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Probabilistic Assessment of Composite Repairs

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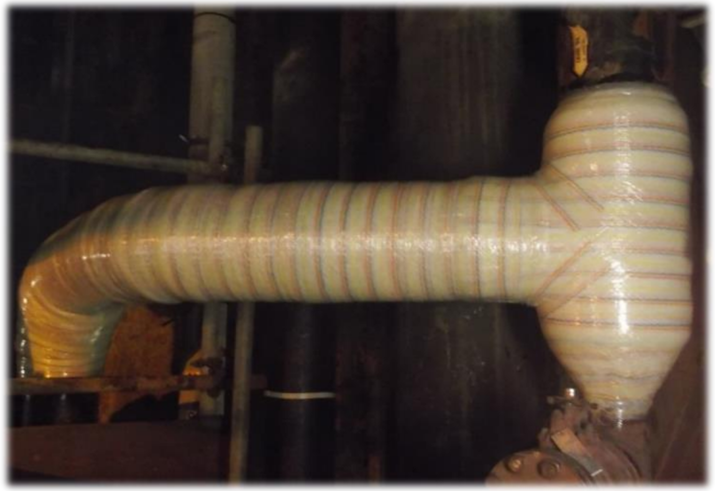
quality | integrity | delivery

Overview

- The use of composite wrap is widespread as a method for repair of metallic pipeline
- Nominally a temporary measure, but in practice repairs may remain in place for long periods
- Large scale replacement is time consuming and expensive, hence it is desirable to understand the safe operating life of existing repairs to prioritise replacement of existing repairs.
- Repairs are predominantly installed on areas of thinned wall thickness, rather than cracked / leaking pipework, however leaks may subsequently develop under the repair.
- Lifetime analysis of these repairs is complicated by high levels of uncertainty around the installation, material properties, bond strength etc.

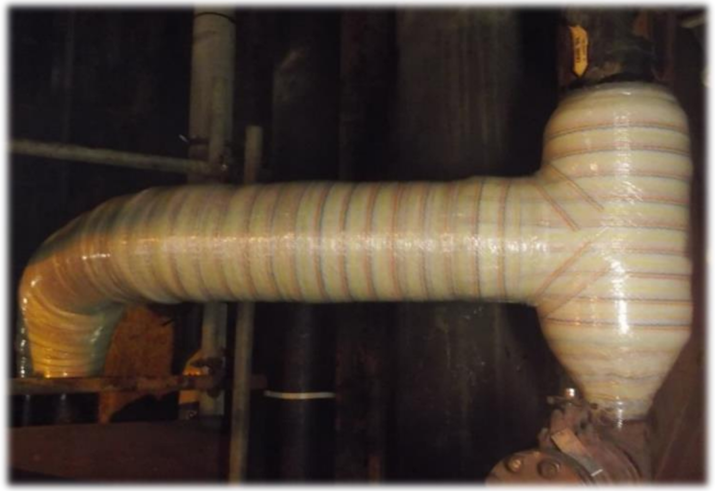


Overview

- ✓ Cheap
- ✓ No requirement for hot working
- ✓ Relatively quick and easy to install
- ✓ Can be designed to carry structural loads
- ✓ Corrosion resistant
- ✓ Can be applied without shutdown

- X Generally regarded as a temporary repair
- X Long-term behaviour not well understood
- X Integrity can be very dependent on correct installation surface prep.
- X May not be suitable in high temperature regions

Given the large population in service and the high cost of replacement / metallic repair – how best to manage the risk of existing composite wrap repairs?



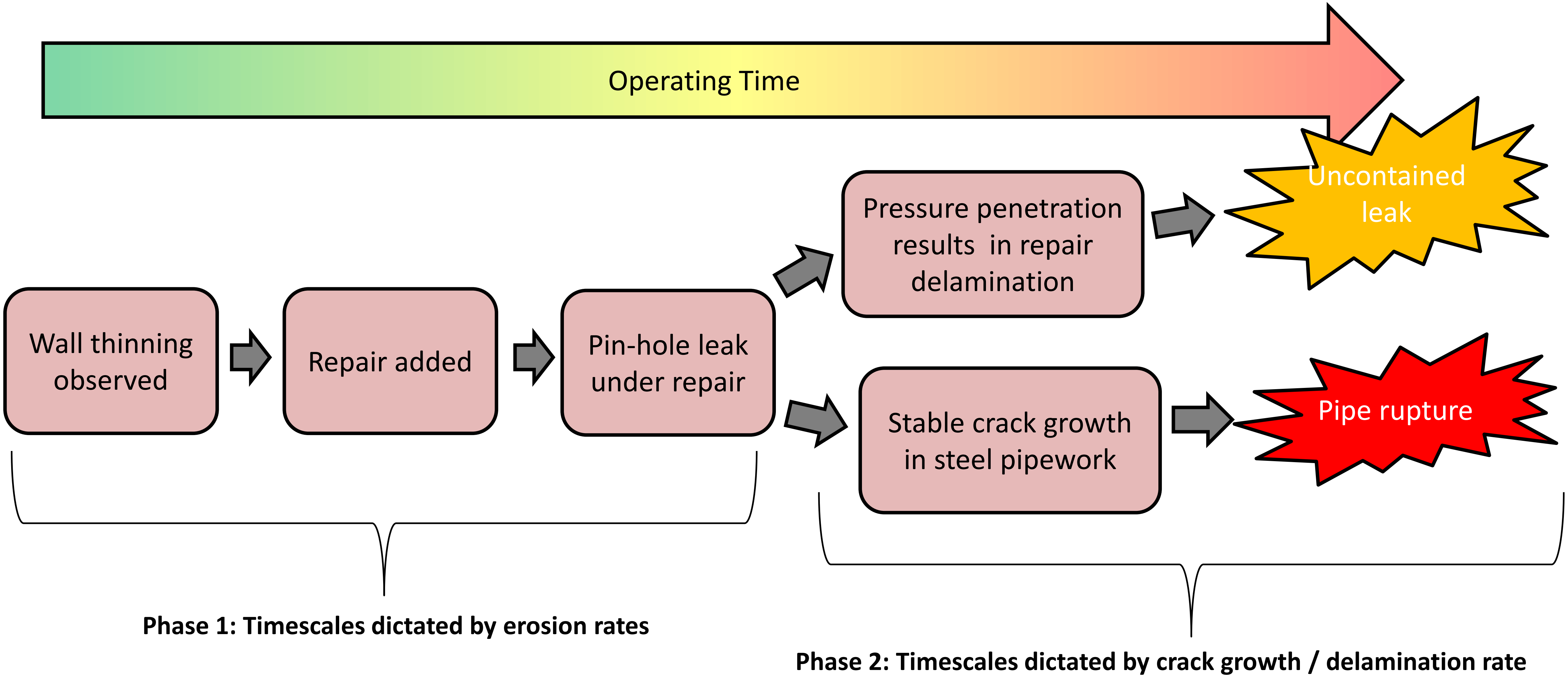
Lifetime Assessment

Design calculations allow repair lifetime to be estimated….

……but high levels of uncertainty typically result in very conservative estimates of safe life.

Can alternative approaches be used to help justify safe operation and prioritise limited resources on replacement of the highest risk repairs?

Progression of Failure



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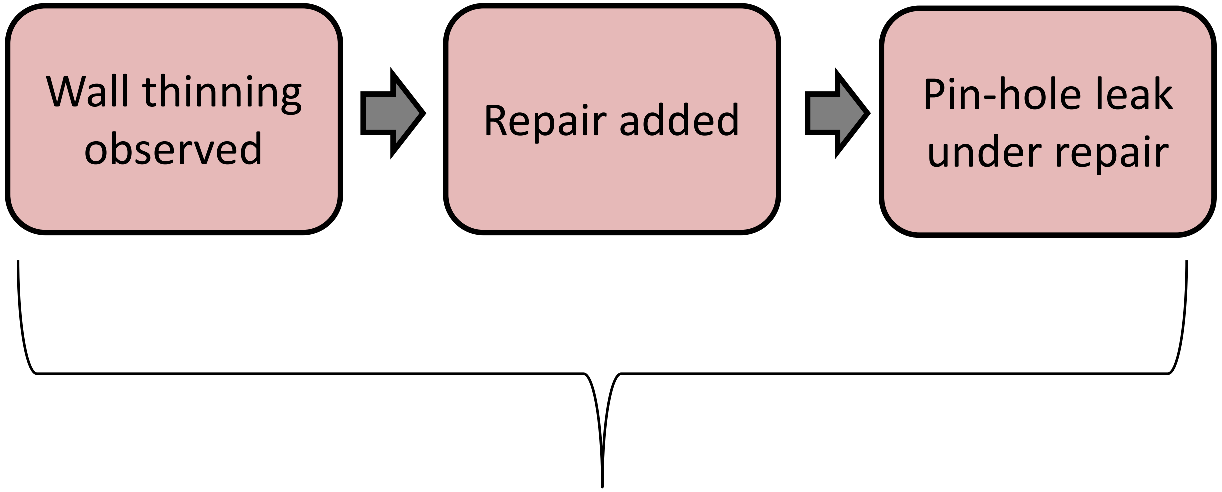
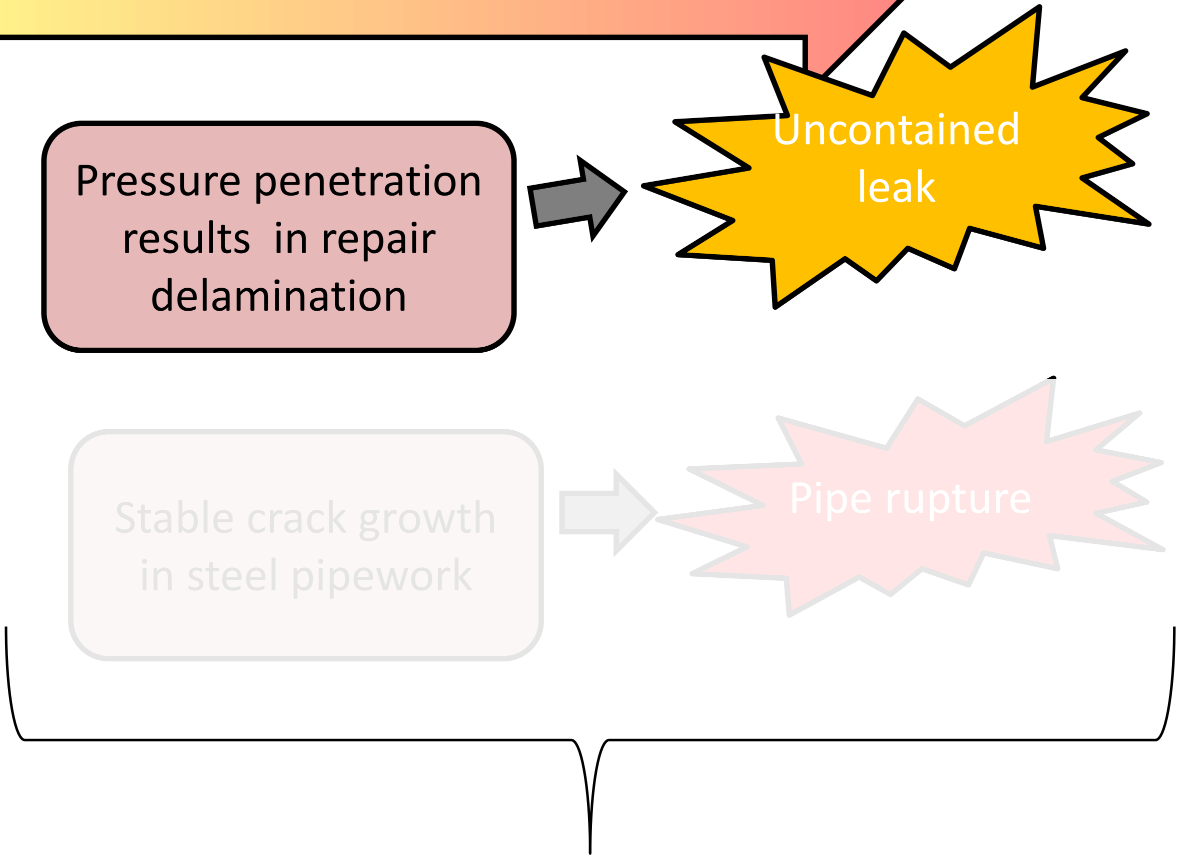


Phase 1: Timescales dictated by erosion rates

Calculation of erosion rate is possible but highly dependent on operating history, and availably of data

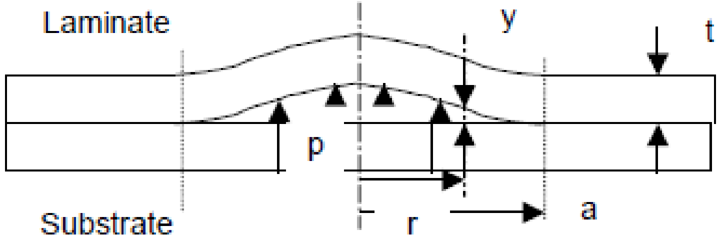
Progression of Failure



Phase 2: Timescales dictated by crack growth / delamination rate

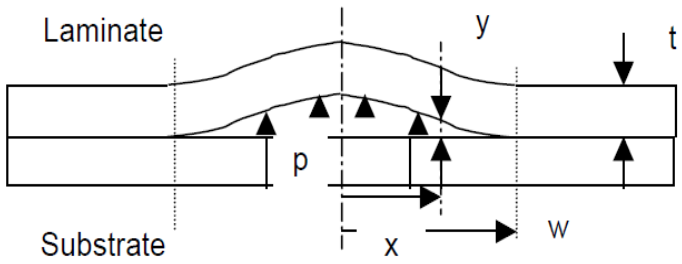
Operating experience suggests failure by crack growth in the underlying pipe does not occur.

Therefore, the focus in this work is on the progression of the repair failure



Bondline / Delamination Failure

- Analytical solutions are used for circular defects subject to internal pressure
- Assumes there is a through wall defect in the pipework, such that the bond line is subject to the fluid pressure

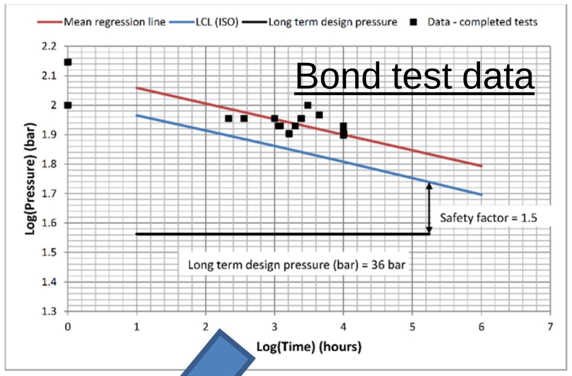


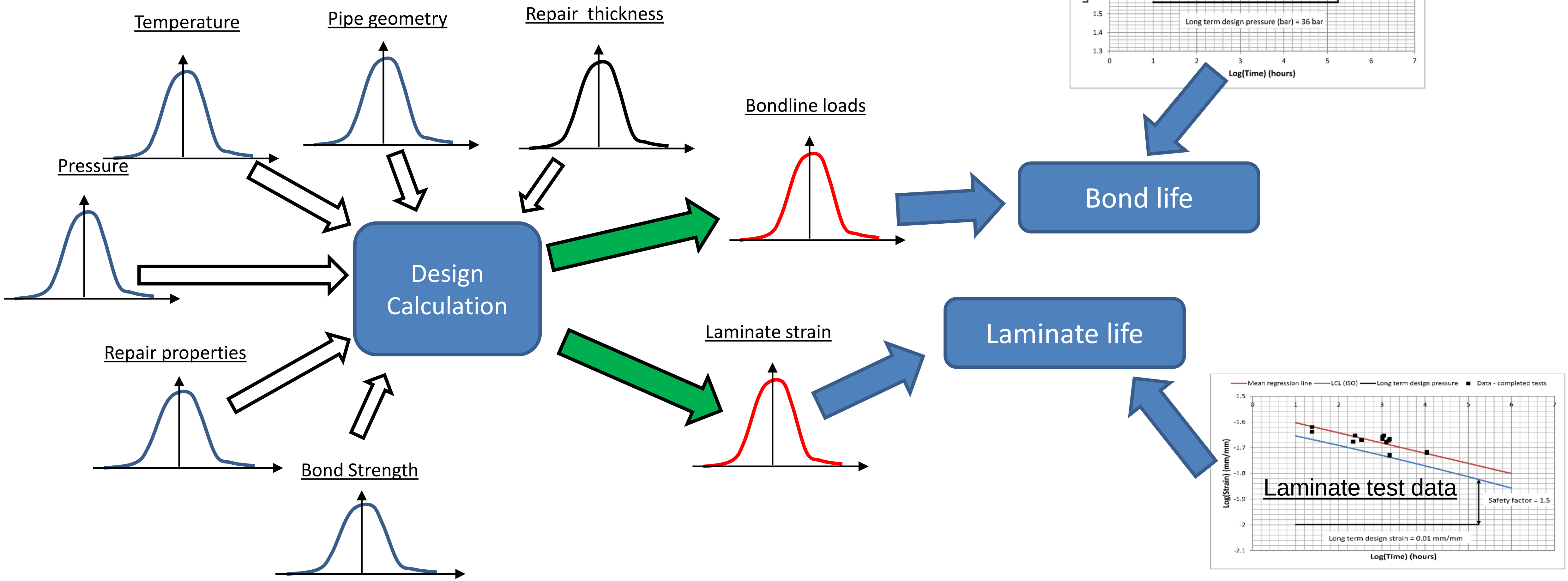
Approach to qualification of repairs

- Repair design calculations typically consider two modes of failure:
  - Failure of the repair laminate, avoided by limiting the strain in the repair
  - Failure of the bond (for a leaking repair), avoided by limiting the bond energy release rate, γ
- Long term performance test data allows lives to failure to be estimated for a particular repair design
  - Bond line life to failure as a function of internal pressure or γ
  - Repair laminate life to failure as a function of laminate strain
- Bounding calculations (as used in the initial repair design), produce very conservative estimates of safe life
- By considering the variation in the design calculation inputs, variation in the outputs (i.e. the predicted lives) can be generated and the risk of failure for a given repair lifetime estimated

Dealing with Uncertainty

- Use Monte Carlo analysis to address impact of uncertainty in the inputs





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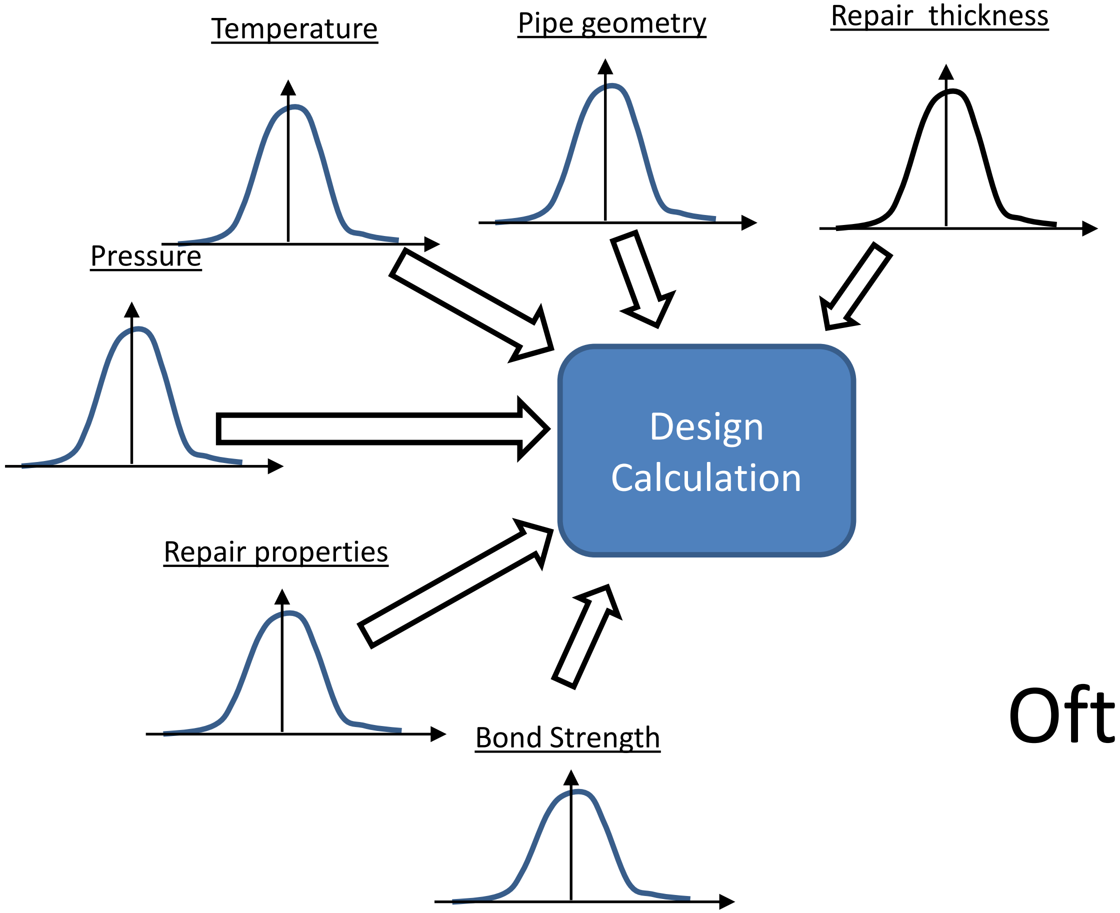


But how do we estimate what our inputs should look like?

Often, you know more than you might think…

Example Calculation

- A wrap report is produced following installation of the composite repair, which confirms the surface preparation and installed repair geometry for each pipe

- Where detailed input data is not available (often!) judgements are used to estimate the input distributions.
  - This allows a more robust treatment of uncertainty, compared to assuming a ‘lower bound’ value where inputs are not well known.

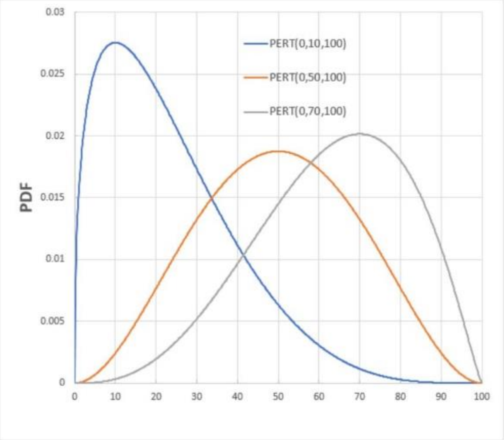
- For example:
  - Installed repair thickness may be taken as equal to the minimum value as determined by the original design calculations.
  - In reality repairs are generally reported as being installed thicker than the minimum requirement.
  - Surface preparation is often to ST3 specification (as opposed to SA 2.5 surface preparation in original design calculations) due to unanticipated installation limitations

Example Calculation Input Parameters

- If (when) detailed input distribution data not available, existing knowledge can be used to make some appropriate assumptions.

Parameter	Nominal	Min	Max	Distribution
Pipe diameter [mm]	610	609.2	613.2	PERT
Defect diameter [mm]	50	37.5	100	PERT
Installed repair thickness [mm]	5	2.6	5.8	PERT
Pressure Load [MPa]	0.4	0.72	0.32	PERT
Energy release rate -gamma_LCL [J/mm2]	0.388			Normal
Repair Ecirc [GPa]	24			Normal
Repair Eaxial [GPa]	8			Normal
Repair G [GPa]	2			Normal

PERT distribution used for parameters where a fixed upper and lower limit can be defined

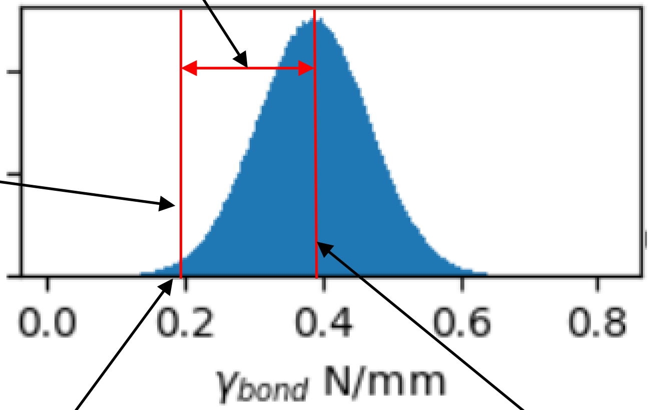


Normal distribution assumed where 'tail' of the distribution is not well understood

Example – Estimating Input Distributions (bond strength)

Estimate standard deviation from mean and ‘lower bound’ values from test

‘Lower bound’ value quoted by manufacturer is associated with an assumed level of statistical confidence – e.g. assumed to represent the lower end of a 95% confidence interval

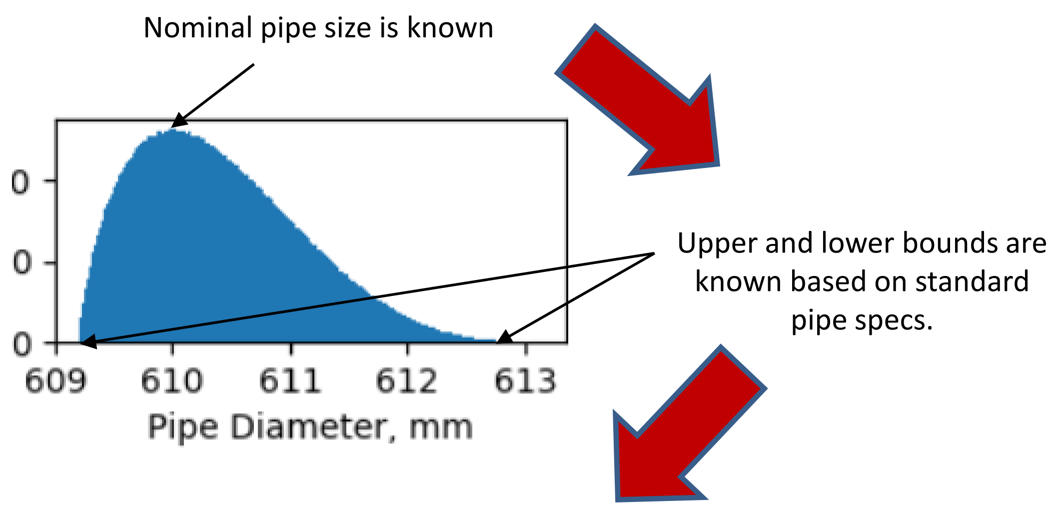


Mean value for bond strength available from manufacturer test data

2.5% of samples may lie below the test ‘lower bound’

Other inputs

- Although detailed distributions are not generally available, there is usually more information than it may appear at first…



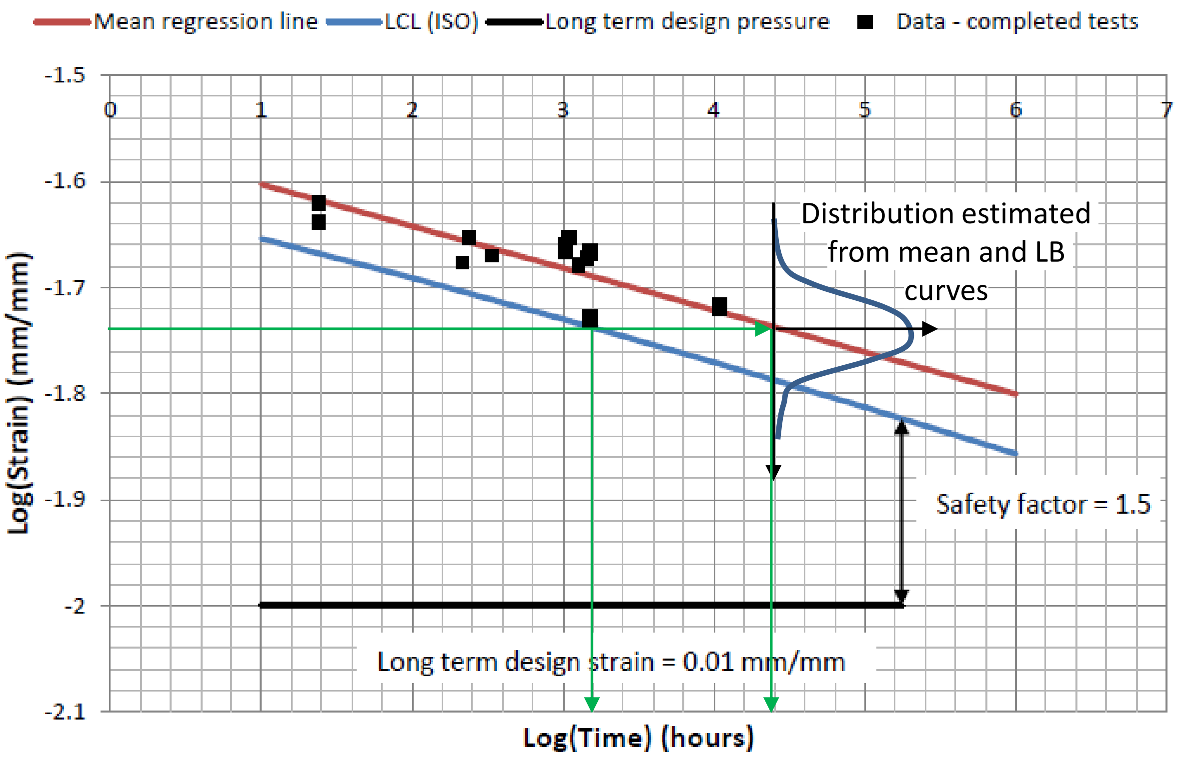
This is enough information to define a PERT distribution

A first estimate of each input distribution can be used to investigate the impact of the various inputs of the most important outputs.

The initial results can then be used to focus any future effort to refine the input data

Laminate failure test data

Test data provided by repair laminate manufacturer, used to estimate failure life distributions

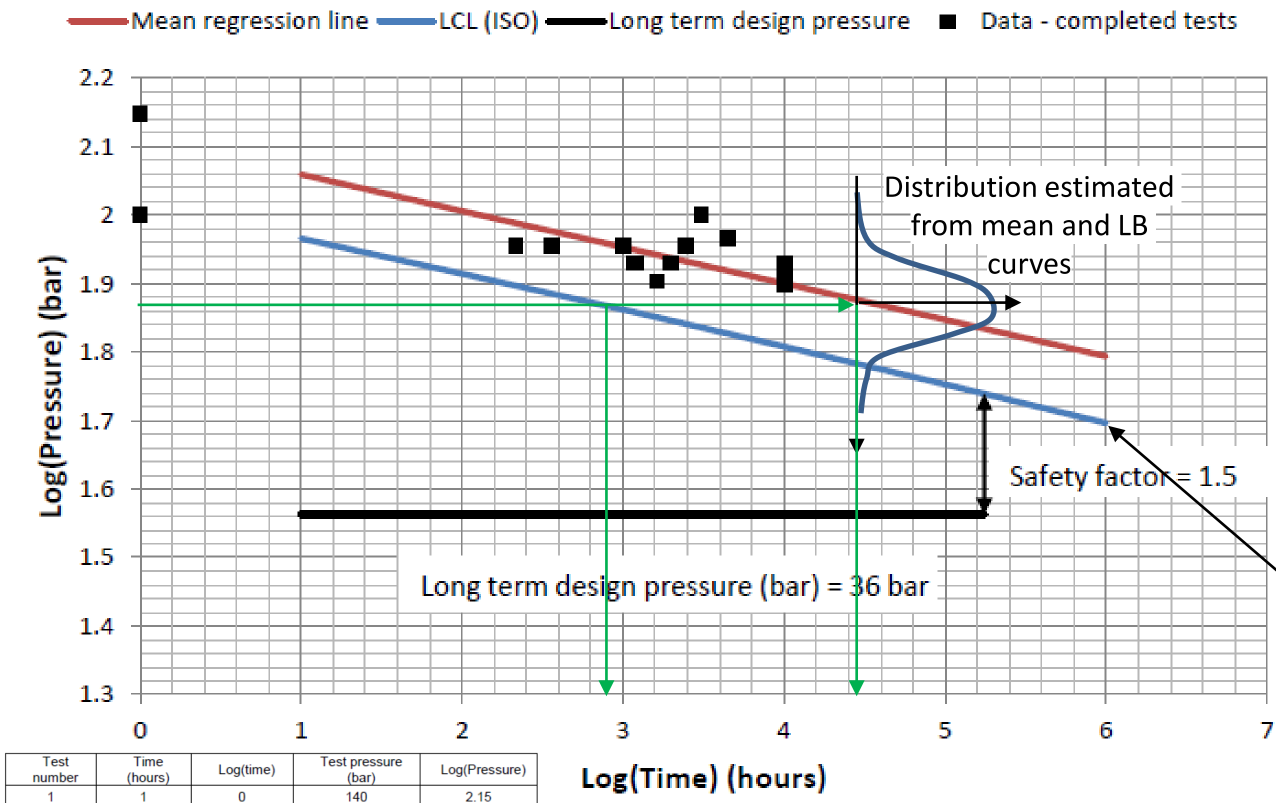


Test number	Time (hours)	Log(time)	Test strain (mm/mm)	Log(Strain)
1	24	1.38	0.024	-1.620
2	24	1.38	0.023	-1.638
3	24	1.38	0.023	-1.638
4	216	2.33	0.021	-1.677
5	240	2.38	0.0222	-1.653
6	336	2.53	0.0214	-1.670
7	1032	3.01	0.0216	-1.666
8	1032	3.01	0.0219	-1.659
9	1104	3.04	0.0222	-1.653
10	1272	3.10	0.0209	-1.679
11	1440	3.16	0.0212	-1.673
12	1512	3.18	0.0187	-1.728
13	1512	3.18	0.0186	-1.731
14	1512	3.18	0.0215	-1.668
15	1512	3.18	0.0216	-1.666
16	10992	4.04	0.0192	-1.716
17	10992	4.04	0.0190	-1.721
18	10992	4.04	0.0192	-1.718

Table 1: Long term pressure test results

Note test data is relatively limited

Pressure tests: long term bond failure data



Test number	Time (hours)	Log(time)	Test pressure (bar)	Log(Pressure)
1	1	0	140	2.15
2	1	0	140	2.15
3	1	0	100	2
4	4464	3.65	92.5	1.97
5	3048	3.48	100	2
6	1992	3.30	85	1.93
7	1992	3.30	85	1.93
8	1152	3.06	85	1.93
9	1632	3.21	80	1.90
10	10008	4.00	85	1.93
11	1200	3.08	85	1.93
12	10080	4.00	80	1.90
13	216	2.33	90	1.95
14	10008	4.00	79	1.90
15	10008	4.00	82	1.91
16	2448	3.39	90	1.95
17	1008	3.00	90	1.95
18	360	2.56	90	1.95

Table 3: Long term pressure test results

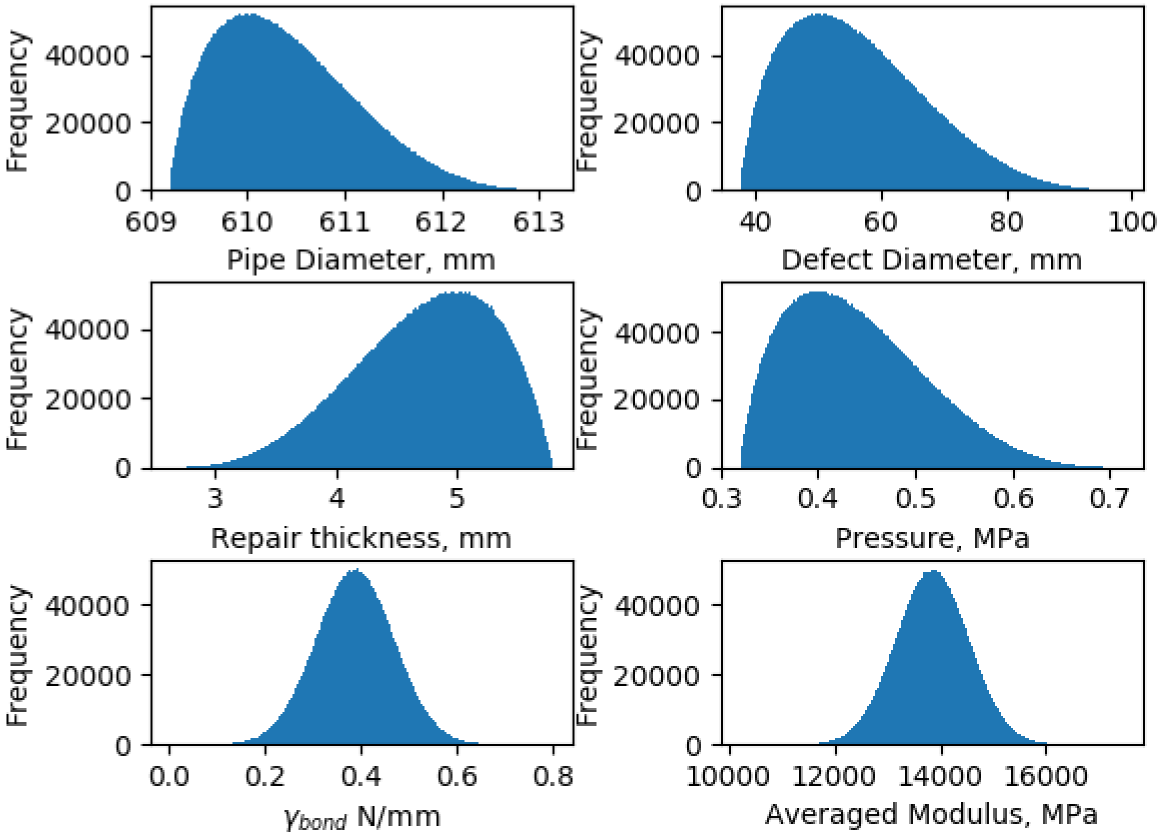
- Data from burst tests provides failure life as a function of pressure
- Pressure can be converted to bond separation energy using design calcs, allowing data to be applied to other geometries

$$\gamma = p^2\left[\frac{(1-\upsilon^2)}{E}\left\{\frac{3}{32t^3}a^4+\frac{2}{\pi}a\right\}+\frac{3}{16Gt}a^2\right]$$

- Resulting lower bound pressure-life curve converted to γ–life and used in lifing calculations.

Note test data is limited to a single surface preparation type

Input Parameter Distributions



- May only be approximate, but it provides a starting point to understand the problem
- Can be refined to improve accuracy if needed
- Initial calculations help to identify where to focus further data gathering effort.

Analysis Approach

Input parameters generated, based on the input distributions

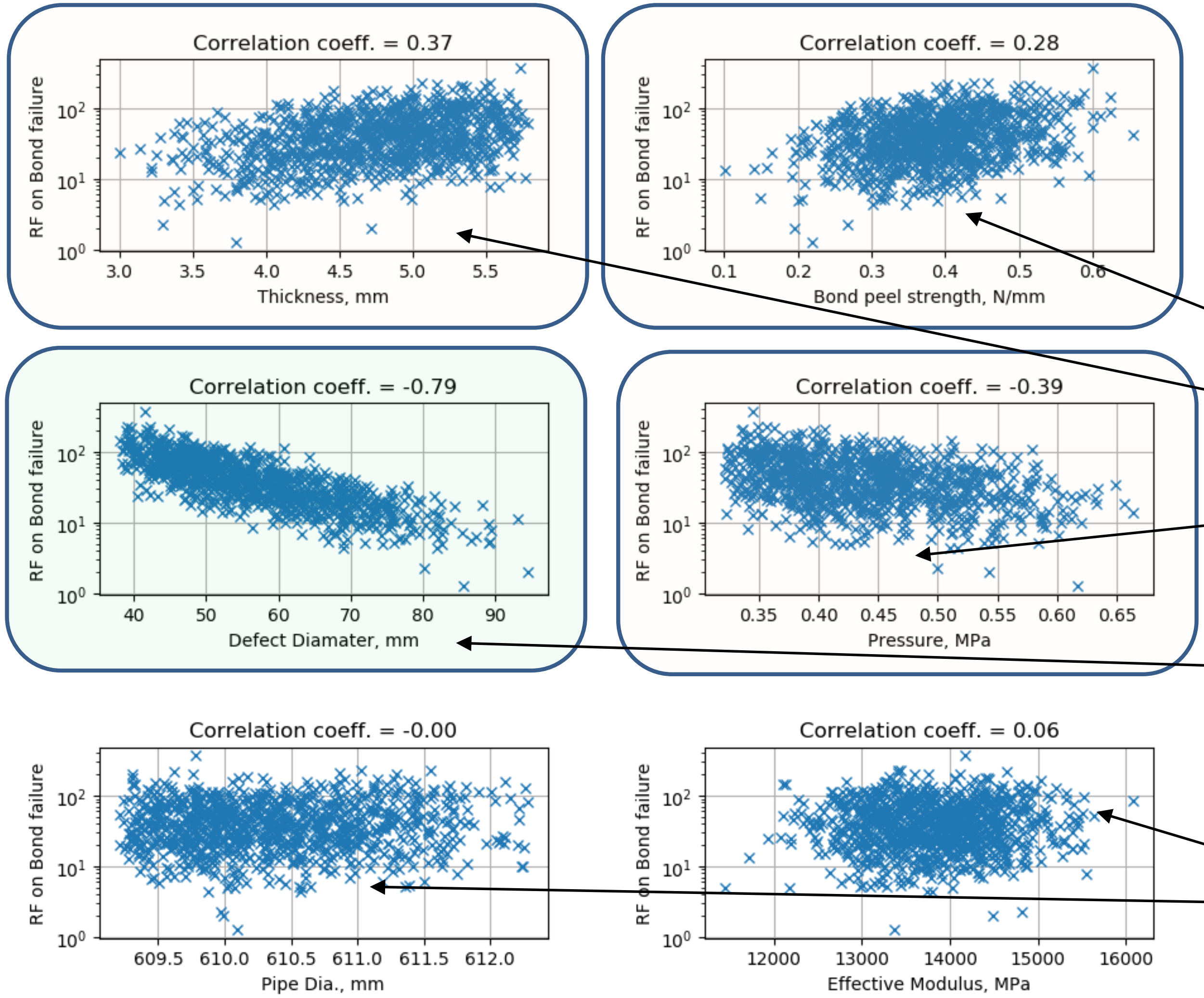
Laminate strains and bond energy release rates are calculated using design equations

Calculate repair lifetime (bond and laminate failure modes)

Repeat! (10^7 samples) to generate a distribution of repair failure lives

Plot probability of failure as a function of repair life

Example – Correlation of Outputs and Inputs



- Reserve factor on bond failure for each trial plotted against various inputs

Bond strength reserve factors are moderately well correlated to repair thickness, bond strength and pressure load

Strongest correlation is observed with the initial bond defect diameter

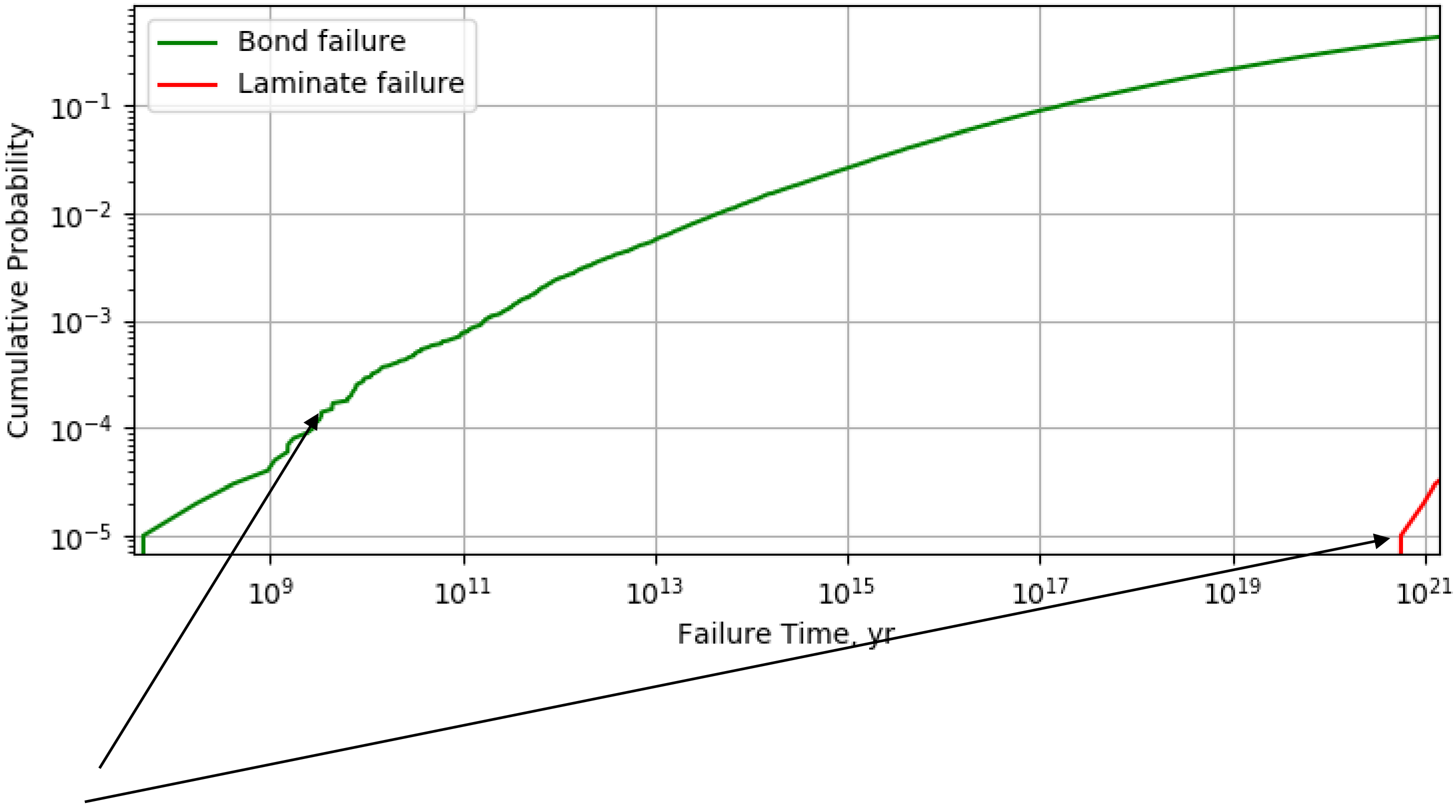
No meaningful correlation with pipe diameter or elastic modulus

So what does this tell us?

- If the results are found to be too conservative – the most benefit could potentially be gained by improving the estimates of initial defect size

- The next most significant inputs are repair thickness and internal pressure

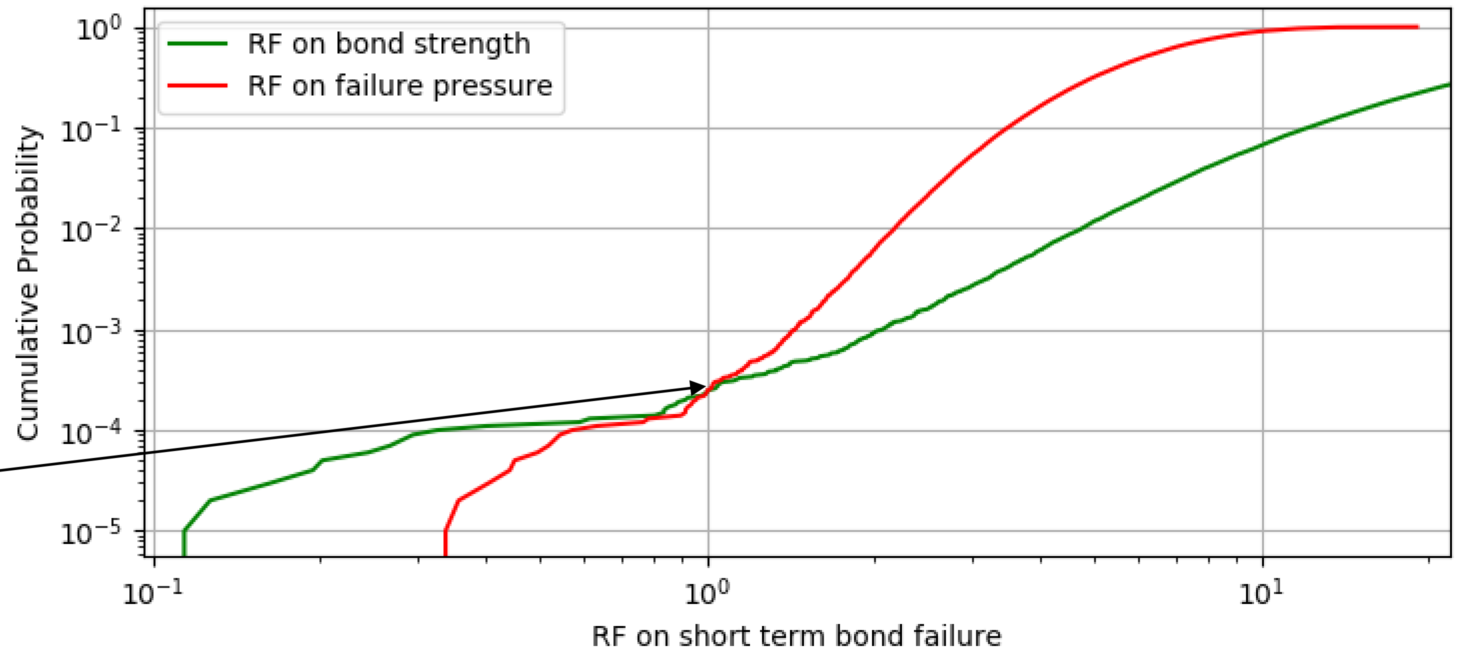
Results: Failure Probability of Repair Laminate



Failure lifetimes remain very large at negligible risk of occurrence – this is not realistic (test data does not extend this far) but suggests long failure times.

Results: Failure Probability of Bond Line

- Reserve factor against short term bond failure can also be calculated (either based on bond strength or margin on pressure)



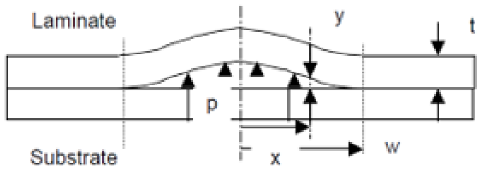
Risk of RF<1 is approximately 2e-4
In practice, the fact that the repairs have not failed tells us short term failure is unlikely unless operating pressures increase

Application to In-service repairs

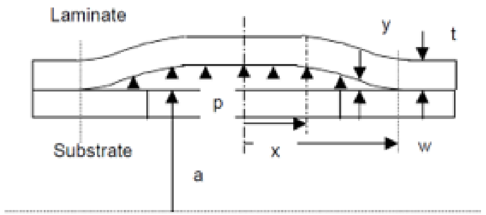
- This approach has been used to evaluate a number of in-service repairs

Case	Pipe OD [mm]	Defect Type	Defect Size [mm]	Installed Repair Thickness [mm]	Surface Preparation	Lower bound bond energy release rate g_{LCL} [J/m^2]	Mean bond energy release rate g [J/m^2]	Operating Pressure [MPa]	Design Pressure [MPa]
CA-0-125-P	33.4	Circular	10	9.8	ST3	178	388	2.8	5
CA-09-173-P	114.3	Circular	30	8	SA 2.5	227	496	0.4	1.89
CA-2014-039-P	610	Circular	50	8.86	ST3	178	388	0.4	0.6
CA-2014-137-P	33.4	Fully circumferential	100	5	ST3	178	388	3.3	4.96
CA-2014-148-P	33.4	Fully circumferential	30	7.2	SA 2.5	227	496	2.94	4.41
CA-2016-207-P	60.33	Fully circumferential	200	9.7	ST3	178	388	0.69	1.89

Circular Defect



Circumferential Slot



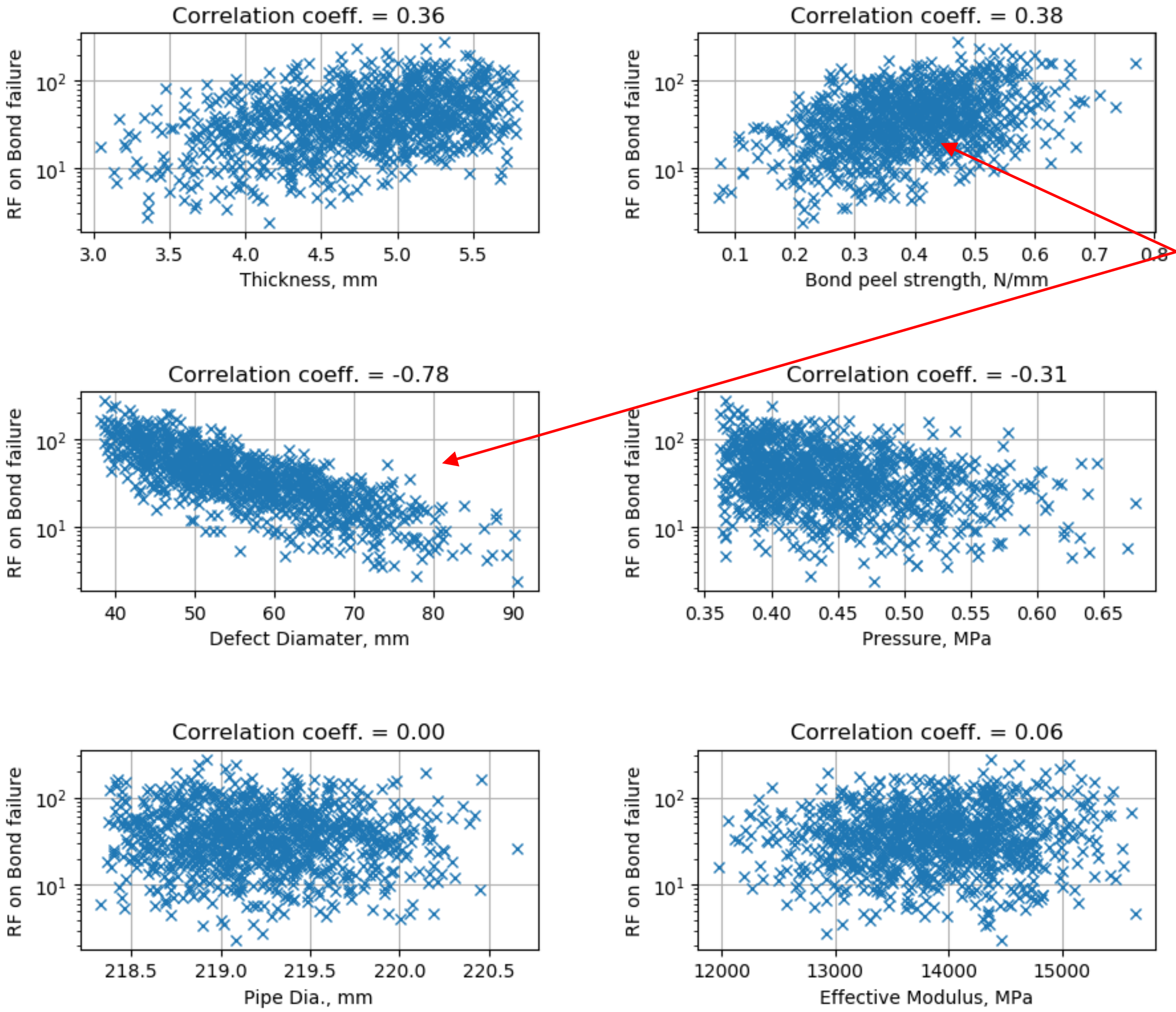
SA 2.5: grit blasting and cleansing
ST3: power tool cleaning

Results

Case	Failure time at $P_f = 10^{-4}$ [years]	Failure time at $P_f = 10^{-3}$ [years]	Failure time at $P_f = 10^{-2}$ [years]	Failure time at $P_f = 10^{-1}$ [years]
CA-0-125-P	1.76E+15	1.44E+16	3.02E+17	3.79E+19
CA-09-173-P	3.77E+13	1.42E+15	2.71E+17	1.24E+21
CA-2014-039-P	8.84E+07	5.87E+09	1.40E+12	4.05E+15
CA-2014-137-P	8.65E+13	2.57E+14	1.25E+15	2.17E+16
CA-2014-148-P	7.49E+13	2.45E+14	1.33E+15	2.46E+16
CA-2016-207-P	9.80E+17	4.42E+18	5.38E+19	7.26E+21

Although lives are all large (beyond extent of available data) one case is markedly worse than the others thought to be of concern

Correlations with inputs (highest risk case)



Provides guidance as to how to manage risk:

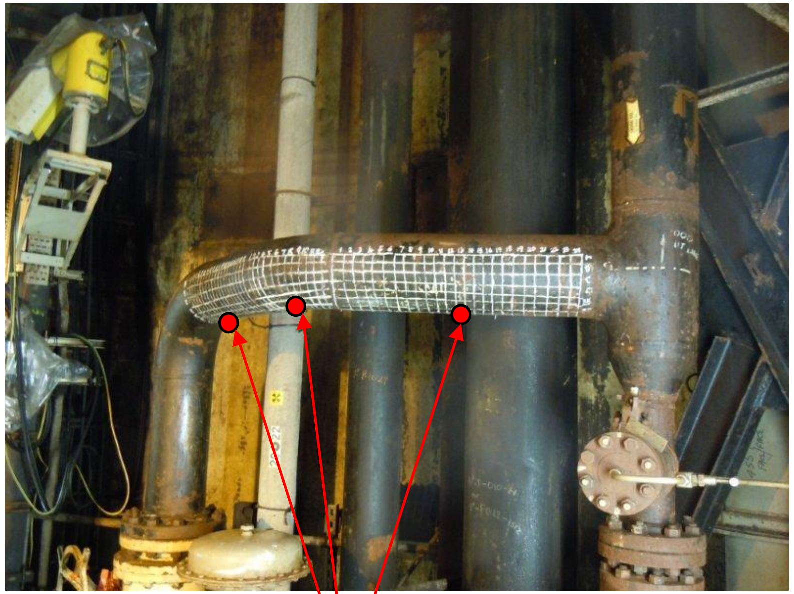
- Monitor defect sizes (de-bonded region)
- Possible damage (loss of effective thickness)

Conservatisms in the current analyses

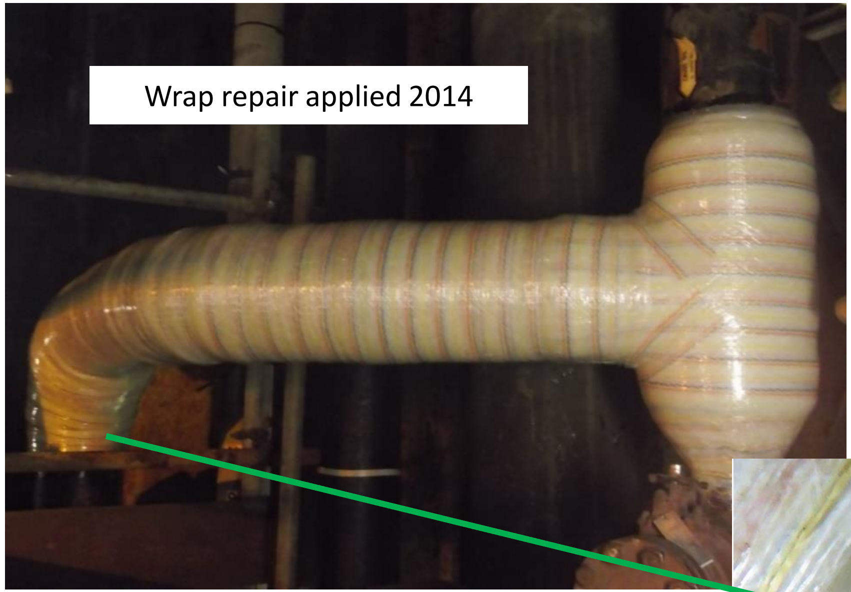
- Results suggest that for the repair cases considered, the expected operating life is well in excess of the design life (2 years)

- But, this does present a problem from a validation point of view in that the calculations have successfully predicted no failure, but with effectively indefinite safe lives.

Validation Case – Failure Repair



3 areas of external corrosion identified



Subsequent failure observed – leaking from bond line - 2016

Failed Case

- A wrap report was produced following installation of a composite repair, which confirms the surface preparation and installed repair geometry for each pipe

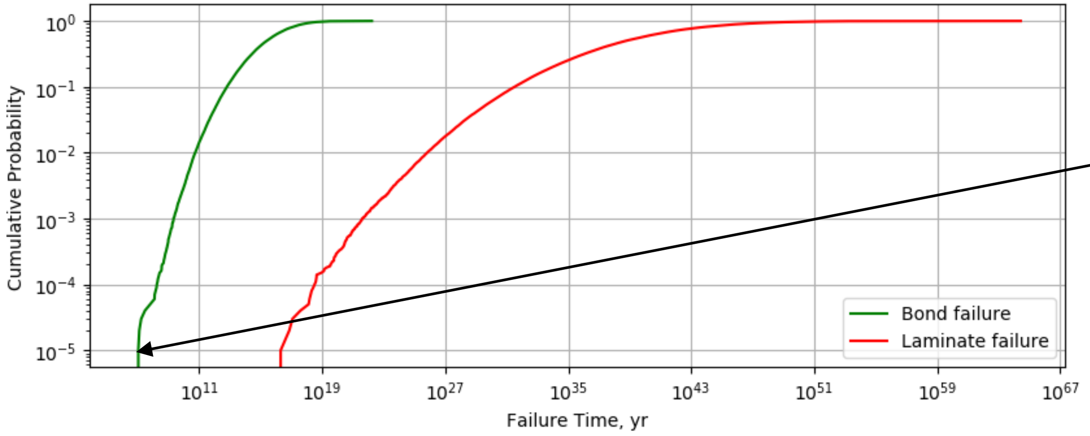
- Wrap report for first repair states repair thickness of 23mm, which is unlikely given 23 layers were used at 0.8mm each. Repair thickness of 18.4mm used.

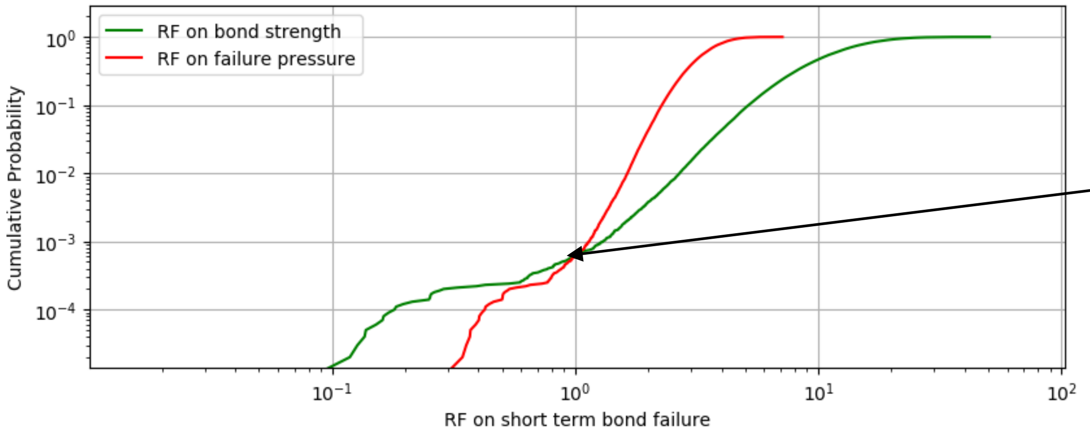
- Wrap report of first repair confirms the surface is prepared to SA 2.5 (grit blasting) specification. Specified bond strengths are:
  - γ_{mean} = 496 J/m^2
  - γ_{LCL} = 227 J/m^2

- Repair was installed in a number of stages, based on wrap report:
  - Surface grit blasted and first 2 layers of wrap installed. Further 4 layers then added (22/2/14)
  - Further 8 layers added to the repair (23/2/14)
  - Further 9 layers added (24/2/14)

- Worth noting, it is not clear if the surface was re-prepped between each phase of installation.

Results: Failure Probability

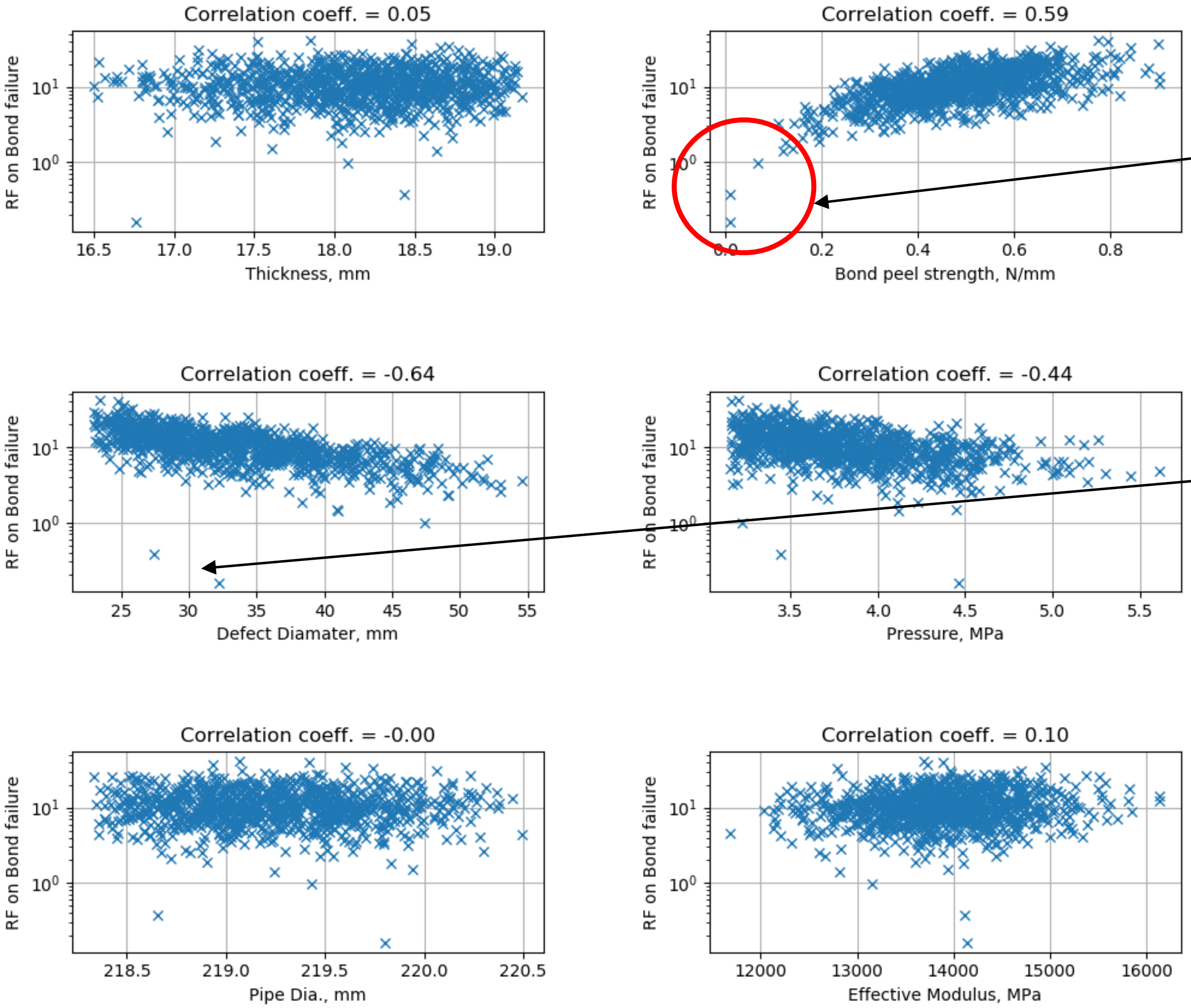




Long term test data suggests no failure would be expected within observed 2 year lifetime

Risk of short term failure predicted to be ~1/1000

Correlation on Inputs to Bond Failure



Failures clustered around cases with low generated bond strength – suggest this may be a likely cause of the observed leaks

Overall correlation against defect size is relatively strong, but failures do not cluster at large defect size

Review of initial results

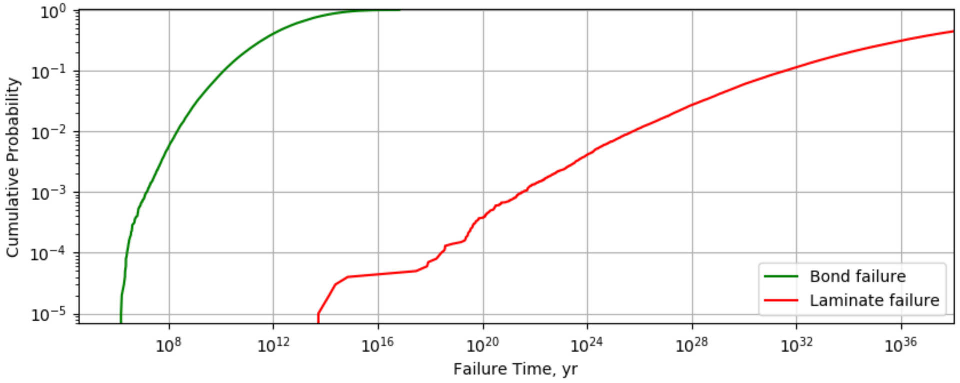
- Based on the design data, the reason for the observed failures is not clear
- Failure of the original repair was by seepage from under the repair, indicating bond line failure

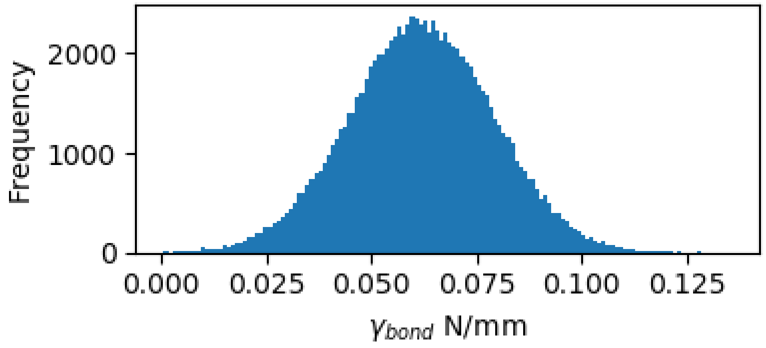
- Possible additional factors
  - Surface prep could be insufficient, leading to lower bond strength
  - If surface was not re-prepped after each stage of application, the different stages of the repair may not be properly bonded together – i.e. 6plies on day 1, then 8 on day 2, then 9 on day 3
  - Possibility of overpressure event, leading to bond failure

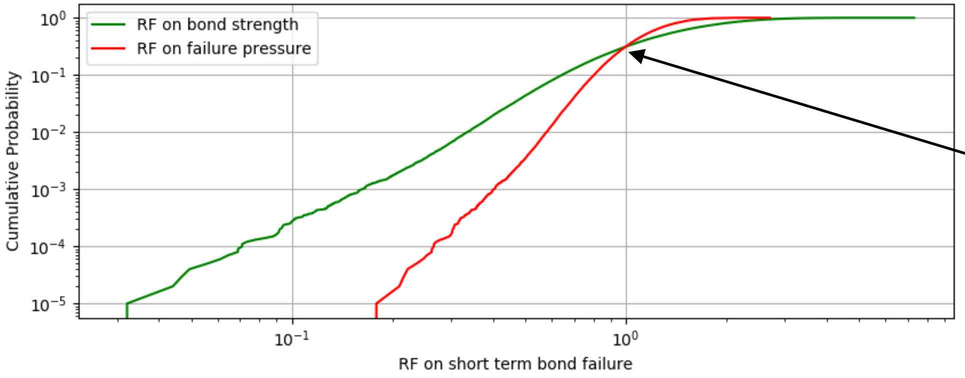
Impact of lower bond strength

- Assume lower quality surface prep, in line with ST2 (hand tool cleaned) finish

Data point	Defect size (mm)	Repair thickness (mm)	Failure pressure (bar)
1	25	6.4	30
2	25	6.4	45
3	25	6.4	45
Mean energy release rate, γ_{mean} (J/m^2)		61.7	
LCL energy release rate, γ_{LCL} (J/m^2)		28.2	



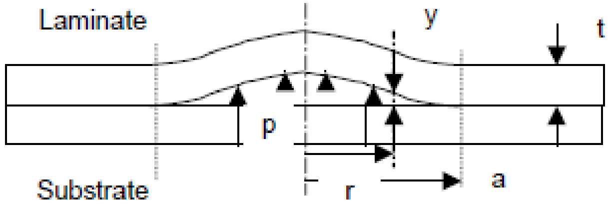




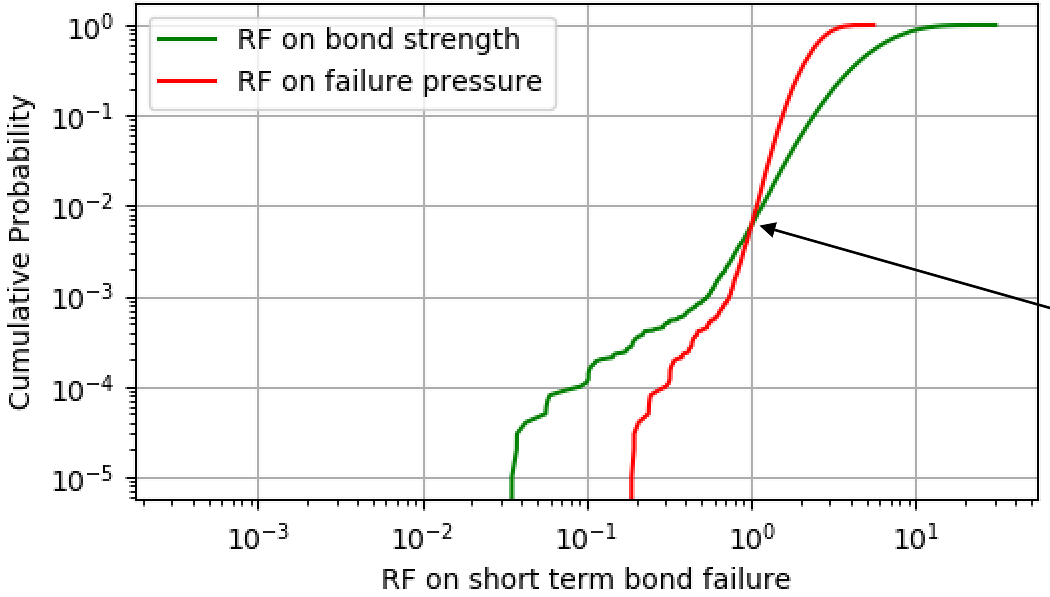
Bond strength consistent with lower quality surface prep results in ~30% predicted failure rate

Impact of poor bond between layers

- If the repair behaves as 3 independent laminate layers, the stiffness of the laminate when ‘blistering’ due to pressure will be reduced
- If the three layers are treated as separate, an ‘effective thickness’ with the same bending stiffness can be calculated:
  - $746^{1/3} = 9.07$mm
- This lower stiffness has been used to estimate the bond energy release rate



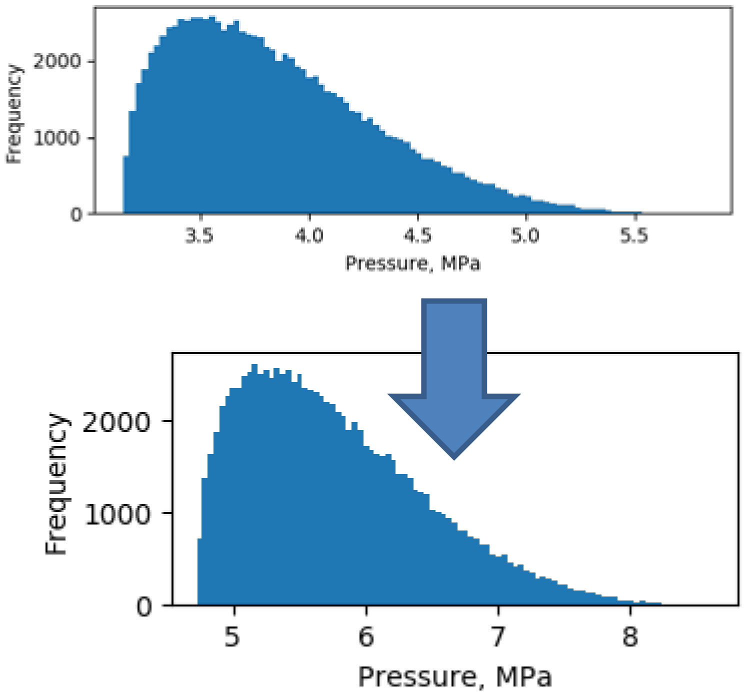
Layer		N Plies	t, mm	Bending stiffness (t^3)
	1	6	4.8	110.6
	2	8	6.4	262.1
	3	9	7.2	373.2
Total		23	18.4	6229.5
Separate Layers				746.0

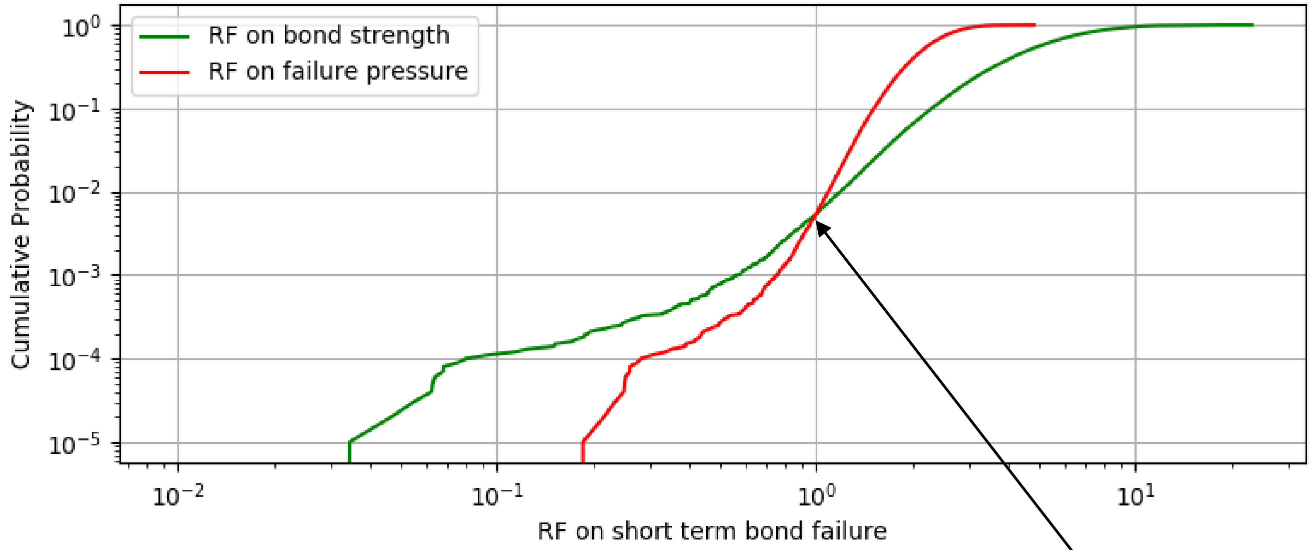


Risk of short term bond failure is estimated to be ~0.6%

Potential for over-pressure

- Repeat baseline calculations, assuming a 50% increase in the input pressure distribution





Sizable over-pressure results in risk of failure of ~0.6%

Summary – Failed Repair Case

- Validation calculations based on a known failed repair case have not reproduced the failure (based on the initial estimated input data).
- Based on the results of the statistical approach, the most likely cause for the observed failure is a reduction in the initial bond strength, for example due to issues with the surface preparation.
- Next steps are to identify further failed cases to improve the level of confidence with the current approach.

Summary

- The statistical approach developed here is relatively crude (due to limited data) but does provide a basis for analysing the safe operating life of composite repairs, beyond the initial (deterministic) design life.

- The approach allows the impact of various operating and installation variables to be assessed and ranked, in terms of their effect on repair life, providing guidance for managing in-service repairs and, which factors to control during installation

- The biggest uncertainties in the current approach surround the long term bond strength data, in particular how it varies with surface preparation. It is suggested this is where further testing effort should be focussed

Many thanks to TAQA for their support

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