

Combining high-resolution in-line geometry tools and finite element analysis to improve dent assessments

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DENT SEVERITY IN THE pipeline industry has historically been characterized through parameters including depth, length and width. Other approaches utilize techniques that estimate the strain in a dent based on the longitudinal and circumferential curvature. However these methods have shortcomings as they degenerate the geometry to a series of curve fits in two planes. Dents interacting with other anomalies and those that have atypical characteristics present particular challenges to both operators and in-line inspection vendors, as they do not fit the traditional analysis molds described above. Advances in high-resolution caliper tools offer an improved means of dent assessment through the use of finite element analysis, which can be performed on anomalies of any shape and size including those with interactions. This paper presents a case study where a plain dent was generated in the lab and characterized with an optical scanner and ROSEN's high-resolution geometry tool. Both sets of data were analyzed using the general purpose finite element code ABAQUS to predict stress concentration factors and expected strains under internal pressure. The analysis results were benchmarked to lab tests where strain gages were used to measure the peak strains. The paper concludes by presenting how the process of conducting finite element analysis has been streamlined to the point where it can be automated and stress concentration factors rapidly provided to operators in conjunction with standard ILI reports. This streamlined process now allows finite element analysis to be used as a primary means of assessment to rank, prioritize and mitigate dents.

HISTORICALLY, REGULATIONS REGARDING dent severity have been governed by one of two metrics: dent depth or strain. In the case of the former, plain dents with a depth up to 6% of the nominal diameter are permitted in both gas and liquid pipelines [1, 2]. However, many operators typically set stricter limits on dent depth targeting those above a depth of 2% for evaluation. Dent depth provides a straightforward means for assessing dents, as the concept relies on the generally accepted principle that all things being equal deeper dents should be more severe than shallower dents.

Strain-based calculations provide another means to assess dents and have become more common as geometry tools have improved and the data necessary to run the calculations has become readily available. In the case of gas pipelines, plain dents of any depth are considered acceptable provided the strains do not exceed 6% [1]. The strain-based approach calculates the strain in the hoop and axial planes of the dent based on the radii of curvature in each plane and the extensional strain based on the length of the dent. An approach is outlined in Appendix R of B31.8 [1]. While the methodology is based on first principles and the approach accounts for the shape of the dent, the application is less straight-forward. Estimates of the radii of curvature can be sensitive to undulations in ILI data typically requiring some form of smoothing or filtering in order to be successfully used. Furthermore, in many cases, the radii of curvature in any plane may vary considerably depending on whether local point-to-point curvature is calculated or if the global shape is considered.

Both the strain-based and dent depth approaches have similar shortcomings. First, neither approach is adequate for complex dents or in cases where interacting dents may be present. In the case of depth, the shape of a dent is completely neglected. A long, deep dent is not distinguished from a shorter, steeper dent. While strain-based approaches improve on this shortcoming and can be useful for well-behaved dents, applying the methodology where varying curvatures may exist in a complex dent becomes significantly more difficult. Furthermore, both approaches do not directly address fatigue which is a significant concern in dents with pressure cycles.

Finite element analysis (FEA) provides a more adequate means for analyzing dents. When combined with today's advanced geometry ILI tools and advances in computing, FEA can readily be used to assess dents. FEA does not suffer from the shortcomings of the aforementioned methods. Complex dents and well-behaved dents are both suitable for FEA, and the results are not sensitive to small undulations in data. The severity is calculated directly based on the response of the dent to the applied loading, regardless of shape or size.

This paper describes the tools that allow for the most advanced dent assessments and provides a comparison of anomalies analyzed according to depth, strain, and stress concentration factor (i.e., finite element analysis). Finally, a case study is presented illustrating the effectiveness of the method.

High resolution geometry ILI (*RoGeo XT*)

An essential prerequisite for highly accurate assessment methods such as finite element analysis is an in-line inspection system that captures the contours of the anomalies with the utmost precision. Otherwise the assessment will yield results based on misleading geometry.

A disadvantage of the traditional mechanical caliper tool design, where the mechanical movement of the caliper is transformed into a position signal, is the dynamic behavior of the "pig" arms under run conditions. Above a certain tool speed, the caliper arms start to lose continuous contact with the internal surface of the pipeline causing inaccuracies resulting in misrepresentations of the dent shape. But also at low speeds abrupt changes at the internal pipe surface such as girth welds and abrupt internal diameter changes may not be captured correctly. Pure mechanical designs that try to overcome these issues are typically fragile and lightweight often resulting in tool damages and compromised ILI data.

Another aspect is the single sensor plane that inevitably causes circumferential coverage gaps. The gaps are required to allow the sensor ring to collapse in smaller diameters. These gaps can cause the deepest spots of deformation to be missed which results in less accurate measurements. For these reasons, such systems are not considered adequate for recording data forming the basis for accurate assessments.

With its mechatronic measurement system, consisting of caliper and eddy current components, the RoGeo XT precisely measures the profile and contour of geometric features, even at higher inspection velocities, abrupt changes at the internal pipe surface and in the presence of wax or debris. Each tool is equipped with two sensor planes resulting in a 100% circumferential coverage.

With this configuration and the ability to accurately measure dent length, width and depth, it fulfills the prerequisite described above for highly accurate measurements. The RoGeo XT tool fleet today covers pipeline sizes ranging from 6" to 48". Figure 1 shows the 16" and 42" tools. In addition, for scenarios where several diameters are present, multi-diameter solutions have been developed.

The principle of combining mechanical caliper and an electronic proximity sensor is depicted in Figures 2 and 3. Figure 2 shows the touchless electronic sensor integrated inside the sensor head and a position sensor attached at the base of the sensor arm recording the mechanical position. The touchless electronic sensor is used to compensate data obtained from the dynamic behavior of the caliper arm. The unwanted effects of the caliper's inertia are fully compensated by the touchless measurement. Sharp transitions at the internal surface, such as a pipe misalignment at a girth weld, are captured very well. A more detailed description can be found in [3]. In Figure 3 a simulation

example explains how the contour of a dent is measured by the compensation method. In this simulation the tool was run at a speed of 6.72 mph (3 m/s).

Among other aspects, the example in Figure 3 emphasizes the tendency of oversizing the dent length using the pure mechanical caliper arm. Since the electronic sensor is insensitive to non-conductive material, the compensation method is always capturing the internal surface of the pipeline. Scale or wax debris, although detected by the system, will not affect the geometry evaluation of the pipeline. Since the introduction of the RoGeo XT numerous large scale tests and field verifications confirmed these simulation results. Both tests and field verification comprised challenging deformations such as steep and tapered pipeline wrinkling.

Finite element analysis and stress concentration factors

Stress concentration factors (SCFs) are a widely recognized means for characterizing the severity of discontinuities in otherwise uniform load bearing members. By definition, an SCF represents the ratio of the peak stress in a body to the calculated nominal stress. For instance, the nominal axial stress in a member may be calculated by dividing the applied load by the cross-sectional area of the member (i.e., $\sigma = P/A$). However, if the cross sectional area contains a discontinuity such as a hole or tapered cross section, the stress state in the member is no longer simply a function of the area and the applied load. Instead, localized stresses will be present near the discontinuity that may be several times higher than the nominal stress depending on the geometry of the discontinuity. In many cases, these local stresses are of interest to the designer. Therefore, it is useful to define a relationship between the nominal stress and the local maximum stress near the discontinuity. This relationship is referred to as a SCF.

Analytical SCFs have been calculated for numerous simple shapes such as holes, ellipses, and corners. These SCFs are typically shown in graphical form and documented in textbooks such as Roark's Formulas for Stress and Strain, or Peterson's Stress Concentration Factors [5, 6]. Characterizing discontinuities with an SCF is convenient because it allows for the peak stress in a member to be calculated for any stress state and also conveys the severity of a particular discontinuity in a member.

It is also common that a particular shape or member may have a detail so complex that the SCF cannot be derived through equations. In these cases, a finite element model may be constructed and the SCF determined through numerical analysis. This approach is widely used in offshore structural analysis where SCFs are combined with published S-N curves when determining fatigue lives for structural connections. The approach is documented in multiple standards [7, 8]. In general, the approach relies on coarse global models to determine nominal stresses in a member. Local refined models are used to determine SCFs which can be used to calculate the peak stresses required for fatigue.

It is straightforward to expand the SCF methodology to the assessment of dents in pipelines. The nominal stress state in a pipeline is easily classified as a function of the internal pressure according to Barlow's equation. If the unique geometric information can be provided for a particular dent, then a finite element model can be assembled. With the advent of high resolution caliper tools described in the previous section, this data can now be provided with in-line inspection tools.

Once a finite element model is built, the process of determining the SCF is relatively simple. When an internal pressure is applied to the model, localized high stresses will develop near the dented region. The magnitude of these stresses will be a function of the dent shape, pipe diameter, and wall-thickness. Numerous stresses can be calculated from a finite element model including von Mises, Tresca, component, or principal stresses. It is typical to use the maximum principal stress for

calculating the SCF since fatigue calculations require maximum principal stresses. Therefore, the SCF for a dent can be defined as the ratio of the overall maximum principal stress in a dent to the nominal hoop stress in the pipe. This analysis is akin to a level III fitness for service analysis outlined in API 579 [9].

A common question in using this methodology is how the plastic strains in the dent are accounted for. When a dent is created, it is understood that the material must be plastically strained in order for the deformation to be permanent. However, if the dent is subjected to cyclic stress ranges that are less than twice yield, the stresses will shakedown to elastic behavior, and additional plastic strain will not be accrued. In other words, the material will behave in an elastic manner and can be analyzed as such. This behavior is commonly seen in dents that are subjected to cyclic pressure testing, and was observed in the case study presented in this paper. In the case of existing pipelines that have been in operation for any appreciable period of time, it is likely that any dents have experienced a shakedown to elastic action.

Development of the finite element dent analysis tool (FE-DAT)

Historically, finite element analyses have been costly and time-consuming for operators. Prior to 2000, finite element analyses of dents were not practical except in extreme circumstances. Gathering the required data to characterize the dent typically involved an excavation of the affected pipeline which is a costly and time-consuming endeavor. In addition, computer resources were limited and creating analytical models represented a fairly advanced assessment approach. This typically limited dent analyses to only the most costly scenarios.

Advances in technology have removed both of these limitations. Through the use of new ILI tools, detailed geometrical information for a dent can now be made available without excavating the pipeline. General purpose finite element packages are widely available and increases in processing power have reduced analysis times to minutes rather than days. These two developments have permitted the creation of a streamlined process referred to as the Finite Element Dent Analysis Tool (FE-DAT).

The FE-DAT was developed to facilitate the analysis of dents on a large scale. Rather than analyzing a single dent or selected dents, an elastic analysis can be performed for every dent detected in a tool run. The FE-DAT works by taking data directly from a high-resolution ILI tool, building a finite element model, and post-processing the results. A set of dent analyses that may have previously taken weeks can now be reduced to a few hours. The results from the analysis provide the SCF for each dent which is directly proportional to the severity of each dent and indirectly proportional to the life. In addition, the stress profile in the region surrounding the dent is also provided in the form of stress contours. With this data, operators can make improved decisions on which dents require mitigation.

Through the joint efforts of SES and ROSEN, the FE-DAT also provides another important advantage to operators. Historically, the analysis process outlined above typically involves an analysis consultant performing the assessment at the request of an operator. The operator essentially acts as a middle-man transferring ILI data from the inspection vendor to the consultant. Any requests for clarifications or issues that arise in the data are transmitted through the operator, placing additional burden on the operator and often creating confusion if the requests are not well understood. Through the partnership of SES and ROSEN, the FE-DAT allows the analysis to take place completely on the side of the ILI vendor, reducing the involvement and stress placed on the operator.

Case study

In order to demonstrate the effectiveness of the FE-DAT and the accuracy of the high-resolution RoGeo XT tool, a case study was performed where a plain dent was generated in a laboratory setting. The shape of the dent was characterized through the use of an optical scanner as well as ROSEN's RoGeo XT tool. The goal of the case study was to illustrate the effectiveness of the SCF method and provide a comparison between test data and analytical methods.

The dent was generated in a 24-inch OD, 0.25-inch wall thickness, Grade X52 pipe. A photograph of the test set-up showing the sample and the indenter is shown in Figure 4. Strain gages were placed at the locations shown in Figure 5. The dent was generated by pressing a 2-inch diameter indenter into the pipe to a depth of 3.61-inches (15% OD) in an unpressurized configuration. Next, the indenter was removed and the pipe was subjected to pressure cycles of 0% – 100% and 10% – 80% SMYS nominal hoop stress. This denting process produces a stable dent for inspection and pressure cycling.

After creating the dent, an independent third-party used an optical scanner to capture the shape of the dent. Next, the end caps were removed from the sample and it was shipped to ROSEN's facilities in Houston, TX where the RoGeo XT tool was pulled through the pipe. The pipe was returned to SES's facilities where the strain gages and end caps were reinstalled and the sample was subjected to target pressure cycles ranging from 100 – 780 psi (9% - 72% SMYS) until failure occurred. The strains were recorded at intermittent points during cycling. The sample failed after 39,800 cycles when a longitudinally oriented thru-wall crack developed in the shoulder of the dent near strain gage #5. Photographs of the failure are shown in Figure 6. The processed hoop strains for gages 2 and 5 (i.e., nominal and peak strains respectively) are shown in Figure 7 for cycles 100 to 110. Using a recorded pressure range of 690 psi, the nominal stress is 33,120 psi (1104 $\mu\epsilon$). A hoop strain range of 3491 $\mu\epsilon$ was observed at gage 5 which is equivalent to an elastic stress of 104,731 psi. This results in a calculated SCF of 3.16 from the experimental data.

It should also be pointed out that the dent remained stable throughout the cyclic testing. The shakedown to elastic action was evident at an early stage in the cycle as the strains varied linearly with pressure. This is shown in Figure 8 where the hoop strain is plotted verse internal pressure for cycles 100 to 110. The strains also did not change significantly throughout the testing as the final calculated SCF at 30,000 cycles was 3.23.

The ILI data from the RoGeo XT tool analyzed using the FE-DAT. The FE-DAT was developed using the general purpose finite element code ABAQUS for the assessments. A desired element spacing of 0.25-inches was specified. An internal pressure of 208.3 psi was applied to the model corresponding to a 10,000 psi hoop stress. The analysis completed by the FE-DAT showed a maximum principal stress of 32,784 psi on the OD of the pipe resulting in an SCF of 3.28. The data from the optical scan was provided in the form of an IGES surface file generated by the vendor. The surface file was meshed using a characteristic element length of 0.25-inches and analyzed using ABAQUS in order to maintain consistency with the FE-DAT. The same internal pressure of 208.3 psi was applied to the finite element model. The calculated maximum principal stress on the OD of the pipe was 38,014 psi yielding a SCF of 3.80. A comparison of the contour plots from the two analyses is provided in Figure 9. It can be seen that while the magnitude of the principal stresses are slightly different, the shape of the stress contours are nearly identical. A comparison of the SCFs is shown in Table 3.

In general, the calculated SCFs and depths compare well, particularly between the FE-DAT and the test data. The slightly higher SCF shown in the optical scan could be due to a number of reasons. First, some smoothing algorithms are required in order to generate a surface from point cloud data. It is possible that the dent SCFs may be sensitive to this smoothing algorithm. Second, the optical scan utilized data from the outer diameter while the ILI data was taken on the inner diameter. Finally, a summary of the dent depths in Table 3 shows that the optical scan produced a slightly larger depth

than the lab measurements and ILI data. The FE-DAT and the test data showed closer agreement for the dent depths and the resulting SCFs.

Remaining life analysis

The calculation of the SCF for a dent also permits a fatigue analysis to be performed if the operator can provide pressure history data. Using actual data, a rainflow analysis can be performed in order to calculate an equivalent number of cycles a particular dent experiences. This equivalent number of pressure cycles can be combined with the calculated SCF to determine the remaining life of a dent. This approach has been documented in previous papers by Alexander [10].

When calculating fatigue lives, it is important to discuss the sensitivity of life to the calculated stresses. The relationship between stress and fatigue life is highly nonlinear being a factor of a third or fourth power. This is important when considering the scatter that can arise in fatigue calculations. For instance, if the stresses increase 25% in an analysis, the life will be reduced by more than half. This is one reason why fatigue analyses typically carry large factors of safety.

Since pressure history data was not available for the dent considered in this paper, example pressure data is taken from a study published by Kiefner [11]. In this study, equivalent pressure ranges based on the yield strength of the pipe are provided representing light, moderate, aggressive, and very aggressive usage. Using the S-N design C-curve from [8] and the calculated stress concentration factor of 3.28, the factored design life of the anomaly varies from 21.3 years for light usage to 0.8 years for very aggressive usage as shown in Table 2. It should be noted that the design life includes a factor of safety of 10 combined with the design curve which is typical for fatigue calculations. Published design S-N fatigue curves can be found in several sources including [7], [8] and [12].

Since the sample presented in this paper was ultimately destructively pressure cycled in the lab, comparisons can also be made between the predicted cycles to failure and the actual cycles to failure. Using the calculated SCF of 3.28 and a nominal stress of 33.1 ksi, the predicted number of cycles using the design curve is 3674. The calculated number of cycles is significantly lower than the actual number of cycles, and there are several reasons for this difference.

First, fatigue results from laboratory tests typically have a significant amount of scatter and variation from the predicted number of cycles is expected. As mentioned previously, small changes in stress can have significant impacts on expected life. In this example, if the stresses are off by 20% due to ovality or variations in material thickness, the predicted cycles would more than double to 8024. Second, the design curve used in calculating the number of cycles represents a lower bound estimate since the curve is located 2 standard deviations below the mean. Finally, while the published S-N curves can be used for calculating fatigue at high stress ranges, it would likely be more appropriate to use a material specific strain-based fatigue curve at such high stress levels. The combination of these factors explains why physical testing of re-created dents typically results in higher fatigue lives than those predicted by analysis as found in [10].

Comparison of dent depth, curvature strain (B31.8) and SCF (FE-DAT)

In order to assess the significance of depth as indicator for dent severity in terms of fatigue, a comparison of dent depth and stress concentration factors was carried out on a larger set of actual dents. To further investigate the impact of dent curvature the maximum total strain calculated from ASME B31.8 [1] was included in this assessment.

In total the test population of this assessment comprised 113 dents of depths ranging from 0.12" (3.1 mm) to 0.45" (11.5 mm). They were recorded with the high resolution geometry tool in a 14 inch pipeline of 0.375" (9.5 mm) wall thickness.

Based on the ILI geometry data the strain was calculated in according to ASME B31.8 [1], which provides equations to estimate the circumferential, longitudinal, extensional and total strain on the basis of the dent displacement and curvature data. In addition, the ILI data was analyzed using the FE-DAT to calculate the stress concentration factors under internal pressure for each of the dents. Detailed information about depths, strain values and stress concentration factors of the test population are given in Table 3 and histograms in Figure 10.

A correlation analysis between all individual parameters was conducted. In addition, by means of multiple regressions, the correlation between depth and strain as independent variables and stress concentration factor as dependent variable was calculated. The assessment results are summarized in Table 4 and Figure 11. In the table the most relevant correlation coefficients are highlighted in bold. A high correlation between depth and external SCF was observed (0.83). However, as there is only a moderate correlation between depth and internal SCF (0.58) and as dents of practically the same depth yielded significantly different SCF values, the SCF is clearly a more robust tool for ranking dent severity.

The low correlation between strain and SCF (external 0.35, internal 0.27) as well as the multiple regression analyses not resulting in higher correlation coefficients show that the maximum total strain of a dent only slightly influences the stress concentration. The B31.8 strain assessment therewith remains an additional method to assess whether a dent momentarily constitutes a pipeline threat.

Conclusion

Historically, finite element analysis has seen limited use in the assessment of dents in pipelines. Metrics such as depth or strain have provided the primary means of assessing the threat posed by dents. This paper has shown how data available from high resolution caliper tools can be used to calculate SCFs for a dent. The SCF is proportional to the severity of the dent and can be used to calculate the remaining life of an anomaly. The advances in computing and ILI caliper tools have allowed the process of analyzing dents to be streamlined to the point where hundreds of dents can be analyzed quickly and the data be made available as part of ILI reports. This approach has been validated through physical testing and represents an advanced metric that can be used to prioritize dents.

Acknowledgments

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Fig.1: RoGeo Xt tools with two measurement planes (100% circumferential coverage)
 left: 16-inch tool with pull unit and two measurement units
 right: 42-inch single body tool with wheel setup



Fig.2: combination of conventional mechanical caliper concept (β) with a touchless operating proximity sensor (δ).

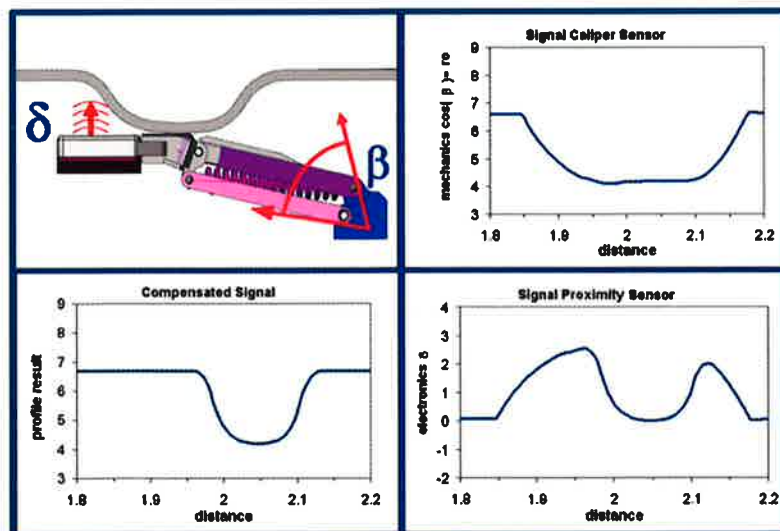


Fig.3: compensated signal from a dent obtained by the summation of the mechanical movement and the touchless proximity signal.

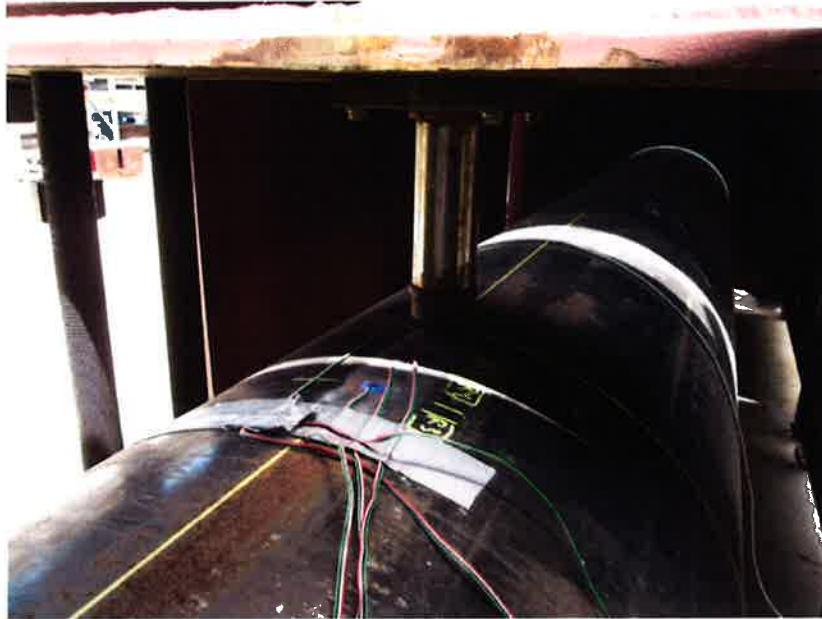


Fig.4: 24-inch test sample prior to denting.

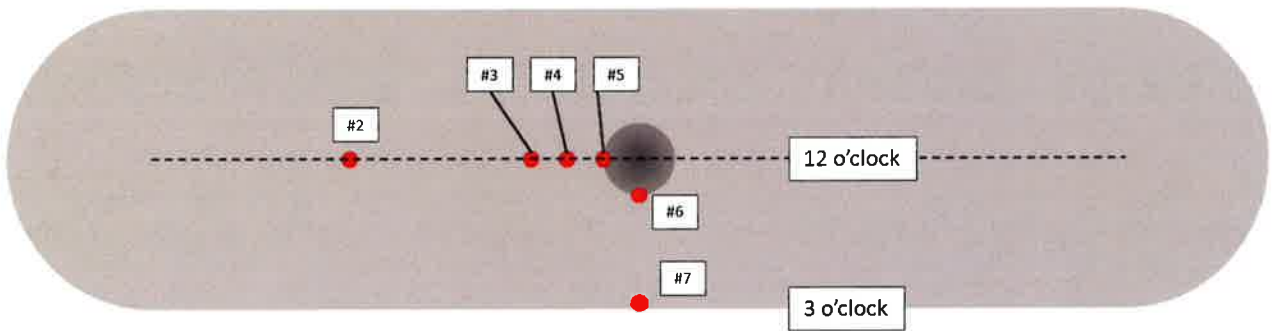


Fig.5: 24-inch test sample strain gage layout.



Fig.6: dent failure after 39,800 cycles.

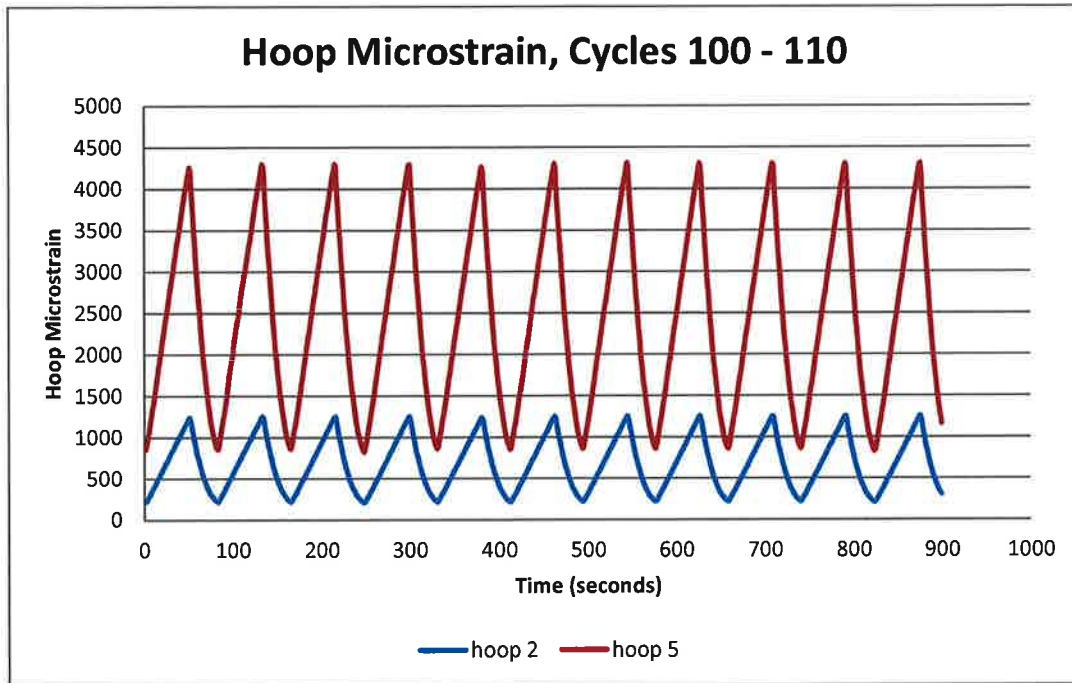


Fig.7: hoop strains for cycles 100 – 110.

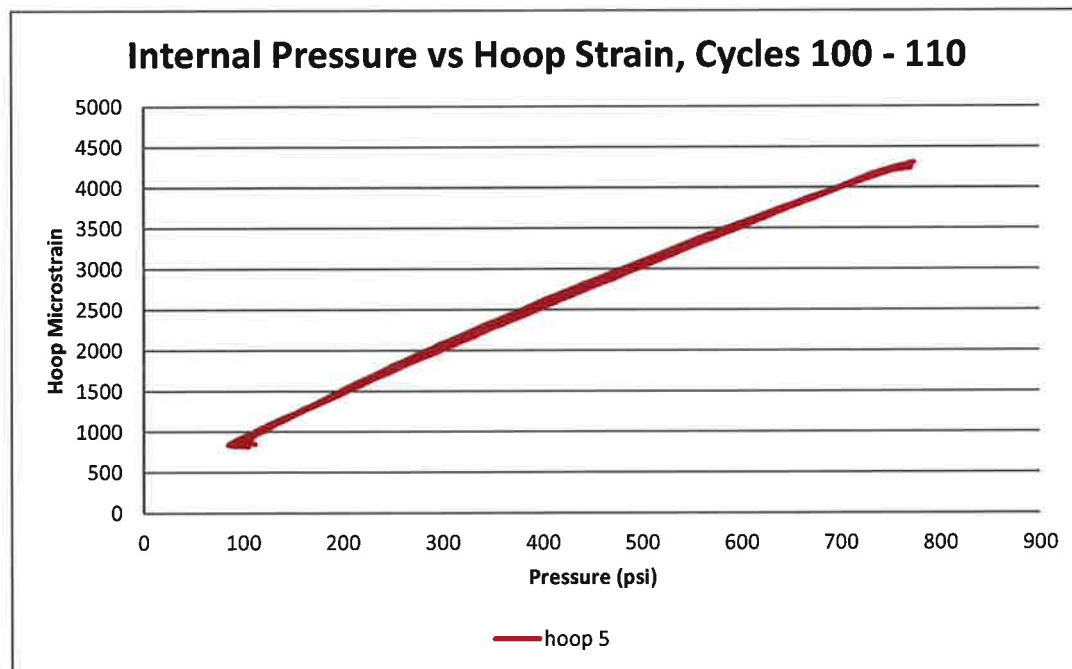


Fig.8: relationship between hoop strain and internal pressure.

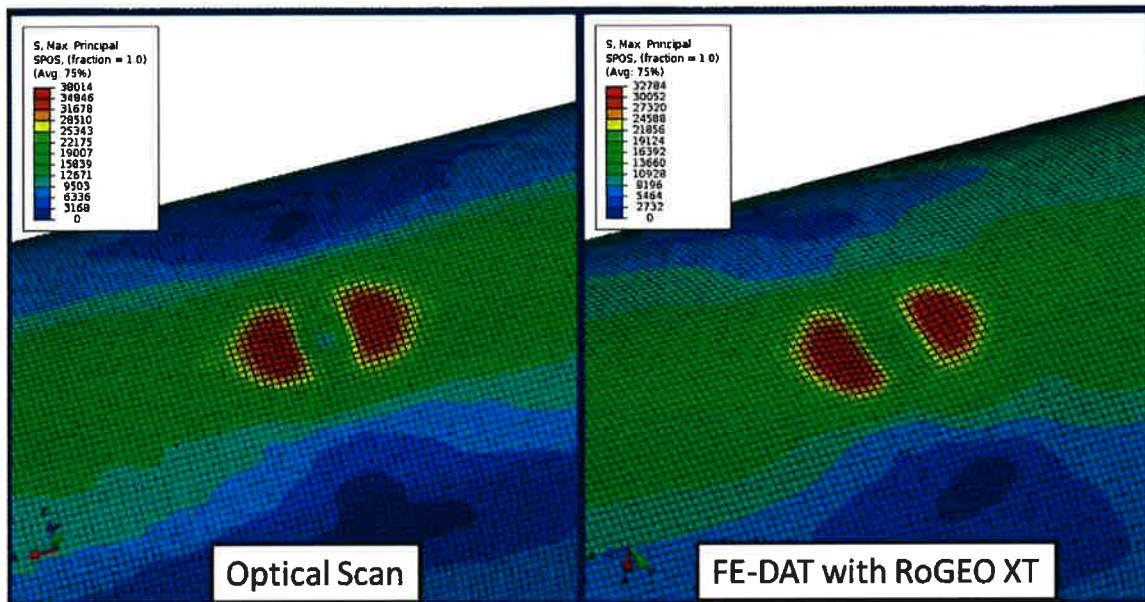


Fig.9: maximum principal stress contours
left: results from optical scan data
right: results from FE-DAT using the RoGeo Xt tool data

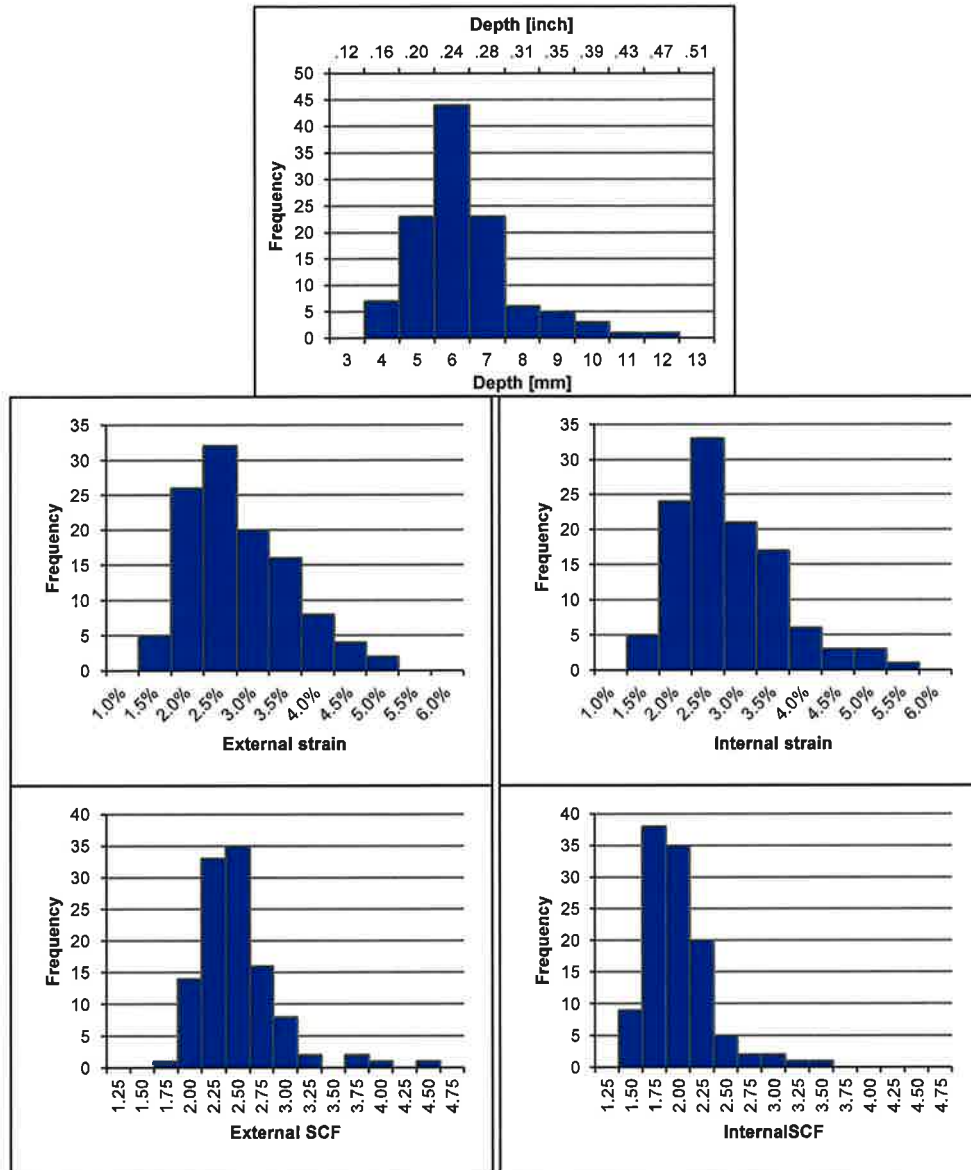


Fig.10: description of test population – dent depth (top), external and internal strain values (middle), external and internal stress concentration factors (bottom).

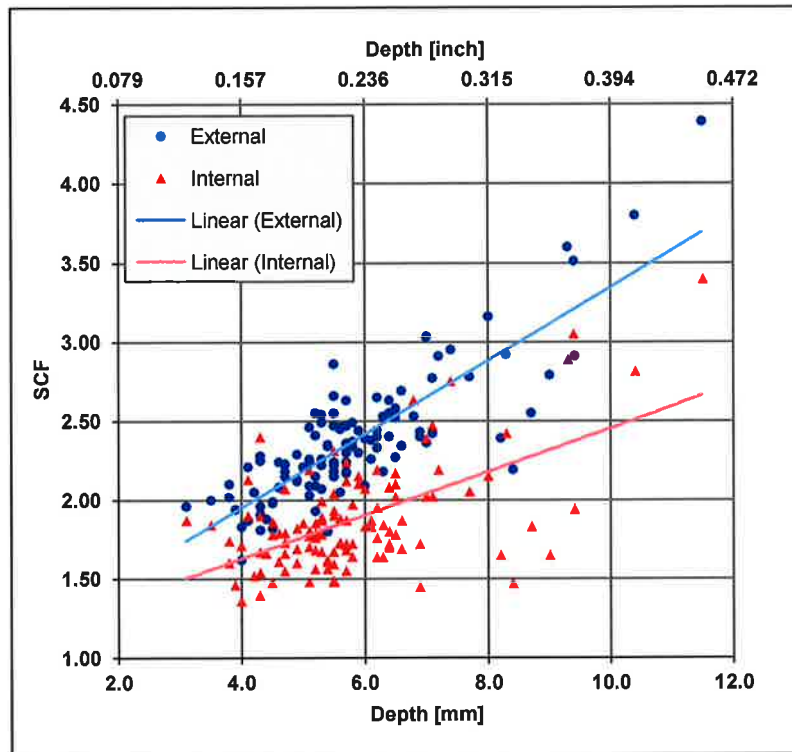


Fig.11: relation between stress concentration factors and dent depth.

Table 1: Dent depth and SCF comparisons.

	Test Data	Optical Scan	FE-DAT with RoGEO XT
Depth (in)	0.486	0.584	0.477
Nominal Stress (psi)	33,120	10,000	10,000
Peak Stress (psi)	104,731	38,014	32,784
SCF	3.16	3.80	3.28

Table 2: Fatigue life calculations.

Pressure Range (psi)	% SMYS	Stress * SCF (ksi)	# Cycles Per Year			
			Light	Moderate	Aggressive	Very Aggressive
271	25%	43	100	200	500	2000
379	35%	60	50	100	250	1000
488	45%	77	25	50	125	500
596	55%	94	0	10	25	100
704	65%	111	0	2	8	40
780	72%	123	0	1	4	20
Life (years)			213	83	32	8
Factored Design (years)			21.3	8.3	3.2	0.8

Table 3: Summary of test population (14-inch od x 0.375wt).

Statistic	Dent Depth			Strain		SCF	
	inch	mm	% OD	External	Internal	External	Internal
Min	0.12	3.1	0.89	1.27%	1.27%	1.62	1.36
Max	0.45	11.5	3.22	4.89%	5.27%	4.39	3.39
Mean	0.23	5.8	1.64	2.59%	2.61%	2.38	1.88
Stdv	0.06	1.4	0.40	0.76%	0.80%	0.40	0.34

Table 4: Correlation coefficients.

	OD Strain	ID Strain	OD SCF	ID SCF
<i>Depth</i>	0.48	0.47	0.83	0.58
<i>OD Strain</i>		0.99	0.35	0.31
<i>ID Strain</i>			0.31	0.27
<i>OD SCF</i>				0.73
<i>Depth & OD strain</i>			0.84	
<i>Depth & ID strain</i>				0.58

