How Reliable is Your Design Against the Impact of Impulsive Loads?
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ABSTRACT
Assessing the vulnerability/integrity of structures and facilities in hazardous industries under extreme or accidental loading conditions requires advanced analysis techniques. Traditional design methods do not always account for dynamic phenomena in structural behaviour. Two examples are given in this paper.

The first example deals with the consequences of an assumed axisymmetric mode of failure of a liquid storage tank. In the case of an LNG tank with a bound wall as a secondary containment, it is shown that the hydrodynamic pressure distribution is not only different from expected, but indicates a 2.5 times increase over the conventionally employed hydrostatic head design calculation.

In the second example assessment of the integrity of a subsea production system under accidental impact load conditions is presented. Detailed impact dynamic analysis of this load case shows that, contrary to general belief, the structural response is not greatly affected by the overall characteristics of the system (well stiffness, soil properties, etc.). Instead, other factors such as impact velocity and ability to deform locally in the impact region are more crucial.
INTRODUCTION

The aim of this paper is to present an advanced methodology for the integrity assessment of structures and facilities in hazardous industries under accidental load conditions. There are two main areas of interest: in the selection of accidental loads which the system should be able to withstand, and in the actual design of hardware to withstand these loads.

In a hazardous plant many of the accidental loads will be of a dynamic nature, i.e. a mechanical impact from a dropped object, or from a blast pressure wave. The modelling of such phenomena may be outside the designers field of experience, and also lacking in engineering codes which apply to the particular design. The result may be that dynamic accidental loads are not treated adequately in the design process.

This paper outlines two examples which clearly demonstrate the significance of proper modelling of dynamic phenomena. In such cases, a conventional design approach may yield results which cause an unintended risk increase, without the designer being aware that he has created such a situation in the system. The first example is taken from landbased industry and concerns the design of a LNG tank. The second example is from a subsea production system and concerns the impact resistance of a wellhead against a dropped object.

ACCIDENTAL RUPTURE OF AN LNG TANK

Introduction

Considerable interest has been aroused in recent years in the loading that would occur on the secondary protection system of a liquid fuel storage tank, if the tank were to fail. There has been much discussion on possible load time histories and the effects of such a failure and there are many possible alternative solutions to ensuring the overall integrity of the storage system should this failure occur. The purpose of this study is to find a design load that can be used with confidence to cope with the consequences and determine what stresses are developed by the liquid on the secondary protection system following failure.

Economy of scale dictates that typically large tanks are constructed with a volume between 5000 m$^3$ and 50,000 m$^3$. In the event of an accident, the consequences of such large volumes of fuel being released and the devastating results of fire, explosion and pollution are such that the probabilities of failure or release are required to be very low. The
provision of the current design of guard and bund walls or dikes alone may not be able to provide the necessary protection, especially as plants tend to be located close to populated areas. There is clearly a need to reassess the overall integrity of such systems.

There is also a diversity of views about the types of credible accident that should be considered in the design which could lead to release of liquid from the primary containment. A scenario that is now accepted as a real possibility is the rapid propagation or cracks in the primary containment, leading to rapid dynamic liquid loads being applied to the secondary containment. The problem facing the designer is often how best to estimate the loading on the secondary containment in such an event and the consequence of it. In this section, a numerical approach available for solving this problem is outlined and the preliminary results shown. It is demonstrated that the use of complex numerical methods can be crucial in obtaining a true understanding of the system behaviour and the design objectives that are to be met.

Formulation of the Failure Modes
Considerable disagreement exists as to the speeds at which cracks will actually propagate in the primary containment (steel tank) and the approach adopted is to conduct a sensitivity analysis to determine a pattern of crack propagation that will result in a "worst case" design condition. In general, vertical crack propagation is considered in conjunction with crack propagation around the base of the steel tank. Clearly the tank will move with the liquid in some way. From some work already carried out (Cuperus [1]), it is apparent that this is not a simple problem to solve and in many ways an experimental solution is intuitively the most satisfactory approach.

Numerical modelling, however, offers perhaps more flexibility and demands a mathematical representation of the physical problem and, provided that agreement can be shown between the numerical approach and experimental tests, it can be used with confidence.

The failure mode under consideration in the event of a tank rupture is a highly complex interaction between fracture propagation and the flow of a fluid with a free surface. In order to understand the physics of the complex interaction problem, two simplifying assumptions were made.

The first assumption is based on the fact that the cracks will propagate at much higher velocity than that of the fluid motion, and that they propagate at the same time in the vertical and the circumferential (round the base)
Structures under Shock and Impact

directions. The effects are that the steel tank loses its integrity instantaneously and from the structural containment point of view, can be considered removed. What is left hypothetically is the cylindrical column of fluid collapsing under gravity within the secondary containment. This greatly simplifies the problem and can be considered to represent an axisymmetric mode of failure.

The second assumption is based on some evidence that the crack will propagate much faster in the vertical than in the circumferential direction. This would result in a section of the tank being removed and the liquid flowing through the gap. This would represent an asymmetric failure mode. After some preliminary calculation of the consequences of such a failure mode reported in (Baldwin [2]), it was concluded that this asymmetric mode may be interesting from a sensitivity analysis point of view, and that in reality a mixture of two failure modes is more probable. This would in effect induce some asymmetry in loading on the secondary containment the effects of which may be marginally more severe than from the purely axisymmetric failure mode.

Methodology Used in the Analysis
The finite difference program used for the fluid dynamic problem is based on an Eulerian formulation. The volume-of-fluid technique (Hirt et al [3]) is incorporated for the treatment of the free boundaries. In an Eulerian representation, the computational grid remains fixed and the flow of fluid through the mesh is computed in small time intervals. Depending on the incompressibility condition (or on acoustic pressure representation) the integration of the Navier-Stokes equations in time can be performed with implicit or explicit schemes. The volume-of-fluid techniques deals with discontinuities and the fluid boundary (free surface) can undergo large deformations. The method is therefore well suited for this type of transient problem.

LNG Tank with a Bund Wall
The axisymmetric failure scenario considered here consists of rapid loss of the primary containment and consequent fluid impact onto the secondary protection system. A typical liquified natural gas (LNG) tank failure is analysed. A tank has a radius of 24 m and a volume of 50,000 m³. The LNG density is 583 kg/m³. The secondary protection system consists of a reinforced concrete cylindrical bund wall, the radius of which is 30 m and the height 20 m.

The sequence of "freeze frames", in Figure 1 depicts the fluid free surface positions at different time intervals. The corresponding hydrostatic (dotted line) and hydrodynamic pressure distribution are shown in Figure 2. This clearly indicates a 2:5 times increase with respect to the con-
ventionally employed hydrostatic head calculation. In the region between 8 m and 12 m from the ground level, the maximum dynamic pressure is more than 4 times greater than the local hydrostatic pressure.

**Conclusions**
The analysis carried out demonstrates that the current design of the containment bund walls may not be conservative and may not contain spillage caused by a sudden tank rupture.

The example shows that the pressures on the secondary containment wall will be higher than the usual design pressures employed. The pressure distribution is also quite different from the hydrostatic pressure profile used in the mechanical design of the walls.

Finally, the application indicates how useful this type of numerical modelling is in representing unusual or catastrophic modes of failure. Actual design configurations can be checked out on a scale that is just not feasible on a full scale experimental basis. The design changes to these protection systems can easily be incorporated and checked with the same numerical model to help the design to converge to an optimal solution from the safety point of view.

**DROPPED OBJECT IMPACT**

**Introduction**
The possibility of dropping an object on the subsea production system is only significant when a vessel is positioned over the template and intervention or inspection works are carried out. It is first of all important to determine an accidental design load, i.e. the worst accident for which a safe design is to be provided.

Due to the size of the system and its geometry two analyses were performed: a global two dimensional analysis in which the model consisted of axisymmetric and plane stress parts, and the detailed three dimensional analysis of the X-mas tree valve block under the boundary conditions obtained from the two dimensional analysis. As the result of the analyses clear design recommendations were laid out which were not previously obvious.

**Description of the Subsea Production System**
The central part of the structure to be considered is made primarily of steel and displays an approximate radial symmetry. Its general disposition is presented in Figure 3. As can be seen, it starts at the top with the workover riser and continues with the universal running tool and the lower...
riser package, thus completing the falling part of the structure. Below the lower riser package are located the X-mas tree with the re-entry hub and the wellhead. At the
time of impact, it is assumed that, as designed, connections between the universal running tool and lower riser package
and between the X-mas tree and the wellhead are active.

The function of the lower riser package is to
(dis)connect the riser system interface from/with the X-mas
tree re-entry hub while providing shear and sealing
capabilities.

The main element of the X-mas tree is the valve block
which holds the valves and actuators required to control the
flow from the well.

The wellhead provides the interface between the well,
the X-mas tree assembly, and the template. The well consists
of several conductors of different lengths. The template is
a frame structure which is piled to the soil at four corners
and which houses a maximum of six production wells.

Impact Load Cases
Whilst running a typical intervention tool, three phases can
be identified (vice versa for retrieval operations). The
first phase involves the assembly being lowered when the
vessel is "off location", i.e. not positioned above the
template. As soon as the assembly is 15-30m above the
seabed, the lowering operation is stopped and the vessel
reaches and the assembly is moved in above the intervention
well (second step). During the last phase guidelines
connected to the top of the guide posts are tensioned, and the
assembly is lowered onto the dedicated slot on the template.

A risk analysis concerning the path of dropped objects
in water showed that the risk of dropping an object onto the
intervention well is most significant during the last phase.
In order to select a design load case, the expected inter-
vention and installation works were considered more
carefully. Each operation was characterised by a frequency
of occurrence (e.g. once per year, or once during the
template lifetime) and a certain mass. It was thus possible
to establish a distribution of number of lifts per mass
category over the lifetime of the template. Based on a
historical drop probability the design load case could then
be selected, i.e. dropping an assembly composed of the work-
over riser, the universal running tool and the lower riser
package. If such an accidental drop were to happen, the well
would have at least one barrier: the primary barrier is the
downhole safety valve and sometimes the x-mas tree master
valve. It will be adequate to require that one barrier
remains intact after impact.
The total mass of the dropped object is 45 tonnes, which is increased by 20% for safety considerations, to 54 tonnes. The stationary part of the structure is composed of the X-mas tree, wellhead, template and the foundation soil together with the casings and cement which penetrate it. Due to the guide posts which will engage the corresponding funnels of the lower riser package, the impact is well centered. The drop height is estimated at 10 m. This is sufficient for the dropped object to approach the terminal velocity of 9.5 m/s by the time of impact. This constitutes the accidental event load condition, i.e. the worst case accident for which a safe design shall be provided.

**Numerical Treatment**

**General strategy** It seems clear from the description of the system that the impact to be analysed maintains an approximate axial symmetry around the axis of the structure. There are a number of features which have four-fold rather than axial symmetry but their symmetry is sufficiently close to axial to justify the approximation without danger of significant errors.

There are, however, some exceptions to the above rule which warrant further considerations. The first and more obvious is the X-mas tree valve block, as it is a part of the object of the study to assess whether its permanent deformation will allow operation of the valves after the event. The approach taken to solve this problem has consequently been a combination of two dimensional and three dimensional models which, while treating the valve block in all its complexity, render the problem soluble by exploiting its approximate axial symmetry. More specifically the analysis then consists of two major parts:

1) Global axisymmetric modelling in which the X-mas tree valve block has been replaced with an axisymmetric structure of identical mass and stiffness distribution along the axis. Such analysis produces the results for all parts of the structure with the exception of the X-mas tree valve block. It also produces time histories of velocities and forces at the top and bottom of the X-mas tree valve block all along the impact duration.

2) Three dimensional modelling of the X-mas tree valve block, which now entertains the multiple bores and other features of that structure. The boundary conditions to be imposed on that model as a function of time are obviously the time histories of forces and velocities saved in the axisymmetric analysis.
Numerical methodology Impact problems are characterised by a short duration and strong non-linear behaviour. The latter arises from the geometrical non-linearities established on contact between bodies and, very often, also from the levels of deformation induced in the materials under the impact stresses. For problems with the above characteristics explicit time-marching procedures have long been recognised to be the best. They easily treat the non-linearities in exchange for a drastic limitation in the size of the time step used for integration of the equations of motion.

Two dimensional model The two dimensional model represented the workover riser, universal running tool, lower riser package, X-mas tree, template beam, wellhead, casings, cement and soil. The model is shown in Figure 4.

Three dimensional model The three dimensional model of the X-mas tree valve block used for calibrating its simpler, two dimensional representation in the axisymmetric analysis, and for detailed calculation of stresses and possible permanent deformation around valve bore holes, is presented in Figure 5. The boundary conditions for the three dimensional model of the X-mas tree block were derived from the global two dimensional analysis in the form of the force time histories at the top and the bottom surface.

Results of Impact Analysis An analysis with impact velocity of 9.5 m/s was performed for the accident event load conditions.

Two dimensional analysis The history of events can be best visualised in the history of different energy components, Figure 6. The major drop in kinetic energy (both target and missile energies included) corresponds to the sum of plastic energy dissipation and elastic energy storage. Most of the dissipation takes place in about 4 to 5 ms. This allows elastic oscillation to start occurring after this time. The contours of plastic strain at the connection between the lower riser package and the X-mas tree are shown in Figure 7. The maximum plastic strains in the mesh are of the order of 15%.

Three dimensional analysis Time histories of axial stresses at the top and the bottom of the X-mas tree block obtained in the global two dimensional analysis were integrated to produce force time histories which represent the boundary conditions for the detailed analysis of the X-mas tree. The maximum plastic strains reached are of the order of 2.3%, in the region where the main vertical 5" bore intersects with the horizontal 5" bore, and also in the region where the horizontal bore intersects with the wing valve. It should be noticed that this is not a region of the greatest importance.
The differential displacement time history across the production master valve bore hole is represented by a maximum change of 0.15 mm in the bore diameter. The production master valve region of the X-mas tree did not exhibit any plastic straining.

Conclusions
One of the main features of this well assembly design are connection flanges between the lower riser package and the X-mas tree, the X-mas tree and the wellhead, and the universal running tool and the lower riser package. These connections act as filters for the force transfer. The most important connection is that of the lower riser package and the X-mas tree. The force transmitted through the re-entry hub flange to the X-mas tree valve block is limited by the cross-sectional area of the flange and the material yield stress. This means that strengthening the flange or any increase in the cross-sectional area due to possible re-design would transmit an increased force to the X-mas tree valve block. This is an important point for designers, since it is contrary to general belief that strengthening the flange would decrease the level of plastic straining and thus be beneficial.

The simple analysis originally carried out, treating the X-mas tree as a rigid mass and the wellhead, conductors and the soil as a spring, indicated that the stress levels in the X-mas tree were influenced by the spring stiffness. It has been shown here that this was not the case and the the stress wave propagation in the impact region is of a primary importance.

The production master valve region of the X-mas tree did not exhibit any plastic straining. The analysis described here shows the way the impact region should be designed in order to maximise the absorbed energy and minimise energy transitions to more vital parts of the assembly. This would hardly be possible without the use of advanced analysis tools.

REFERENCES
FIGURE 1. TANK WITH A SECONDARY CONTAINMENT WALL—FLUID FREE SURFACE AT DIFFERENT TIMES

FIGURE 2. CONTAINMENT WALL PRESSURE DISTRIBUTION
FIGURE 3  GENERAL LAYOUT OF THE WELL SYSTEM