diameter -30 m Initial flame -39 m Duration ->25 min	Damage to structure under deck area Damage to leg adjacent to riser	Collapse of cellar deck Rupture of riser causing catastrophic release	Impossible to use the lowest escape ways, damages on not thermal insulated structure, possible structural yielding

Table 4: examples of hydrocarbon release and escalation effects.

4.4 Structural behaviour under fire - deterministic approach

The main objectives of the work in developing a methodology for the assessment of structural behaviour under tire and blast have been:

a) to review and collect data on temperature dependent material properties; store this data in the form of a suitable database;
b) to develop analytical models for predicting the collapse of structural beam-column members and plates subjected to fire and blast loads;
c) to develop a methodology and corresponding software for assessing the progressive collapse of skeletal structures subjected to fire and blast loads

The work performed has involved:

a) The development of a database of temperature dependent material properties focusing mainly on steel. In particular, the lack of sufficient available data on temperature dependent material properties was highlighted and it was decided to adopt, in the probabilistic analysis; the nominal stress-strain curves recommended by Eurocodes. As to the probabilistic model to be adopted the log-normal distribution was proposed with a coefficient of variation ranging from about 10% for standard room temperature to about 20% for 800°C. A commercial database shell (ACCESS) has been selected and a database program has been developed which stores different experimental curves and calculates the mean and coefficient of variation of each set of curves. These are the required parameters to define the fog-normal distribution that models probabilistically the variability of the steel properties.
b) The development of failure functions for the thermal collapse of beam-column elements and plated components. In particular, a selection of typical structural components used on topsides has been made and computations of the collapse strength of steel plated components were performed taking into account material properties corresponding to different temperatures. Relevant limit states for beam-column members, "plated components and skeletal structures under fire, blast and combined fire & blast events have been identified. The development of software for beam-columns has been based on three alternative formulations, namely API method, ECCS method and elasto-plastic buckling analysis. A systematic series of finite element computations has been performed in order to determine the limit state equations for plated components under heat loads. The results were used to calibrate limit-state equations in ambient temperature. It was shown that the same equations can be applied provided a normalisation that is appropriate to the temperature under consideration is used.
c) The development and verification of the RASOS software for progressive collapse analysis of skeletal structures under fire and blast loading. The developments as per above items (a) and (b) were included into the (existing) progressive collapse model of skeletal structures in RASOS_C software which was enhanced accordingly.

4.5 Structural behaviour under fire - reliability approach

The objective was to develop the reliability formulations that will be the basis for the optimisation procedure. This was achieved by means of

a) development of systems reliability software for non skeletal structures subjected to fire and blast loading
b) development of methods for time-dependent system reliability analysis of skeletal structures under fire and blast loading.

Two sets of software for the objectives a) and b) have been developed and tested. The selective enumeration method has been developed and enhanced to include fire and blast loading and implemented into the (existing) RASOS_R software. Furthermore, a system reliability formulation for a room subject to pool fire radiation has been formulated suitable for analysis of non structural parts.

More specifically, the reliability formulations have been devetoped for plated components and for beam-columns. The first one is the representative structural element for fire walls, decks arid ceiling. A formulation has been developed for plates under the biaxial compressive loading due to thermal effects. The limit state equation is given by:

$$\frac{T_x^2}{\phi_{xu}^2} + \frac{K_\alpha^* T_x^*}{\phi_{yu}^2} - 1 = 0$$

where K_x is the ratio of the longitudinal to transverse loading in the plate, T_x is the longitudinal stresses normalised by the yield stress and ϕ_{xu} and ϕ_{yu} are the ultimate plate strength in longitudinal and transverse direction. The detailed expressions are omitted here for the sake of simplicity.

For fire walls, a different reliability formulation was developed based on a temperature limit state and taking into account the effect of the insulating material. The probability of failure is defined as the probability of the temperature in the plate being higher than its limit temperature. The limit state function is then:

$$g(x) - \Delta T_{lim} - \Delta T_{steel}$$

where, ΔT_{lim} is the temperature differential that leads to plate collapse, and ΔT_{steel} is the actual increase of plate surface temperature due to fire which depend on a number of parameters which expression is here omitted for the sake of simplicity. In view of example, Figure 3 shows the dependence of the reliability index (β) with time for a fire wall 10m from the fire source.

The second formulation is referred to the resisting skeletal structure. A methodology has been developed for the reliability analysis of the primary structure of a platform topside under pool and jet fire loading. The methodology accounts for the uncertainties in the estimation of heat flux from the fire, thermal and mechanical material properties of the structure and the insulation and in the evaluation of the response of the structure to the fire. The failure probabilities are calculated using efficient FORM/SORM reliability methods.

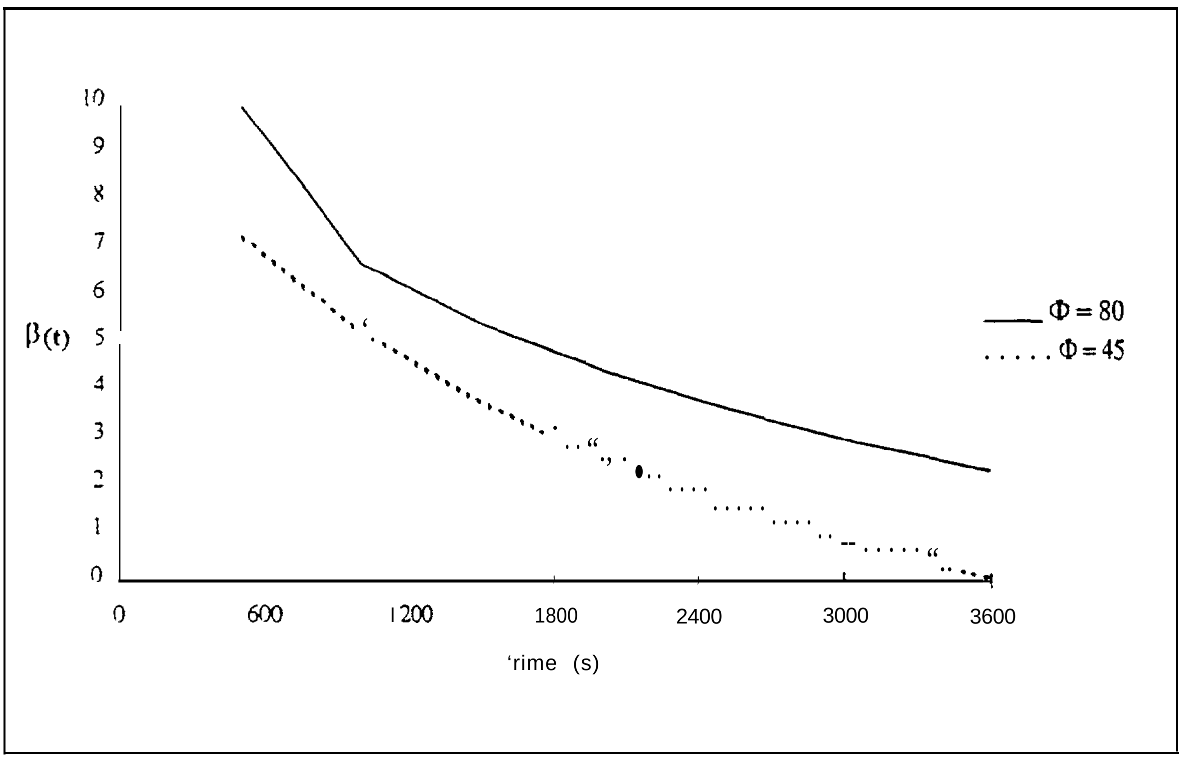

Figure 3: Time dependent reliability index.

For beam-column elements methodologies for component reliability evaluation have been developed for the following limit-states:

1. Limiting heat flux failure criterion. This can be used to develop a probability distribution of heat flux at any point away from the fire origin which may be of interest in determining heat exposure levels for personnel and the availability of escape routes during an accident.

2. Limiting temperature failure criterion. For a specified (random) value of the critical temperature in a member the probability of the actual temperature at a given time exceeding the critical temperature can be calculated. This limit state is less expensive to compute and can be used as a screening tool for choosing the members to be considered in an optimisation analysis of the thickness of Passive Fire Protection (PFP).
3. Member failure by buckling/yielding based on API/AISC and ECCS formulations. This limit state can be used to evaluate the probability of failure of a component at any given time t after the initiation of fire.

These limit state functions have been linked to the software programs RASOS-R and RELIAB for component reliability analysis. The uncertainty in the computed heat flux from a fire is modelled through a number of basic random variables relating to fuel release conditions, fuel properties, environmental parameters and model uncertainties relating to the calculation of flame shape, surface emissive power, transmissivity and the heat received by a member. The thermal properties of the structural material and the insulation, elastic and plastic material properties of the structure are also treated as random.

Figure 4 shows the variation with time of mean heat flux and mean temperature in a member of an example offshore structure. The variation of reliability index with time for the limiting temperature failure criterion is also shown.

As far as the reliability of the whole structural system is concerned, two methods for evaluation of system reliability were considered, namely the β-unzipping method (available in the RELIAB software) and the Selective Enumeration Method (available in the RASOS-R software). In view of an easier integration with the RASOS system, the RASOS-R software was chosen.

The main elements of the developed RASOS-R software for system reliability analysis are:

(i) fire/blast load modelling,
(ii) thermal analysis,
(iii) member collapse modelling,
(iv) non-linear structural response modelling,
(v) uncertainty modelling
(vi) component reliability evaluation,
(vii) reliability analysis for a prescribed failure sequence,
(viii) identification of dominant failure paths, and
(ix) calculation of system failure probabilities.

A time-dependent formulation is used for fire conditions in which the analysis is carried out at discrete time-steps. The development of the fire loading, the rise in member temperatures and corresponding change in material properties is calculated over the time duration from the beginning of the fire.

A number of dominant failure paths for the structure are identified using the Selective Enumeration Method. This approach uses a number of criteria such as conditional safety margin (for the next failure element in the sequence}, the reliability index at the previous branch point and the correlation between failure paths to minimise the number of branches enumerated at each branch point. The failure paths are identified in the order of their importance (i.e. the most-likely failure path is identified first and the next most-likely second etc.), and the failure tree enumeration, is stopped when the difference between the upper bound and lower bound on system reliability becomes acceptably small.

Furthermore, system reliability formulations for a room subject to pool (jet) fire radiation were developed. A formulation was considered for the reliability of a compartment with four fire walls which were modelled as representing a structural system. Failure was defined as failure of one of the four walls based on a temperature limit state. The RTLSYS software was developed based on the limit state function for plate of RTLS and on the plate temperature of HOTPLATE.

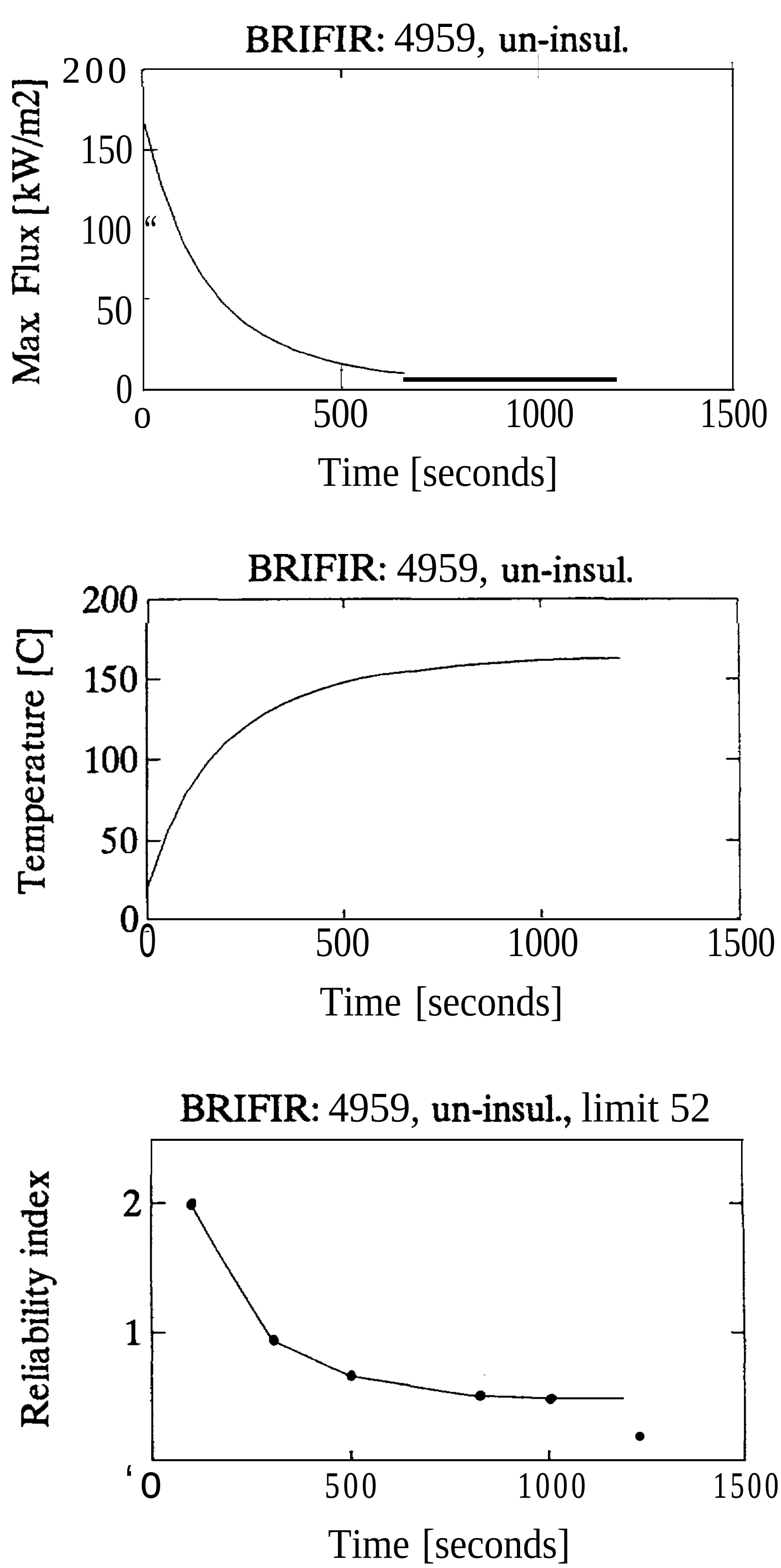

Figure 4: History of heat-flux, temperature and reliability index for one structural element.

4.6 Reliability based design optimisation

The developments and studies undertaken in the previous phases of the project highlighted that a total optimisation of the topside is not realistic and, for the time being, the following subsystems are considered appropriate for an optimisation analysis:

- Safety equipment and active protection
- Passive protection
- Primary and secondary structural elements
- Temporary Safe Refuge (TSR)
- Escape, Evacuation and Rescue systems EER
- Individual hazard sources and hazard scenarios

The optimisation in OFSOS is done in a number of steps. Not all steps to be performed are obligatory. Some are optional, but they must be performed in the order shown below:

1. Modelling/definition/formulation: In this step:
   - the structural model is selected and the FEM model is defined,
   - the fire scenarios are defined,
   - the limit states are defined,
   - the stochastic modelling is performed and
   - the structural elements are grouped.
2. Pre-evaluation. In this step:
   - a FEM analysis is performed and the potential failure modes are evaluated,
   - the structure is modified if one or more limit states are violated,
   - sensitivity analysis parameters are defined,
   - a sensitivity analysis is performed to help with obtaining a feasible design without re-analysis of the structure,
   - design variables are added or removed based on the results of the sensitivity analysis, a corresponding deterministic optimisation problem is formulated (optional) and solved,
   - reliability index and derivatives are calculated so that limit states, stochastic variables etc. may be deleted/added.
   -
3. Optimisation. In this step:
   - the reliability based optimisation problem is defined (design variables, objective function and constraints)
   - the reliability based optimisation problem is solved.
4. Post evaluation. In this step:
   - the optimisation results may be modified, e.g. rounding up of some design variables to nearest allowable value
   - the optimisation results are evaluated to ensure that all assumptions are valid, a new grouping of elements or the use of new PFP material may be done and a new optimisation performed, i.e. repeat from the beginning.

The reliability based optimisation problem can be formulated in the following way

$$\begin{aligned}
&\min_{b} \; C(\bar{b}) \\
&\qquad \bar{b}^T = (b_1, \ldots, b_n) \\
&\text{s.t.} \quad \beta_j(\bar{b}, \bar{x}, T, s_i) \geq \beta_j^{min} \qquad j = 1, \ldots, M \\
&\qquad \beta^{sys}(\bar{b}, \bar{x}, T, s_i) \geq \beta^{sys,min} \\
&\qquad b_i^{min} \leq b_i \leq b_i^{max} \qquad i = 1, \ldots, n
\end{aligned} \tag{1}$$

where s_i is scenario i and T is a reference time. The reference time could be the time where the fire is maximum or the time to evacuate all personnel. $\bar{b}$ is a vector of design variables, $\bar{x}$ is a vector of stochastic variables, M is the number of constraints and n the number of design variables. The solution to this problem is $\bar{b}^{i}_{opt}$ where superscript "i" indicates scenario i. Problem (1) is solved for all N scenarios and as the final optimal solution is used the maximum value for each design variable.

Within the project, it was decided to focus on optimisation of Passive Fire Protection (PFP); this choice has the advantage that it contains all the major aspects related to fire safety with a reduced number of design variables, namely the amount and type of PFP. The optimisation problem is then to minimise the cost of the PFP with requirements on the minimum acceptable safety.

Accordingly, two software packages have been developed, namely OPTIWALL for optimisation of PFP on non-structural parts (firewalls) and OPTIBEAM for optimisation of PFP on structural members. The two programs, which utilise most of the software developed within OFSOS, are able to find optimal PFP for both firewalls and structural members subjected to pool and jet fires.

[t is assumed that all fire walls have insulation material, that the geometry of the fire wall is constant and that only insulation on the hot side of the firewall is optimised. There are only two design variables for a fire wall namely the thermal conductivity for the PFP material and the thickness of the insulation material. The objective function is the cost of the PFP modelled as a linear function of the thickness, a function of the thermal conductivity and a constant term related to the installation. A constraint is in the deterministic case imposed on the temperature at the interior face of the insulation, which at the reference time T (60 minutes for A60 walls and 90 minutes for A90 walls) must be lower than some specified limit state temperature. In the reliability based formulation the constraints are related to the probability that the temperature in the firewall exceeds a limit value.

In figure 5, for the sake of illustration, the output screens from OPTIWALL, namely output from the pre-evaluation phase, is given.

The design variables are the thickness of the PFP on topside beams/columns. Since the number of structural elements on a standard topside structure may be quite large, grouping the design variables into a number of groups is implemented in OPTIBEAM in order to reduce the number of design variables. In order to take into account the effect of other mitigation measures (AFP, improved lay-out, etc.) a third term may be included in the objective function. The objective function is the sum of the total cost of PFP and the expected failure costs. It is assumed the expected failure costs is proportional to the initial cost of the structure without PFP. Constraints are related to a limiting temperature failure criteria or to member failure by buckling/yielding (using the API/AISC model or the ECCS model).

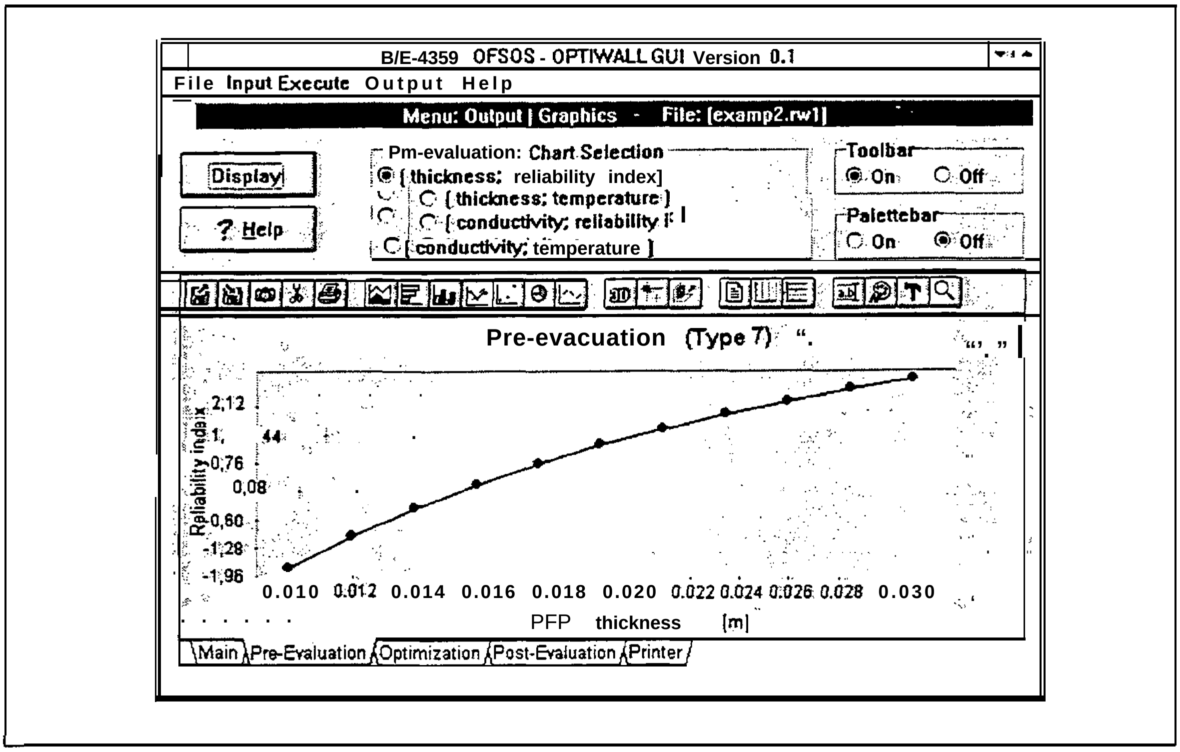

Figure 5: OPTIWALL. Pre-Evaiuation: Reliability index as function of the PFP thickness.

The major achievements on reliability based optimisation can be summarised in:

- Formulation of reliability based optimisation problems for both PFP on firewalls and structural members have been specified,
- Analysis of reports and meetings with engineering companies resulted in definition of relevant cost functions.
- A methodology and specifications for prototype software for PFP optimisation on firewalls and structural members have been developed.
- A prototype DOS program OPTIWALL for optimisation of PFP on firewalls has been implemented and tested.
- A prototype DOS program OPTIBEAM for optimisation of PFP on structural members has been implemented and tested.
- Integration of old and new modules developed my multiple OFSOS partners for fire analysis, heat transfer, reliability assessment, sensitivity analysis and optimisation has been successful for both OPTIWALL and OPTIBEAM.
- Several test-case examples using both programs have been prepared and executed without major problems.

4.7 Integration of the developed procedures and their application

The objectives of this activity have been:
a) to develop an unified approach for fire safety assessment and optimal design by integrating the component methodologies developed in the different tasks of the project;
b) to implement the above methodologies into an operational prototype software;
c) to demonstrate the developed methodologies and software on realistic case studies.

Accordingly, a fully-probabilistic approach to fire safety assessment and optimal design of fire protection on offshore topsides was developed within the project by integrating:

- Quantitative Risk Analysis techniques
- Fire and explosion models
- Heat transfer models
- Non-linear structural analysis methods
- Structural System Reliability Analysis techniques, and
- Reliability-Based Design Optimisation methods.

This integration has been achieved by enhanced event-trees where the final failure events in an enhanced event-tree being: loss of escape ways, loss of Temporary Refuge, loss of evacuation systems and structural collapse of the topside (cf. e.g. Figure 2).

The (conditional) probabilities of the above events are calculated using structural reliability methods by taking into account the uncertainties in the fire loading parameters (exit size, flow-rates, fuel properties, fire models), thermal properties (insulation thickness, thermal properties of structural steel and the insulation), structural properties (yield strength, expansion coefficient, etc.). In this way, dominant accident scenarios leading to loss of TR, EER or structural collapse can be identified and their probabilities quantified. The optimisation of passive fire protection on structural systems is performed by adopting the above mentioned method.

A broad framework for the organisation of the OFSOS software system has been developed which involves the integration of a number of available commercial and background software with the foreground software to be developed under the project. The overall architecture of the OFSOS system is shown in figure 6.

The OFSOS system is organised as a suite of programs, each suite dedicated to performing a major component task of the unified procedure for fire *safety assessment and optimal* design. A closer integration, with automatic communication (shown using arrows with full lines), has been achieved for the software either developed or enhanced during the project. The communication with commercial software has intentionally been kept to be manual so that users can easily replace these commercial software with any other equivalent systems,

The main functions of each of the suite of programs is described below:

Hazard Identification	These programs are used for identifying various hazard *initiating events* on an offshore platform which could potentially lead to a fire or blast.
Risk Analysis	These programs are used for fault-tree and event-tree analysis.
Release Rates	For a given hole size and exit conditions, these programs calculate the flow-rates as a function of time which is a necessary input for fire/blast load calculations.
Blast & Fire	The program/s calculates a time-history of heat flux on specified components for pool and jet fires and the overpressure in the case of an explosion The RASOS_B software has been developed by integrating AST's in-house software programs into the RASOS package
Material Database	The material data base holds temperature dependent material properties which are required for structural response calculations. The CURAN code has been developed using the ACCESS database system.

Structural Response — The RASOS_T and HOTPLATE programs have been developed to evaluate the temperature rise as a function of time in skeletal and plated structures. The deterministic linear and non-linear response of skeletal structures is calculated using the RASOS modules L, D & C which have been enhanced during the project.

Structural Reliability — The RASOS_R software has been enhanced for performing time-dependent system reliability analysis of skeletal structures. The RELIAB program has been enhanced and integrated with the RASOS limit-state functions for performing reliability analysis of plated structures and beam-column components.

Optimisation — The program OPTIWALL/OPTIBEAM have been developed based on the general purpose program OPTIM for the optimisation of passive fire protection.

As mentioned in the pervious, the developed methodology is demonstrated on some test cases carried out for the four platforms selected as guiding cases, these included the following:

Platform	Scenario	Location	Notes
North Sea Gas	Jet fire	Riser above m.w.l.	Different release sizes considered
Mediterranean Gas	Jet fire	Module on the topside	Likelihood to obstruct emergency escape route evaluated

The structures are analysed at a given time instant only corresponding to the time needed for the evacuation. In view of example, the jet fire scenario for the North Sea Gas platform is shown in figure 7 while the most-likely failure sequence with the reliability indices after each component failure is shown in figure 8. Results of sensitivity” analysis show that, for” the un-insulated condition, the uncertainty in the heat flux due to the fire is the dominant source of uncertainty, while for the insulated condition, the uncertainty in the insulation thickness and thermal properties of the insulation are also seen to be important.

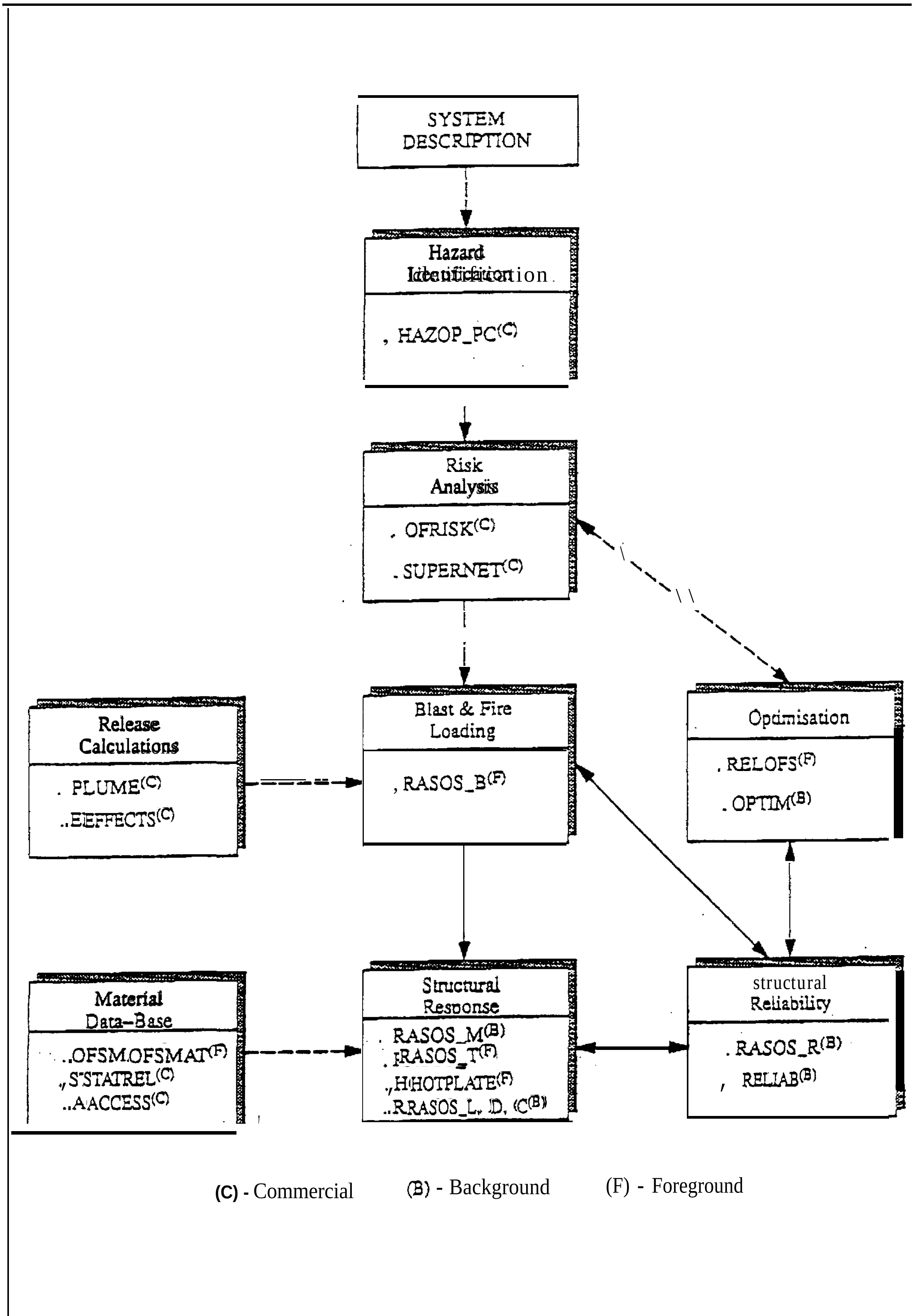

Figure 6: integrated assessment of topside facilities and structure under fire and blast conditions.

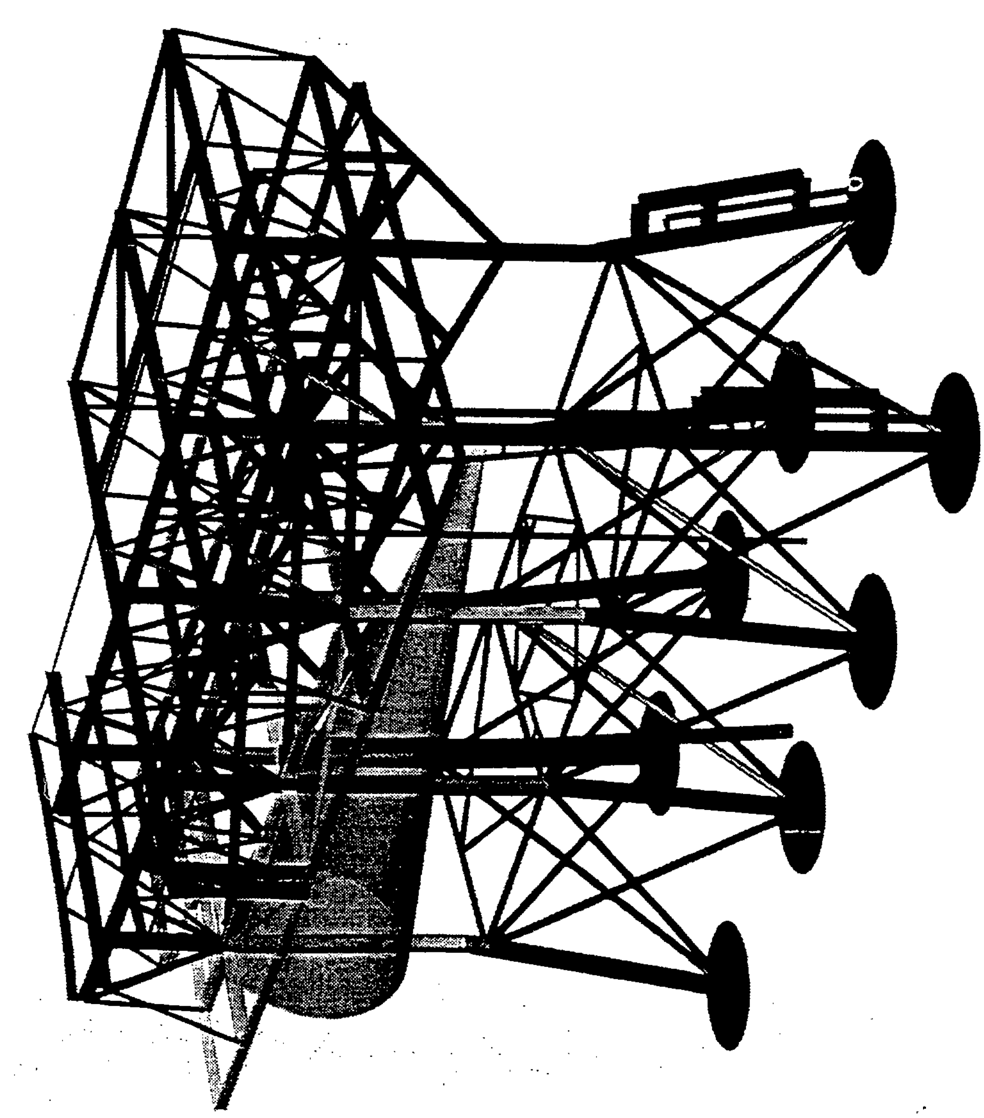

Figure 7: Model analysed.

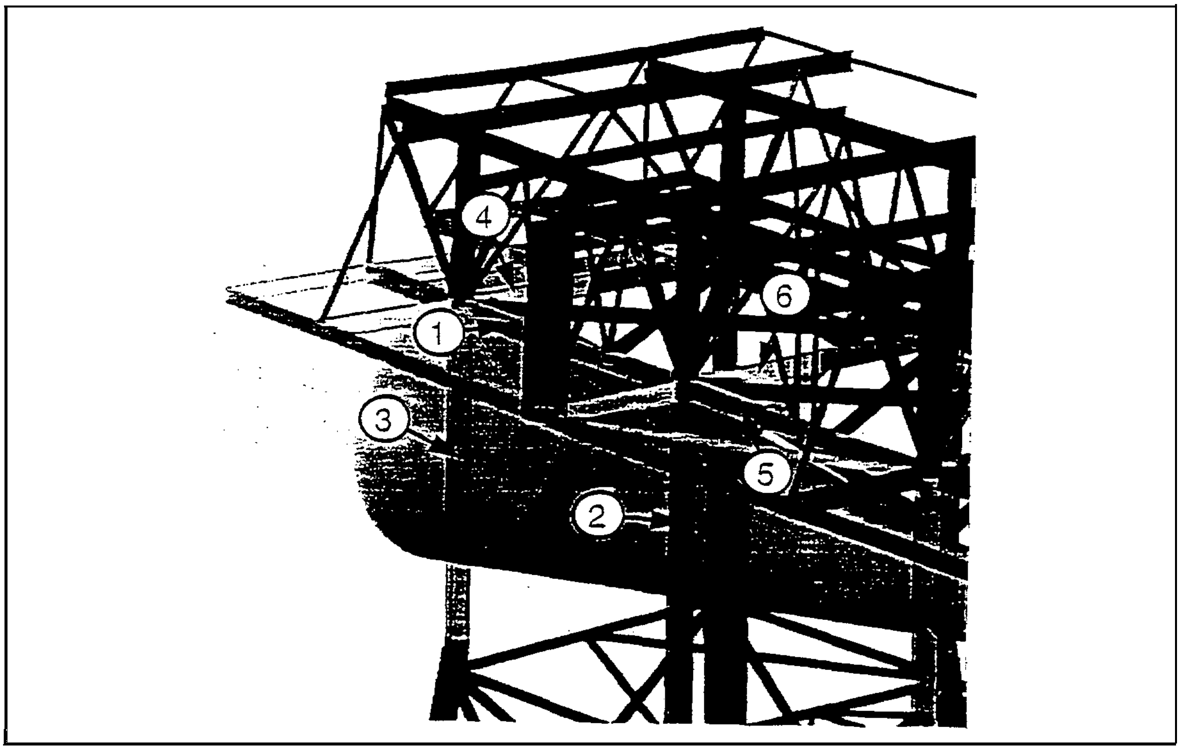

Figure 8: Failure sequence under jet fire.

Finally, guidance notes have been developed, mainly addressed to the perspective users of the developed procedures and software, explaining into details the philosophy and the use of the OFSOS methodology for the assessment of offshore structures subject to fire.

5. Conclusions and recommendations

The following conclusions and recommendations are drawn from the whole OFSOS project:

- structural reliability methods have proved to be valuable tool for the enhancements of traditional QRA techniques when addressing the effects of fire on offshore structures;
- although considerable insight in the problem can be achieved by deterministic analysis, the possibility of applying a consistent fully probabilistic approach to fire safety is an important step in view of the (large) uncertainty which is present, for the time being, in this kind of evaluation. Even more important, reliability based evaluations constitute the basis for a non-subjective comparison of different fire safety strategy;
- the developed software is very complex and still at research level, as such further work is necessary both on its evaluation/validation and on its optimisation from the computer time demand point of view (at its present status, both the reliability and optimisation modules are very much time consuming and their use in routine deign is not realistic);
- from the theoretical and algorithmic points of view, reliability based optimisation have been considerably enhanced within the project reaching the forefront of the world-wide developments on the matter; nevertheless this is an area where major R&D efforts are needed in order to allow for the use of the developed techniques in practical problems;
- system effects are often dominating when considering fire and blast effects on the structure: for this reason it is recommended that calibration efforts are carried out with OFSOS software (or similar ones) to provide designers with suggestions and indications on possible ways to mitigate fire&blast induced risk of structural collapse and, in particular, to evaluate the time to structural collapse of platforms designed according to present practice, in order to design temporary safe refuge, evacuation means and fire safety management systems accordingly.

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