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Awareness of crucial design aspects for pressure vessels

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--- ***ABSTRACT***---
Despite the fact that many recognized design codes and standards are available for the design engineers involved in the design process of pressure vessels, crucial aspects are regularly underestimated or even overlooked. Awareness of all relevant design aspects is essential for designing pressure vessels in order to ensure their pressure and structural integrity. As design rules were developed there was a conscious effort to avoid various modes of failure. Nevertheless, the design engineer should be aware of the potential failure modes during the design life of the pressure vessel. This paper provide the design engineer with more insight into potential failure mechanisms together with associated strength aspects and failure prevention. Finally, the difference between failure modes and failure mechanisms is further considered and explained.
KEYWORDS;- *pressure vessel, pressure and structural integrity, failure modes, failure mechanisms, strength aspects, failure prevention.*

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I. INTRODUCTION

Pressure vessels and piping are used in a wide range of industrial facilities to contain and transport fluids which may be intrinsically hazardous or are in a potentially hazardous thermodynamic state. A major part of the pressure designer's work is to ensure that such equipment can operate safely under the expected working loads, temperatures and pressures; that is, to ensure the structural integrity of the plant. This is traditionally done by designing pressure systems according to criteria given in recognized codes of practice using the so-called Design-by-Rule (DBR) or Design-by-Formula (DBF) approach. The added annex highlights the DBR versus DBA approach. The design by rule procedure could be applied to any conventional vessels comprising common shell, head, nozzle etc. configurations under intended operating conditions. However it does not relieve the design engineer of his responsibility, in the case of applying the design by rule approach, to prudently convince himself of potential causes of failure and to take appropriate measures to prevent damage. Understanding of the potential failure mechanisms is therefore essential. In addition, there is a desire to take advantage of contemporary advances in the understanding of the behaviour of pressure vessels to eliminate potential weaknesses in existing codes and at the same time to reduce over - conservatism in conventional vessels. The following sections enable the design engineer to gain insight into potential failure mechanisms and also emphasize related strength aspects and failure prevention.

II. FAILURE MECHANISMS and FAILURE MODES

Before the reliability of a vessel or piping system is evaluated, it is first necessary to identify the potential failure mechanisms and failure modes of concern. One must also relate different failure modes to possible safety and/or economic consequences. Judgment is needed to focus evaluations on those failure scenarios having highest likelihoods of occurrence.
A failure mode could be defined as any event which is likely to cause an asset (or system or process) to fail. More precise:

A failure mode is any event which causes a functional failure. It is also referred to as: the basic manner or mechanism of the failure or deterioration process also known as 'damage mechanism'

To avoid any confusion one may say that failure modes are associated with deviant function or behaviour, while failure mechanisms are associated with deviant physical condition or physical state either a failure mode is the direct effect of a failure mechanism, or a failure mechanism is a direct cause of a failure mode.

Categories of Failure Modes
- When capability falls below desired performance
- When desired performance rises above initial capability

- When the asset is not capable of doing what is wanted from the outset.

Failure Effects

- What evidence (if any) that the failure has occurred
- In what ways (if any) it poses a threat to safety or the environment
- In what ways (if any) it affects production or operations
- What physical damage (if any) is caused by the failure
- What must be done to repair the failure

Failure Consequences

- Technically Feasible and Worth Doing

A proactive task is worth doing if it reduces the consequences of the associated failure mode to an extent that justifies the direct and indirect costs of doing the task.

- Hidden and Evident Functions

An evident function is one whose failure will on its own eventually and inevitable become evident to the operating crew under normal circumstances.
A hidden function is one whose failure will not become evident to the operating crew under normal circumstances if it occurs on its own.

- Safety and Environmental Consequences

A failure mode has safety consequences if it causes a loss of function or other damage which could or kill someone.
A failure mode has environmental consequences if it causes a loss of function or other damage which could lead the breach of any known environmental standard or regulation.

- Operational Consequences

A failure has operational consequences if it has a direct adverse effect on operational capability.
For failure modes with operational consequences, a proactive task is worth doing if, over a period of time, it costs less than the cost of the operational consequences plus the costs of repairing the failure which it is meant to prevent.

- Non-operational Consequences

For failure modes with non- operational consequences, a proactive task is worth doing if over a period of time, it costs less than the cost of repairing the failures it is meant to prevent.

- Hidden Failure Consequences

For hidden failures, a proactive task is worth doing if it secures the availability needed to reduce the probability of a multiple failure to a tolerated level.

It is a responsibility for design engineer of power plants, refineries, gas plants and chemical plants to design and construct high quality pressure vessels and piping systems. To complete this responsibility, it is very important to understand failure modes of pressure vessels, piping and their components, relation between each failure mode and stresses, and design consideration to prevent the failure.
Failure modes to be considered are depicted in Table 1:

Table 1: Overview failure modes and associated control parameters

FAILURE MODE	CONTROL PARAMETER
Excessive elastic deformation , elastic instability	Geometry and material
Excessive plastic deformation	Maximum membrane stress
Brittle fracture	Material selection
Stress rupture/creep deformation (inelastic)	Maximum membrane stress
Plastic instability-incremental collapse	Stress range
High strain-low cycle fatigue	Cyclic stress
Stress corrosion	Environment, material, stress level
Corrosion fatigue	Environment, material, stress level

Tabel 2: Overview of a number of failure mechanisms and other causes that are known to result in defects of pressure vessels and piping systems.

Failure mechanisms associated with pressure vessels and piping systems
Operation at loads and/or pressures exceeding design limits
Operation at temperatures over design limits
Operation at temperatures below brittle fracture limits
Improper design and fabrication
Improper repairs and alterations
Structural damage from maintenance
Improper or degraded supports for components
Structural damage from external events (impact, crushing, etc.)
Excessive vibration
Improper or degraded overpressure protection
Material or welding defects
General corrosion
Flow-assisted corrosion
Wear (excessive maintenance)
Thermal fatigue cracking
Vibration fatigue cracking
Stress corrosion cracking
High-temperature creep
Long-term embrittlement
Loose or missing fasteners

Above overview is intended only to show examples and will not be discussed in detail. Many failures come from gradual material degradation (e.g., corrosion, fatigue cracking, wear, etc.) that occurs over time spans of many years before it advances to a stage sufficient to cause a structural failure (leak or rupture event). Metal fatigue is one common failure mechanism. Small-diameter piping is prone to vibrational stresses that cause cracking. Fatigue failures of larger sizes of vessels and piping are more likely to come from cyclic thermal stresses such as at locations exposed to cyclic exposures to hot and cold fluids. Corrosion mechanisms are a particularly common cause of failures both in the form of widespread loss material (wall thinning) or as local attack such as pitting or cracking. In other cases, a single short-term event (e.g., overpressure, extreme overheating, water hammer, etc.) can cause a sudden failure. Some loading events are natural occurrences such as earthquake loadings; whereas, other events come from human errors in operating and maintaining the facility such as from improper repairs and operation at pressures or temperatures over design limits. Pressurized systems are usually protected from excess pressures and temperatures by safety devices, but these devices can fail to function due to time-related degradation or improper installation or maintenance.

III. STRENGTH ASSESSMENT

A pressure vessel may become unsuitable for its duty in various ways. This section gives directives for the assessment for the most important of these [3]. Two ways of stress classification are used, which result in the following stress categories:

1. classification by origin:
- primary stress (Σ_p); the stress which is in direct equilibrium with the external loading;
- secondary stress (Σ_s); the stress as a result of satisfying displacement or compatibility conditions;

2. classification by distribution across the section:
- membrane stress (Σ_m); the value of a stress uniformly distributed across the section with the same force resultant as the stress distribution under consideration;
- bending stress (Σ_b); the extreme value of a stress varying linearly across the thickness, having zero force resultant and a moment resultant equal to that of the stress distribution under consideration;
- peak stress (Σ_a); the maximum of the stress distribution remaining after subtracting the membrane and bending stress.

Table 3: Overview of stress categories and the corresponding equivalent stress (σ_v) and failure modes

	stress category description	symbol	equivalent stress σ_v	failure mode
A	primary membrane stress	Σ_{pm}	$\sigma_{v;pm}$	plastic deformation
B	primary bending stress	Σ_{pb}	$\sigma_{v;pb}$	-
C	total primary stress	$\Sigma_p = \Sigma_{pm} + \Sigma_{pb}$	$\sigma_{v;p}$	plastic deformation static rupture

D	secondary membrane stress	Σ_{sm}	$\sigma_{v;sm}$	-
E	total membrane stress	$\Sigma_{tm} = \Sigma_{pm} + \Sigma_{sm}$	$\sigma_{v;tm}$	plastic deformation
F	secondary bending stress	Σ_{sb}	$\sigma_{v;sb}$	-
G	secondary peak stress	Σ_{sa}	$\sigma_{v;sa}$	-
H	resultant of primary and secondary stresses, excluding the peak stress	$\Sigma_r = \Sigma_p + \Sigma_{sm} + \Sigma_{sb}$	$\sigma_{v;r}$	static rupture incremental plastic collapse
I	total stress	$\Sigma_t = \Sigma_r + \Sigma_{sa}$	$\sigma_{v;t}$	fatigue

Combination results in nine stress categories, each with a corresponding equivalent stress. Table 3 summarizes the stress categories resulting from combination and the corresponding equivalent stresses and failure modes.
The assessment criteria are given in Table 4 below.

Table 4: Assessment criteria

A	primary membrane stress	$\sigma_{v;pm} \leq 0.67\ R_e(\vartheta_m)$
B	primary bending stress	-
C	total primary stress (minimum of)	$\sigma_{v;p} \leq 0.5\ R_m$ (for ductile material) $\sigma_{v;p} \leq R_e(\vartheta_m)$
D	secondary membrane stress	-
E	total membrane stress	$\sigma_{v;tm} \leq R_e(\vartheta_m)$ resp. $0.73\ R_e(\vartheta_m)$ See explanatory note
F	secondary bending stress	-
G	secondary peak stress	-
H	resultant of primary and secondary stresses, excluding the peak stress	$\sigma_{v;r} \leq R_m$ (for ductile material) $\sigma_{v;r} \leq 2\ R_e(\vartheta_m)$ (incremental collapse)
I	total stress	$\sigma_{v;t} \leq S_a$ (alternating stress obtained from a fatigue curve for the specified number of operating cycles) Detail are given in [1],[5] and [6]

$R_e(\vartheta_m)$ = yield stress @ temperature (ϑ_m) ; R_m = tensile strength @ 20°C

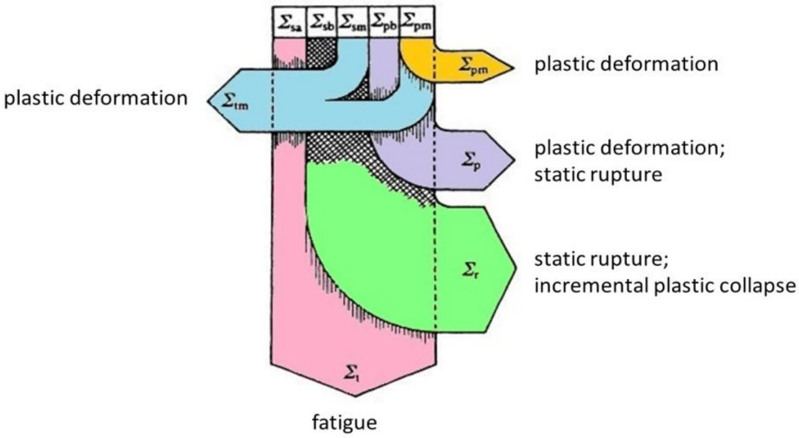
Explanatory note
For a rotationally symmetrical shell, the following three conditions must be satisfied :
$\sigma_{v;tm} \leq R_e(\vartheta_m)$
$l_1 \leq (r.t)^{½}$ respectively $l_2 \geq 1.25\ [(r' + r'').(t' + t'')]^{½}$
Where:
l_1 = the greatest dimension in meridional direction of a region in which $\sigma_{v;tm} > 0.73\ R_e(\vartheta_m)$
l_2 = the smallest interval in meridional direction between two such regions
r = the length of the normal to the centre of such a region, measured from the centre of the wall to the axis of rotation of the shell
t = the smallest wall thickness within such a region.

Cautionary note
These classifications and limits shall not be used with the results of non-linear finite element analysis.

IV. STRESS CATEGORIES

The classification into stress categories has the same bases as that in [1]: the stress across the section is subdivided by its origin (equilibrium or compatibility conditions) and by its distribution across the section (membrane, bending or peak stress). This classification, together with the corresponding assessments is illustrated in Figure 1.

Figure 1



Corresponding stress categories with ASME VIII Division 2 [1]
Σ_{pm} =^ P_m = primary membrane stress
Σ_{pb} =^ P_b = primary bending stress
Σ_{tm} =^ P_L = total (local) primary membrane stress
Σ_r =^ $P_m + P_b + Q$ = resultant of primary and secondary stresses, excluding the peak stress
Σ_{sa}=^ F = secondary peak stress
Σ_t =^ $P_m + P_b + Q + F$ = total stress

V. PREVENTION of PRESSURE VESSEL FAILURE

How failure occurs

Fortunately, catastrophic structural failures are rare. However, when structures such as pressure vessels, storage tanks or pipelines fail, the ramifications can be extensive, in terms of human injury, together with financial and environmental damage. There are failure modes that occur instantly after installation, such as buckling, overload and fast fracture. Other failure modes only occur after a period of time in service, such as fatigue, corrosion, creep, stress corrosion cracking and hydrogen embrittlement. In order to prevent failure there are a number of approaches that can be adopted.

During design

Most failures, and almost all installation failures, can be prevented by ensuring that the design, build, maintenance and inspection of the pipeline or pressure vessel are carried out to a recognised Code or Standard. This may include requirements for post-weld heat-treatment, proof testing and welder and weld procedure qualification. The general approach is to ensure adequate material toughness; design to prevent high stress; to stress relieve thick sections; to fabricate and inspect using qualified welders and procedures; to minimise the incidence of defects, and then proof test. Proof testing is a traditional method for demonstrating that pressure vessels and pipelines do not contain flaws that can initiate catastrophic failure in service. The vessel is pressurised with water to above the maximum service stress, and if the component survives then the service conditions will be safe. However, failures of large components during proof testing can be very costly, and this method will not take account of any crack growth that occurs during the life of the component.

During service

Failures during service can be due to unforeseen or unaccounted-for cyclic stresses or environmental conditions, causing fatigue or corrosion related problems. Often these issues will be addressed at the design stage. However, cracking that has occurred during service can sometimes be analysed using an Engineering Critical Assessment (ECA).

Engineering Critical Assessment (ECA)

This is an analysis, based on fracture mechanics principles, of whether or not a given flaw is safe from brittle fracture, fatigue, creep or plastic collapse under specified loading conditions. An ECA can be used during design of a pipeline or plant, to assist in the choice of welding procedure and/or inspection techniques. It can also be used during fabrication, to assess the significance of known defects which are unacceptable to a given fabrication code, or a failure to meet the toughness requirements of a fabrication code.

ECAs can also be used during operation, to assess flaws found in service and to make decisions as to whether they can safely remain, or whether down-rating/repair are necessary. The ECA concept (also termed 'fitness-for-purpose analysis') is widely accepted by a range of engineering industries. If the standard ECA cannot demonstrate that a structure is safe then there are other options. It could be assessed using more advanced techniques such as probabilistic analysis, crack arrest or leak before break. Alternatively the structure can be repaired, replaced or down-rated, or the operating temperature and/or environment changed.

Fatigue improvement techniques

Fatigue improvement techniques can be used during service to extend a component's life. Small flaws that survive the proof test may grow under cyclic loading in service to an extent that they can cause failure of the component during its lifetime. Fatigue crack growth can be prevented or controlled by the use of standard fatigue design methods, or an ECA can be used for flaws found in service. Removing tiny non-metallic intrusions from the weld toes by methods such as toe grinding, and putting the weld into local compression by peening will also improve the fatigue life.

VI. LOADINGS TO BE CONSIDERED IN ADDITION TO PRESSURE

In the design of a pressure vessel it may be necessary to take into account the effect of the following loadings in addition to the calculating pressure:

- Additional loads due to pressure testing
- Loadings from supports and connected piping
- Loadings from different thermal expansion
- Fluctuating pressure and temperatures
- Shock loads due to water hammer or surging of vessel's content (characteristic dynamic load)
- Wind - and /or seismic loadings

VII. LOW TEMPERATURE PHENOMENA

The following phenomena should be considered because they are prone to catastrophic brittle fracture [7]:

- Blowdown (depressurisation; low temperature caused by Joule-Thompson (JT) effect)
- Low ambient temperature exposure whilst under pressure (LODMAT = Lowest One Day Minimum Ambient Temperature), mainly during winter period.
- Auto-Refrigeration , lower metal temperatures resulting from process excursions ,wherein a process fluid changes phase from liquid to gas resulting in significantly lower temperature of the fluid and, in turn, the metal that contains the fluid.

VIII. DISCUSSION

This paper concerns calculation methods based on the Design-by-Analysis (DBA) approach rather than Design-by-Rule (DBR). Essentially DBA is based on the idea that if a proper stress analysis can be conducted then a better, less conservative , assessment of the design can be made than would otherwise be the case by the usual approach of DBR. Some cautionary words are necessary for the unwary. Confusion arises because of the tendency to denote the stress intensity in a particular category by the symbol for that category, e.g. Σ_{pb} is the stress intensity for the primary bending stress category. However, ($\Sigma_{tm} + \Sigma_{pb} + \Sigma_{sb}$) is not the sum of the local primary stress intensity, the primary bending stress intensity and the secondary stress intensity. It is the stress intensity evaluated from the principal stresses after the stresses for each category have been added together in the appropriate way. This can be summarised by simply stating: Only add stresses ; Do not add stress intensities. The DBA approach is an attempt to provide a systematic method for general design to cover any load and geometry combination. The greatest problem lies in the classification of the stresses and this has not yet been satisfactorily resolved particularly where modern methods of analysis are employed.

A new pressure vessel design by analysis method avoiding stress categorization is the developed Direct Route. Hence within this DBA route, there are two possibilities available:

- the so-called Direct Route (DR), and
- the Stress Categorization Route (SCR)

The main advantages of the Direct Route are:

- it overcomes all of the problems associated with the stress categorization route,
- it addresses failure modes directly, and, thus, gives better insight into critical failure modes and the corresponding safety margins – of special importance for in-service inspections – and thus, it may lead to improved design philosophy,

• it allows for direct incorporation of other actions than pressure, especially thermal and environmental ones,
• it is stated generally in general terms, allowing for different approaches

The disadvantages of this route are:
• non-linear calculations are required, leading to more computation time, and, because of this non linearity,
• linear superposition is, in many checks, not possible anymore,
• quite often requires a good knowledge of the underlying theories.

To allow for easy incorporation of other actions than pressure, and especially the environmental ones – usually prescribed by local codes or regulations – this route follows, quite closely the Eurocode (for steel structures) [4]; like the Eurocode, it uses a multiple safety factor format (partial safety factor format).

However further treatment of the Direct Route falls outside the scope of this paper.

IX. CONCLUSION

This paper enables the design engineer of pressure equipment to gain a realistic view of the different manifestations of pressure equipment failure during its design life. Attention is also paid to the prevention of failure and the associated remedies. An important part concerns the strength assessment if a Design-by-Analysis (DBA) approach is used. Finally, some attention was paid to the so-called Direct Route (DR)[2], which can offer advantages over the DBA route, which can be used to circumvent the categorization of different stress categories.

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ANNEX

Design by Rule versus Design by Analysis

Pressure equipment of complex geometry and / or loadings are safety critical and can have complex stress distributions. Pressure vessel codes such as ASME VIII Division 2 [1] and EN 13445 [5] incorporate 'Design by Analysis' methodologies which can be implemented using finite element analysis (FEA), and which offer an alternative to traditional design rules i.e. DBR or DBF. 'Design by Analysis' enables the designer to accurately assess the component against each failure mode, as stresses and structural behaviour can be predicted. By contrast, traditional design rules often incorporate conservatism to compensate for the fact that design rules do not accurately predict the entire stress distribution within the vessel, and do not address all modes of failure, such as fatigue and fracture.

Implementing the 'Design by Analysis' methodologies using FEA in line with industry standards allows for a more efficient design, while not compromising on safety. It also enables an accurate determination of the margin of safety for each failure mode. As a consequence, 'Design by Analysis' is used in the following areas:

- Design of vessels and components having dimensions outside of those covered by traditional design rules
- Optimisation of designs in order to reduce material and manufacturing costs
- Fitness for purpose assessments where manufacturing tolerances have been exceeded
- Assessment of complex loadings such as temperature distributions
- Nozzle external load capacity evaluation
- Fatigue assessments
- Detailed buckling assessments