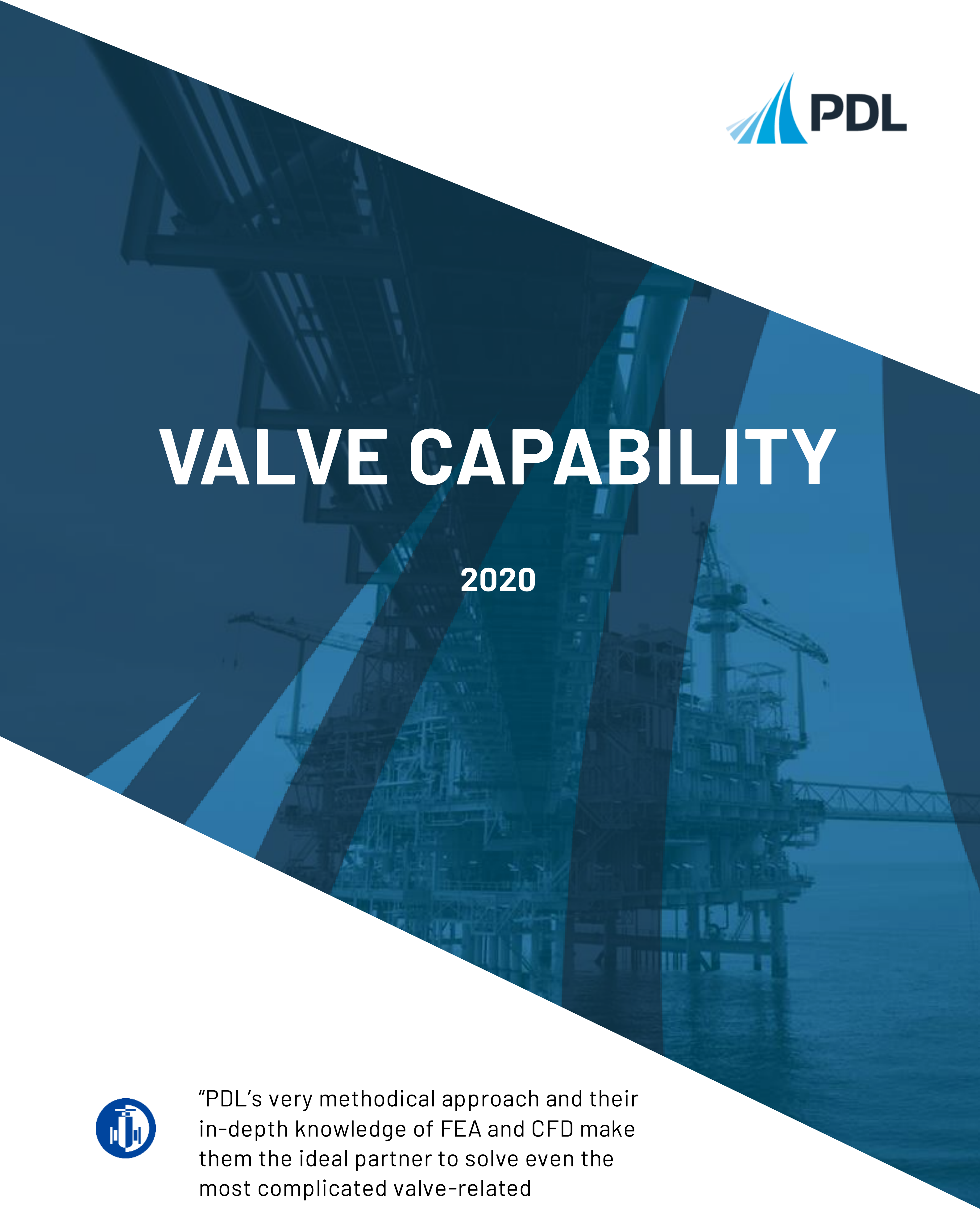


VALVE CAPABILITY

2020

> “PDL’s very methodical approach and their in-depth knowledge of FEA and CFD make them the ideal partner to solve even the most complicated valve-related problems.”

CONTENTS

FIGURES

WHO WE ARE:
PDL is an engineering consultancy. We aspire to be the 'go to' people for advanced engineering analysis consultancy services for our current and future clients and the 'go to' company for our current and future employees.

People are the key to any business, and we are certainly no exception to that rule. Our engineers are held in high regard by our clients and deservedly so. Since our inception back in 2001, our engineers have supported some of the most technically challenging projects at some of the most notable regional, national and international entities.

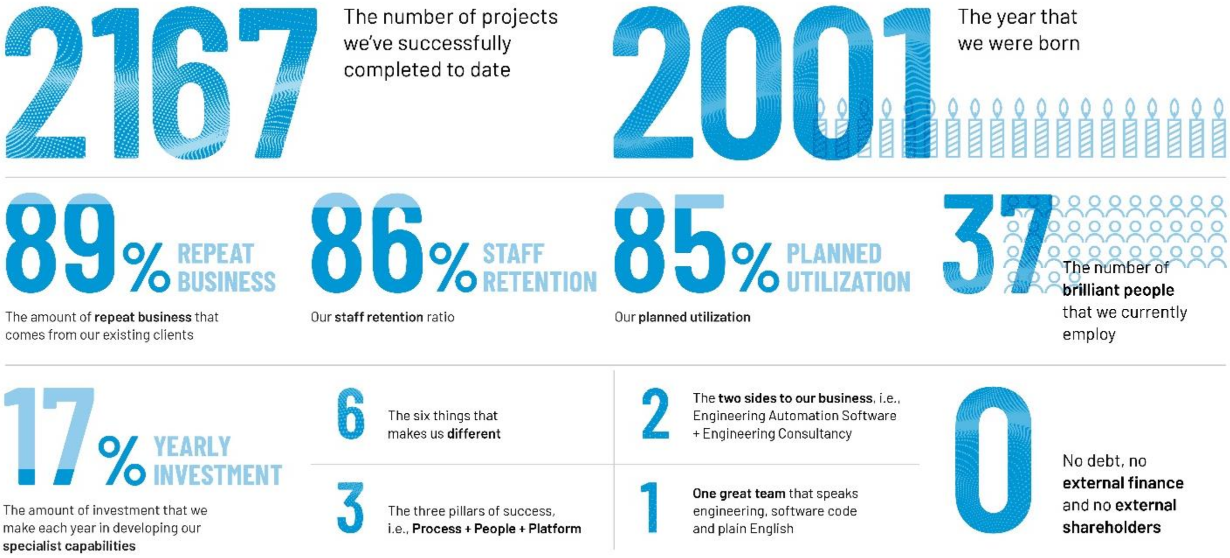
Over 80% of our new business comes from existing clients. This high level of repeat business is the cornerstone of our success and it is testament to the quality of the work that we deliver on a consistent basis and the trust that we establish with our clients.

As we approach the end of our second decade, we have shown sustained growth and net profitability. We have no debt, no external finance and no external shareholders. This means we can work with our clients in accordance with our own beliefs and uncompromising values.

WHAT WE DO:
We deliver technical solutions to complex problems at any point in your product lifecycle, from the design optimisation or validation of a new product, to solving an issue with an existing product that's already in the field.

We will give you solutions to problems, not just answers to questions, we will give you a competitive edge in your market and we will build your standing and credibility with your clients.

In the words of our Chief Engineer, "we will do the right work and we will do the work right". **No exceptions**.



2167 The number of projects we've successfully completed to date

2001 The year that we were born

89% REPEAT BUSINESS
The amount of **repeat business** that comes from our existing clients

86% STAFF RETENTION
Our **staff retention** ratio

85% PLANNED UTILIZATION
Our **planned utilization**

37 The number of **brilliant people** that we currently employ

17% YEARLY INVESTMENT
The amount of investment that we make each year in developing our **specialist capabilities**

6 The six things that makes us **different**

3 The three pillars of success, i.e., **Process + People + Platform**

2 The **two sides to our business**, i.e., Engineering Automation Software + Engineering Consultancy

1 **One great team** that speaks engineering, software code and plain English

0 No debt, no **external finance** and no **external shareholders**

WHAT MAKES US DIFFERENT

In Q4 2017, as part of the process to define our overarching Unique Value Proposition as a business, we undertook a series of 1-2-1 interviews with several our clients. The clients were carefully selected to give a broad sampling of client size, type and industry focus. During the interview, the clients were asked to give open, honest and frank answers to a set of common questions. The results were invaluable, and they have helped us to clearly define what makes PDL different.

In terms of why clients choose to do business with us in the first place, the overriding answer was that we are perceived by the market as being **the best at what we do** and in terms of why clients then stay with PDL, the overriding answer was that **we always deliver**.

The interview questions then probed deeper into each of these two important areas to determine the fundamental reasons behind these two critical decisions. Once again, the results were invaluable:

1	**RELIABILITY**	"...PDL you impress me. You do what you say in the time you say. Very good work..."	**TechnipFMC**
2	**PEOPLE**	"...you make it so easy to do business with you; reliability and delivery and it's all done with a smile..."	**BEL Valves**
3	**FLEXIBILITY**	"...the way you work, your flexibility and the sheer willingness to get the job done, is simply brilliant..."	**Cummins**
4	**KNOWLEDGE**	"...highly skilled engineers...who are comfortable to adjust their level of support as the project develops; these are features we haven't had available from elsewhere..."	**GMC**
5	**COMMUNICATION**	"...a great level of engagement before the work was even done; you were clear and concise; you gave us a great understanding from the start..."	**Viking SeaTech**
6	**QUALITY**	"...after working with you, it is clear the quality and competence of your engineers is your differentiator..."	**Murphy Group**

So, in the words of our clients, what makes us different is our;

- ✓ **Reliability**
- ✓ **People**
- ✓ **Flexibility**
- ✓ **Knowledge**
- ✓ **Communication** and
- ✓ **Quality**.

THE BENEFITS THAT WE WILL DELIVER

DELIVERY WITHOUT DOUBT

We will **mitigate the risk of failure** in a new product by assessing the valves' code compliance and functionality before you commit to manufacture.

If an existing valve fails on test or underperforms in service, we will determine the root cause of the issue and propose validated design changes to fix the problem and **optimise performance**.

We will **shorten your time to market** on new product development by giving you a right first-time solution at the start and eliminate the need to build and test multiple prototypes.

We will **reduce your costs** and increase your profit by extending the reach and lowering the cost of your existing products.

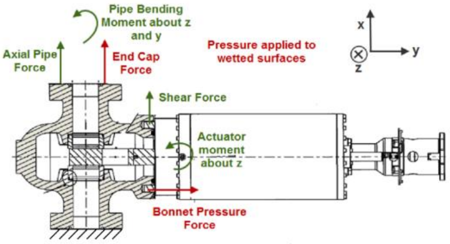


Figure 1: *Force diagram of a gate valve accounting for the actuator assembly*

STRUCTURAL ANALYSIS

Verification is fundamental to valve design; it provides complete assurance of the structural integrity. We are well placed to provide all types of structural analyses in accordance with the valve-related design codes.

ASME VIII Div.2 or 3 'Design by Analysis'

The ASME BPVC VIII rules for construction of pressure vessels are often used for the validation of topside and subsea valves using allowable stress limits from API 6A.

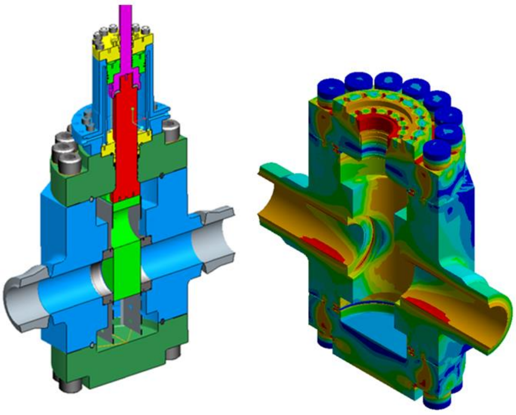


Figure 2: *Slab gate valve geometry and a typical stress profile from an FEA model*

Elastic Stress Analysis Method

- This linear elastic assessment methodology is typically a conservative assessment.
- It uses stress classification lines (SCL's) to linearize stresses into membrane and membrane plus bending stress for assessment against the plastic collapse criteria.
- Allowable stress limits are taken from ASME VIII Div.2:
  - Primary General Membrane Stress limit $\leq S_m$
  - Primary Local Membrane + Primary Bending stress limit $\leq$ 1.5 S_m
- API 6A allowable stresses can be applied:
  - Design stress intensity at working pressure:
  - $S_m = \frac{2}{3} S_y$

Where S_m *= ASME stress limit for membrane stress intensity at design pressure*

And S_y *= minimum yield strength of the material at the required temperature*

- Protection against local failure is also assessed (typically for potential cracking).

Elastic-Plastic Stress Analysis Method

- Takes account of material deformation; allowing for stress distribution and a reduction in unrealistic stress peaks.
- Material curves are generated using ASME VIII Div.2 Annex 3-D.
- Protection against plastic collapse criteria (global) assessments require convergence at factored loads.
- Protection against local failure assessments require the peak equivalent plastic strain to be below a calculated limiting tri-axial strain limit.

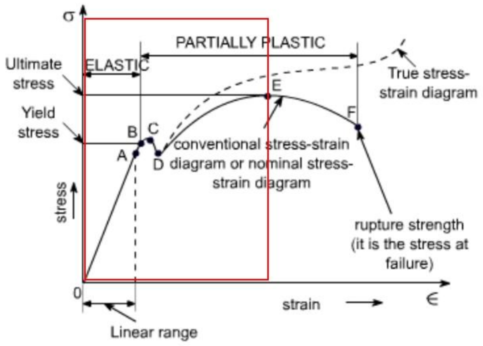


Figure 3: *Elastic-Plastic model takes account of non-linear material behaviour*

DNV-RP-F112 (HISC)

Hydrogen Induced Stress Cracking (HISC) analyses are used for duplex or super duplex stainless steels exposed to cathodic protection in a subsea environment. Two material models can be used. In most cases, the linear elastic stress assessment is more conservative than the non-linear strain criteria assessment.

Linear Elastic Stress Criteria

- The ASME VIII Div.2 stress linearization method is used to determine membrane and membrane plus bending stresses over the wall thickness.
- Principal membrane stresses and equivalent membrane stresses (calculated from the membrane stress components in the principal direction) are assessed against the limit:

$$\sigma_m < \sigma_m \times \gamma_{HISC} \times SMYS$$

- Principal membrane plus bending stresses and equivalent membrane plus bending stresses (calculated from the membrane plus bending stress components in the principal directions) are assessed against the limit:

$$\sigma_{m+b} < \sigma_{m+b} \times \gamma_{HISC} \times SMYS$$

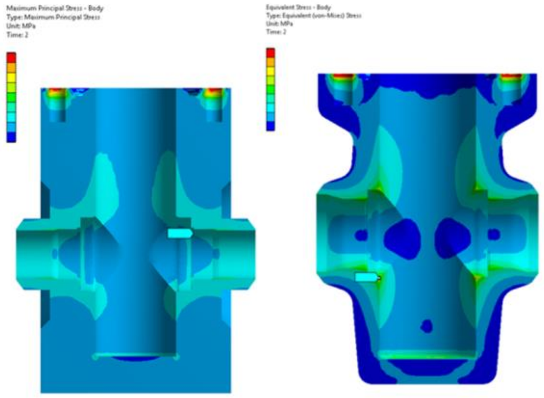


Figure 4: *Typical principal and equivalent stress plots of a valve body during HISC analysis*

Non-linear Strain Criteria

- When using the non-linear elastic-plastic approach, strain assessments are undertaken to ensure loading does not initiate significant cold creep and hydrogen induced stress cracking in the material.
- A material hardening curve is typically generated from DNV-RP-F112 where it is normally corrected for relevant high temperatures. The curve may have linear elastic characteristics to 0.1% total strain, 80% of SMYS corresponds

to 0.3% total strain, SMYS corresponds to 0.5% total strain and the material strain hardens after 0.5% strain in line with an appropriate standard, typically ASME VIII Div.2 Annex 3-D.

- Allowable initial maximum principal strain depends on various material parameters and the location of strain.

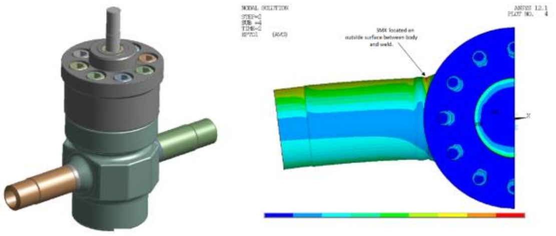


Figure 5: *Principal strain during a HISC analysis*

GASKETS & BOLTING ASSESSMENTS

- Gasket assessments are undertaken to provide confidence of sealing in many situations, such as during the application of preload and full working pressure, or under the application of actuator loading and external loads.
- Contact pressures are obtained and compared against ISO-13628-7 (Annex H) factors of >1.2 and 2.0 for liquids and gases respectively. Any continuous contours of contact pressure observed above these factors offers assurance in sealing.

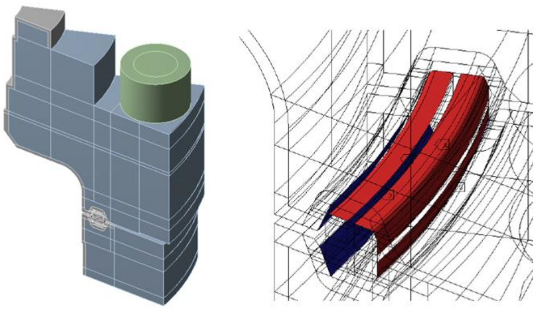


Figure 6: *Cyclic - symmetry model of body, bonnet, gasket and bolt component*

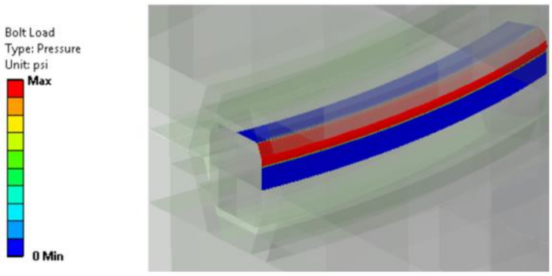


Figure 7: *Gasket contact pressures during bolt pre-load and pressure application*

- Bolting assessments are undertaken to demonstrate compliance with ASME VIII Div2, Part 5 (Design by Analysis), Service Stress Requirements and Fatigue Assessment.
- There are two parts to Service Stress Requirements where:
    - The maximum value of membrane stress across the bolt cross section shall not exceed two times the allowable stress values.
    - The maximum value of membrane plus bending stress at the periphery of the bolt cross section shall not exceed three times the allowable stress values.
- Fatigue Assessments for bolts involves calculating the alternating stress, determining the maximum number of load cycles and in turn calculating the fatigue damage.

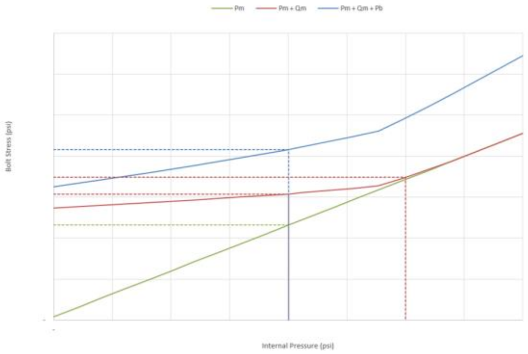


Figure 8: *Bolt stress as a function of Internal Pressure*

TRIM COMPONENTS & DRIVE TRAINS

- Trim components are structurally assessed to validate calculation designs.
- Contact pressures between seat ring/gate/ball/disc can be extracted to determine the sealing behaviour.
- Similar to gasket sealing assessment, contact pressures are compared against ISO-136258-7 (Annex H) factors of >1.2 and 2.0 for liquids and gases respectively.
- Closed and near-open positions can be considered for stiffness variations.

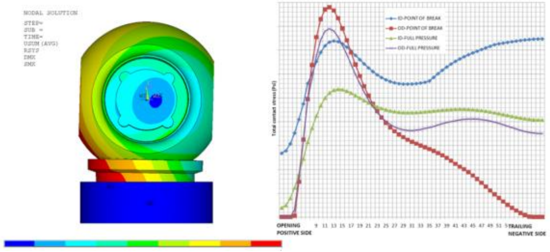


Figure 9: *A ball valve contact pressures during closed and near open positions at ID and OD*

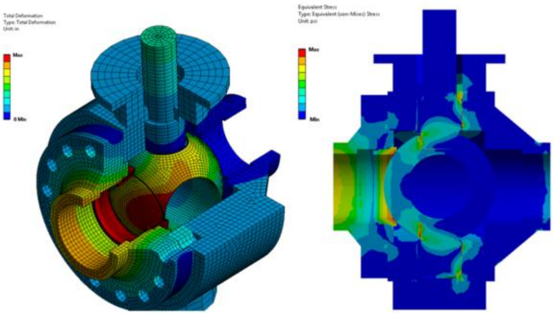


Figure 10: *Deformation and equivalent stress plot of a ball valve*

- Drive train assessments can verify if the assembly is suitably designed for operating conditions or investigate failure modes under extreme load cases.
- Assembly models may consist of the gate, T-Nut, stem, drive threads, piston etc.

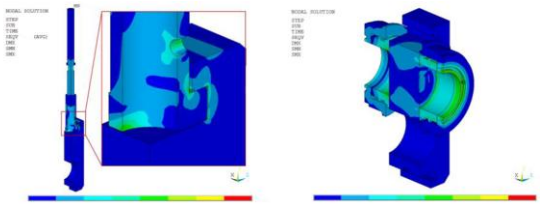


Figure 11: *Equivalent stress plots of drive train and trim components*

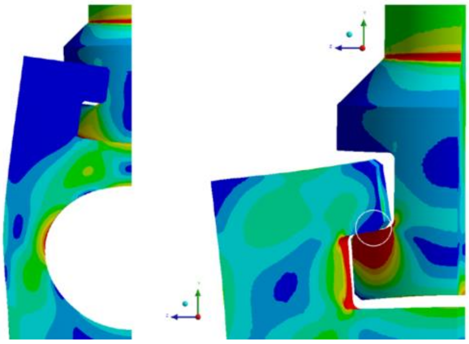


Figure 12: *Exaggerated results from a gate and stem structural analysis*

QUALITY WITHOUT QUESTION

SEISMIC ANALYSIS

There are several ways to perform \seismic analyses. These include:

- Equivalent Static Analysis (Static) – a series of loads representing ground motion is applied and the valve response is obtained.
- Full Dynamic Transient Analysis (Time) – A linear and nonlinear analysis where time-varying loads are applied to determine the time-varying responses.
- Modal (Frequency) – A fundamental technique in which vibration characteristics of structures are determined, such as natural frequencies and the corresponding mode shapes.

- Mode-Superposition Transient Dynamic Analysis (Time) – Linear mode-superposition method scales the mode shapes obtained from a modal analysis and sums them to calculate the dynamic responses of a structure.
- Harmonic (Frequency) – Sinusoidally-varying excitations across a range of frequencies are applied to the model which outputs the steady state responses of a structure.
- Spectrum (Frequency) – A spectrum is a representation of a load's time history in the frequency domain. The maximum response is obtained. However, some information is lost (phase).

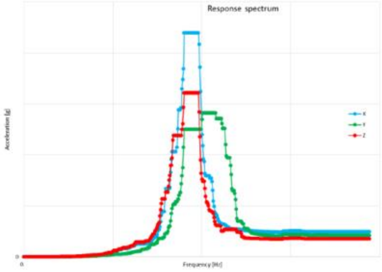


Figure 13: *A typical response spectrum acceleration input curve*

The choice of method is largely dependent on the project. Spectrum analysis is the preferred analysis method. It has the following characteristics:

- Fast and efficient, linear-only method where the focus is to obtain the maximum response quickly compared to a full transient solution.
- Deterministic analyses, both input and output are actual maximum values.
- Single-point response spectrum or multi-point response spectrum is available as a solution method.
- Velocity or acceleration base excitation can be applied directly with the standard analysis method. Direct displacement base excitation is available via the Large Mass Method (LMM) and Effective Force Method (EFM).
- Value typically calculated on "Operating Basis Earthquake" (OBE) and the "Safe Shutdown Earthquake" SSE rather than a single historical event.
- The maximum response (deflection, velocity, acceleration, stress etc.) is computed as a scale factor multiplied by the mode shape. They are then combined to obtain total response.
- Several different combination methods are available:
    - Square Root of the Sum Squares (SRSS) method
    - Complete Quadratic Combination (CQC) method
    - Rosenblueth (ROSE) method
    - Grouping Method (GRP)
    - Double Sum method (DSUM)
- These methods can consider missing mass and/or rigid responses effects via the Lindley or Gupta method.

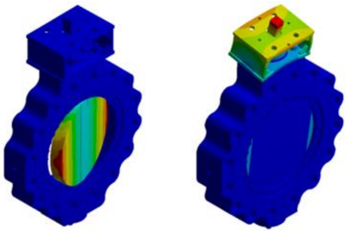


Figure 14: *A selection of modal results of a butterfly valve*

SHOCK ANALYSIS

- Marine propulsion systems incorporate resiliently mounted lubrication modules to supply lubricant to the primary drive gearboxes. The lubrication modules are complex systems integrating pipework, valves, pumps, filters and coolers. In defence applications, the vessel must be designed to withstand shock loading from subsea explosive devices. The response of the system, including the valves, when subjected to such a load can be simulated by analysis.
- A transient dynamic shock load is applied to the geometrically simplified system in the form of a transient shock spectrum. This is typically taken from a defence standard such as MAP-01-470.
- Outputs from this analysis are abundant and could include accelerations, velocities, and stresses at all nodal locations, at all time-steps throughout the transient response.
- Peak accelerations observed by the valve (or other components) can be used as pseudo static load inputs to detailed sub-model analyses. These detailed local models can then be used to ascertain the peak response of the valve (or other components) to the shock load in terms of stress and deflections.

> **CAPACITY WITHOUT CONCERN**

THERMAL STRUCTURAL ASSESSMENT

- Often within valve systems, the temperatures of the liquids or gases can vary greatly. Problems might arise when there are induced thermal stresses which might push areas close to the allowable limit to just over the limit. Additionally, without sufficient flexibility in the system, over constraint can cause high compressive stresses due to thermal expansion of components.
- Steady state or transient thermal analyses can provide the response of the valve when exposed to thermal gradients. The stresses and deflections induced from the thermal loading can be inputted into the structural assessment to obtain an overall loading response of the valve.

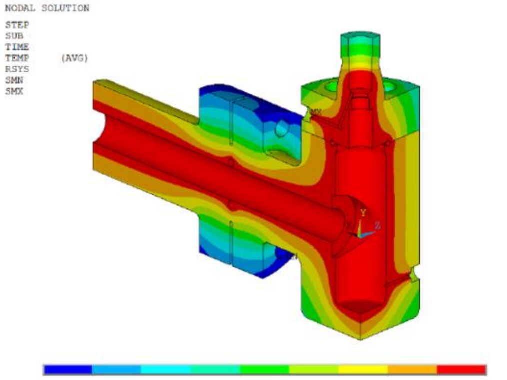


Figure 15: *Thermal profile of a body, bonnet and an end connection*

- Thermal assessments can be performed on seat rings, gate and seat pockets to determine the extent of axial and radial expansion. From this, any thermal clamping of the gate, or any clamping of the seat ring within the seat pocket due to radial expansions of the seat ring, can be identified. As such, clearances between these components can be assessed.

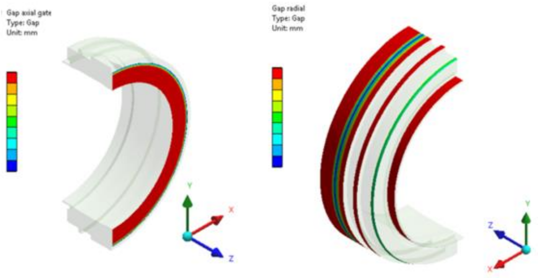


Figure 16: *Axial/Radial deformation plots of a typical seat ring under thermal loading*

HIGH PRESSURE HIGH TEMPERATURE (HPHT)

- There is a growing requirement for valves to operate at higher pressures and higher temperatures in the subsea industry.
- Transitioning from 15ksi to higher rated working pressure tends to change designs from 'thin-walled' to 'thick-walled' valves.
- High internal stresses can concentrate at sharp corners, bore intersections and seal pockets, which are possible locations for crack initiation sites, and could potentially lead to fatigue failure or fast-fracture failure.
- Potential problems with thicker-walled pressure containing equipment include difficulties with manufacture, fabrication and handling the heavy valve. It is also more difficult to maintain uniform material strength through the wall sections.
- Use of elastic stress analysis on thick-walled valves can produce non-conservative results, so use of non-linear elastic plastic analysis is recommended.
- There are several options available when developing HPHT components for the subsea industry and as such, API 17TR8 has been developed to provide guidance.

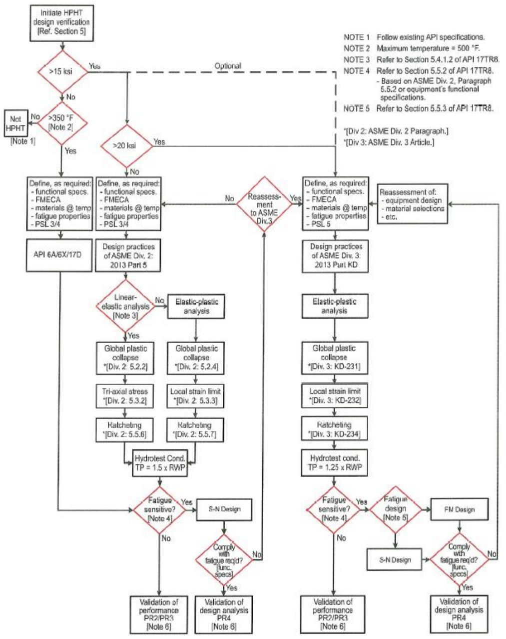


Figure 17: *HPHT design flow chart (API 17TR8)*

- A design flow chart is provided within API 17TR8 to help design engineers develop HPHT components, with pressure, analytical complexity and quality control requirements increasing the further to the right that you go in the flow chart.
- The path within the flow chart can determine design margins, product specification level and test pressures.
- Design margins are larger for ASME VIII Div.2 when compared against those of Div.3.
- However, product specification levels are higher for Div.3 where quality assurance requirements are tighter to pass. This could include higher Charpy toughness values, limits on ovality and misalignment, NDE capability for flaw detection etc.
- Use of Div.3 could allow for the design of thinner walled valves for a given pressure and temperature and could help reduce manufacturing problems.
- Assessments to consider when verifying a HPHT design are plastic collapse analysis, local strain limit analysis, ratcheting analysis, fatigue

analysis and fracture mechanics analysis; of which PDL are world leading experts.

You can view our technical webinar 'A Practical Awareness of Qualifying Product to the HPHT design guideline API 17TR8' here.

FRACTURE MECHANICS (LEFM)

- Fracture mechanic assessments are performed by determining:
    - a likely crack initiation site
    - an existing flaw size based on NDT or, in lieu of available data, an initial flaw size based on design code recommendations
    - a path along which the crack will likely propagate
- Calculations are performed to determine incremental crack growth based on the stress intensity factor at the crack tip. As the crack grows the stress intensity factor changes, as such it is important that small crack size increments are considered.
- A critical crack length is determined from the assessment code. The number of cycles to reach this critical crack length can then be calculated.
- As a first approach, closed form solutions available in design codes, are used for the evaluation of the stress intensity factor at the crack tip based on the local geometry and the type of applied loading.
- For complex geometries and loading type not covered by design code provisions, FEA can be used for the evaluation of the stress intensity factor and the definition of the crack propagation characteristics.

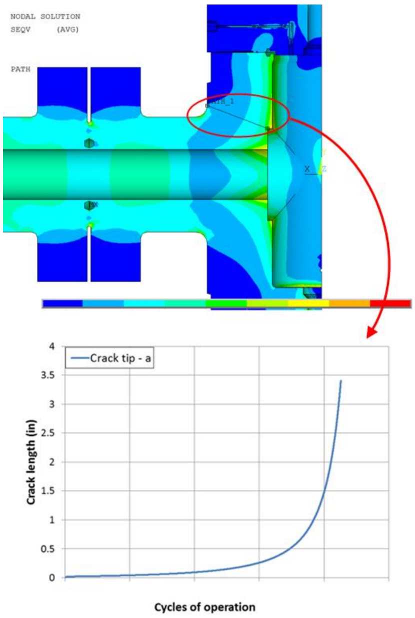


Figure 18: *Crack size evolution over number of cycles for the path depicted*

- A crack with a semi-elliptical profile is introduced in the FEA model. The stress intensity factor is evaluated based on the local stress field and the crack propagation direction is defined based on the distribution of the local principal stresses. Through a stepped process, the crack propagation path and the corresponding number of cycles are defined. This approach provides more realistic (less-conservative) fatigue life predictions.

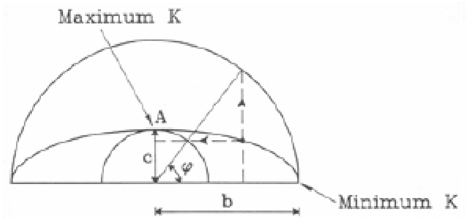


Figure 19: *Semi-elliptical crack profile (DNV-OS-J101)*

FLOW ASSURANCE

Flow assurance involves modelling fluid flow to ensure the safe and most economical fluid transfer across the system. The financial loss from asset damage and the associated interruption to production can be substantial. In the oil and gas industry, flow assurance is particularly of importance for deep-water oil production, where the flow conditions can be very extreme (temperature, pressure and flow rate) and are difficult to replicate in physical testing.

VALVE CLOSURE TIME

- Valve closure times can be critical to the safety of a piping network, ensuring that global pressures remain within system limits. Steady state and transient analyses can be undertaken to determine valve closure times for different flow rates.
- Using a swing check valve as a case study, Fluid Structure Interaction can be implemented using Immersed Solid capability within one of our core toolsets – ANSYS CFX. This applies a momentum source in the fluid domain to force the fluid to move with the solid disc.
- The valve disc position can be determined by balancing rigid body dynamics and fluid forces acting on the disc. A steady open valve flow is obtained, after which the flow is shut off to initiate valve closure, with different flow deceleration rates applied.
- Valve flow and deceleration rates are optimised to achieve the desired closure time.

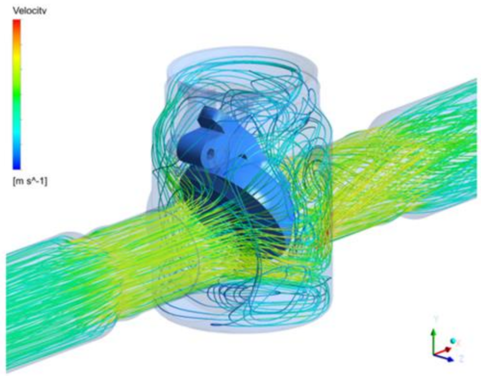


Figure 20: *Flow rates and valve closure times of a swing check valve*

EROSION ANALYSIS

- Pumps and valves that transfer fluids containing solids can experience significant levels of erosion, especially in areas with high velocities. Using steady-state multiphase CFD analyses, solid shear stresses can be determined on the valve walls, indicating likely places for erosion.
- Large particle size and high solid concentration requires the use of an Eulerian formulation for solid particles, as opposed to Lagrangian particle tracking which gives erosion rates directly.
- Complex mesh refinements in constricted regions are required to achieve convergence.
- After determining erosion areas, design recommendations can be advised to reduce erosion.

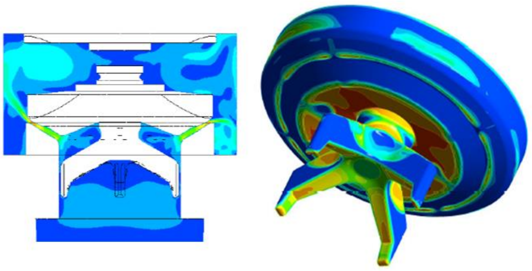


Figure 21: *Erosion analysis on a check valve*

JOULE-THOMSON EFFECT

- CFD modelling allows for the treatment of complex compressible flow behaviour, along with the associated thermal effects.
- Real gases, where intermolecular forces are significant, exhibit the Joule Thomson effect. This is where the gas undergoes a change in temperature as a result of a throttling process, where the gas is passed through a valve or porous plug, experiencing compression followed by an expansion.
- Typical flows which require a real gas treatment are hydrocarbon gas flows under high pressure; this is of particular relevance to the Oil & Gas industry.
- The temperature changes involved can become significant depending on the flow conditions and localised flow geometry, for example, in valves involving small openings, such as a choke valve. It is important for valve manufacturers and designers to determine the extent of the temperature change in advance of manufacture to validate the safety of the valve components.
- The CFD model should incorporate the following:
    - The gas modelled as a real gas (as opposed to an ideal gas which neglects intermolecular forces); the Peng-Robinson Equation of State is a good choice of real-gas model, which is suitable for modelling the subcritical gas phase and supercritical properties, as well as providing reasonably accurate results for the subcritical liquid phase.
    - Mixture properties applied using real-gas mixing rules (for hydrocarbon gas mixtures).
    - Heat transfer between internal, external fluid and solid domains.

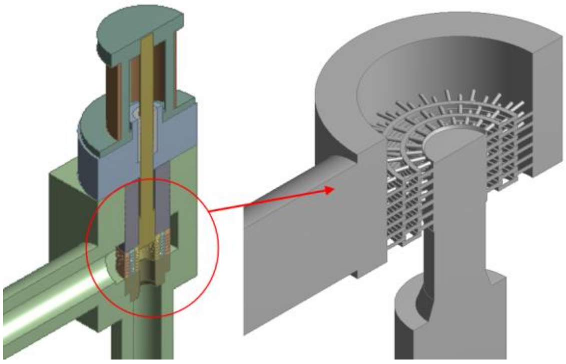


Figure 22: *Modelling the fluid domain of a choke valve*

- High flow rates and small constrictions in the flow result in high Mach numbers, which can cause convergence difficulties with the CFD simulation. These issues can be overcome using solver relaxation parameters, which are dependent upon the severity of the Mach number. A highly resolved mesh is also required in the shock-wave region.
- These CFD projects are computationally expensive. PDL has the capability of solving on an in-house 48-core dedicated High Performance Computing Cluster. If there are larger CFD projects that require more computing power, then PDL have access to the Edinburgh University Cluster. This places PDL on the forefront of CFD valve related projects.

MEMBERSHIP ORGANISATIONS

BVAA

ACCREDITATIONS

ISO 9001:2015 (Certificate No. FS 90756)

Achilles FPAL (10052551)

OHSAS 18001:2007 (OHS 666092)

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