Calculating Effective Flaw Dimensions at Operating Pressures

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DNV

Pipeline Pigging and Integrity Management Conference

February 12-16, 2024

Organized by
Clarion Technical Conferences

https://doi.org/10.52202/072781-0081

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Abstract

Effective area calculations[1] are used to identify which corrosion depth measurements control the failure pressure of a cluster of metal-loss anomalies reported by an in-line inspection (ILI). The depth measurements usually correspond to individual anomalies that are grouped or "clustered" together based on defect interaction criteria. The effective area calculations determine an effective length and depth based on the ILI reported cluster and box lengths and depths at the time of the inspection. As corrosion growth occurs, the depths of some or all of the individual anomalies within a cluster can increase. As a result, the maximum or average depth of the cluster increases, while the effective length can increase or decrease.

Growth of individual anomalies within a cluster is often non-uniform, with some anomalies increasing in depth (and possibly length) more quickly than others. As a result, local "hot spots" can develop and eventually dominate the effective area calculations. Understanding how corrosion growth affects the effective dimensions of a cluster is important because it affects estimated remaining lives and determination of which anomalies in the cluster are most likely to fail first. The flaw geometry at failure depends on the local operating pressure, the corrosion growth rates, and the initial cluster geometry.

Remaining life calculations depend on reliable estimates of both initial and final metal-loss depths and lengths. Because differences between individual metal-loss box corrosion growth rates can affect effective flaw dimensions, accuracy is important. Initial corrosion depths and lengths are reasonably well known from typical ILIs. Overestimating or underestimating the flaw geometry at failure under operating conditions can lead to overly conservative or unconservative remaining life predictions.

This paper evaluates the effects of corrosion growth on the effective dimensions, flaw geometries at failure, and remaining lives of clusters. The paper examines artificial and real-world clusters ranging in length from short to long and containing few to many individual anomalies. The paper determines when and how each cluster's effective length and critical depth change as corrosion growth takes place along the cluster until it reaches a failure condition at the local operating pressure. Then, the paper evaluates how the changes in effective lengths and critical depths affect remaining life predictions. Conclusions regarding how to best estimate remaining lives of clustered anomalies are developed and documented.

Introduction

The burst pressure of a cluster of metal-loss anomalies is typically analyzed using an effective area approach. The effective length and depth depend on the dimensions of the anomalies that comprise the cluster. Remaining lives are then estimated from the effective area by numerically "growing" the depth, and possibly length, to a critical size. In many cases, the depth is increased by an assumed corrosion growth rate and the effective length is held constant.

This paper considers the remaining life of anomalies calculated from Equation 1, which assumes a constant corrosion growth rate (in time) between the initial and critical depths.

$$Remaining\ Life = \frac{Depth_{Critical} - Depth_{Initial}}{Growth\ Rate} \tag{1}$$

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Keys to obtaining reliable and accurate remaining life estimates include using realistic corrosion growth rates as well as accurate initial and critical (final) depths. For isolated metal-loss anomalies, a common assumption is that the anomaly grows equally in all directions – depth, upstream/ downstream length, and clockwise/counterclockwise width. By assuming uniform growth, it is relatively straightforward to predict when an isolated anomaly will reach a critical size as a function of time.

Clusters are more complex. Clusters are comprised of multiple individual anomalies that are considered close enough to interact and possibly contribute to failure. When failure occurs, it does so over some or all of the anomalies within the cluster, each of which may grow in a unique fashion. The portion of the cluster that drives failure is determined using an effective area approach, such as RSTRENG (an iterative algorithm used to calculate effective lengths). Effective area approaches determine which subset of the clustered anomalies produces the lowest calculated burst pressure.

Corrosion growth can change the length, depth, and effective area of a cluster. This paper develops an approach to predicting how the size of clusters changes by growing the individual anomalies in the cluster. The methodology assumes each metal-loss anomaly in the cluster grows at a rate proportional to the anomaly's depth – that is, deeper anomalies grow more quickly than shallow anomalies. For this simulation, each axial end of the cluster grows at the same rate as the cluster's maximum depth. Therefore, the cluster's overall length increases at twice the rate the depth increases. Other length growth assumptions can be used.

The depth contour of the cluster is described by a river-bottom profile, where the maximum individual anomaly depths are aggregated and used to estimate the path a failure may take. As the individual anomalies within the cluster grow, the deeper locations approach full wall thickness before the shallower locations. By running effective area calculations after each growth increment, changes in which anomalies contribute to failure can be considered. This in turn will change the effective length of the cluster. As will be seen, as the cluster grows deeper, the effective length tends to shrink due to the failure being centralized around the deepest location(s).

Remaining life assessments depend on accurately predicting how quickly a cluster will grow to a critical depth and length (i.e., grow to failure). Generally, the initially cluster dimensions are reasonably well known from in-line inspections, but the final flaw dimensions are uncertain. Predicting final flaw dimensions requires assumptions on how the depth and length increase as a function of location or distance along the cluster. Making the wrong assumptions can lead to either overly conservative or overly unconservative remaining life predictions.

Effective Length Calculations

The effective length of the cluster is determined using effective area calculations (e.g., RSTRENG). These calculations are based on a river-bottom depth profile created from the individual anomalies within the cluster. Iterative calculations determine the subset of the river-bottom profile that produces the lowest estimated burst pressure where all contiguous portions of the profile are considered. A cluster typically has a single effective area and effective length.

Figure 1 shows a river-bottom profile for a set of 25 individual anomalies that comprise a cluster. Each individual anomaly is rectangular in shape, while the overall cluster resembles a semi-ellipse.

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Clusters similar to the one in Figure 1* are used in the discussion below to describe how the effective length of a group of individual anomalies behaves as the depth of the individual anomalies increases.

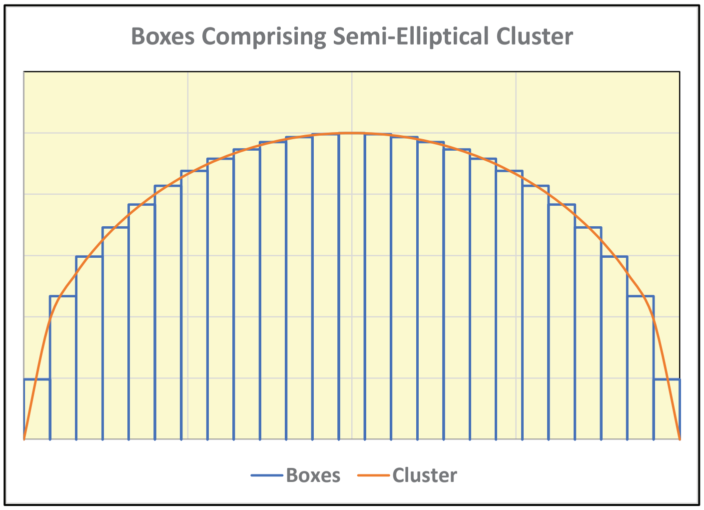

Figure 1. Individual anomalies comprising a semi-elliptical cluster

The individual anomalies of a cluster, like the one shown in Figure 1, that contribute to the lowest burst pressure change as growth occurs. That is, the effective length is not constant and does not necessarily equal the total length of the semi-elliptical cluster.[2] In the case of a shallow semi-elliptical cluster, the initial effective length is close to the overall length (i.e., nearly all the anomalies contribute to failure). But as anomaly depths increase, the effective length approaches zero because failure becomes dictated by the few anomalies approaching the full wall thickness.

Shallow clusters have relatively high failure pressures, while clusters with a depth near the full wall thickness fail at pressures close to zero. The difference between the current depth and the critical (failure) depth at the operating pressure is needed to estimate the remaining life. Since the effective length changes as the cluster grows, the critical depth that corresponds to failure at the operating pressure will also be changing. This requires an iterative process at each growth increment that calculates the effective length and maximum depth, as both are needed to determine remaining lives.

Historically, these types of remaining life analyses are performed assuming the effective length remains constant. Basing the critical depth on the initial effective length of a (non-critical) cluster can underestimate the critical depth at the operating pressure. This is because longer anomalies have smaller critical depths than shorter anomalies. Because critical depths increase as the effective length decreases, assuming a constant effective length is conservative, sometimes largely so. By iteratively re-evaluating the effective length and critical depth during anomaly growth, more accurate remaining life estimates will be produced.

Growth Proportional to Initial Depth

Figure 2 shows six river-bottom profiles, each comprised of 500 individual anomalies whose aggregate can be described as a semi-elliptical cluster (each solid color represents one cluster; each cluster equals

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* Figure 1 is used to illustrate the concept of a semi-elliptical cluster comprised of 25 individual anomalies. In this study, the number of individual anomalies used to represent the semi-ellipse was 500.

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one set of 500 individual anomalies), similar to that shown earlier in Figure 1. Each cluster is subdivided into simulated individual anomalies (not shown in Figure 2) to demonstrate how the effective length of this simple geometry, a semi-ellipse, changes as growth occurs. Each simulated anomaly within each cluster is approximately 0.008 inches (0.2 mm) long with an individual depth selected to provide a semi-elliptical shape.

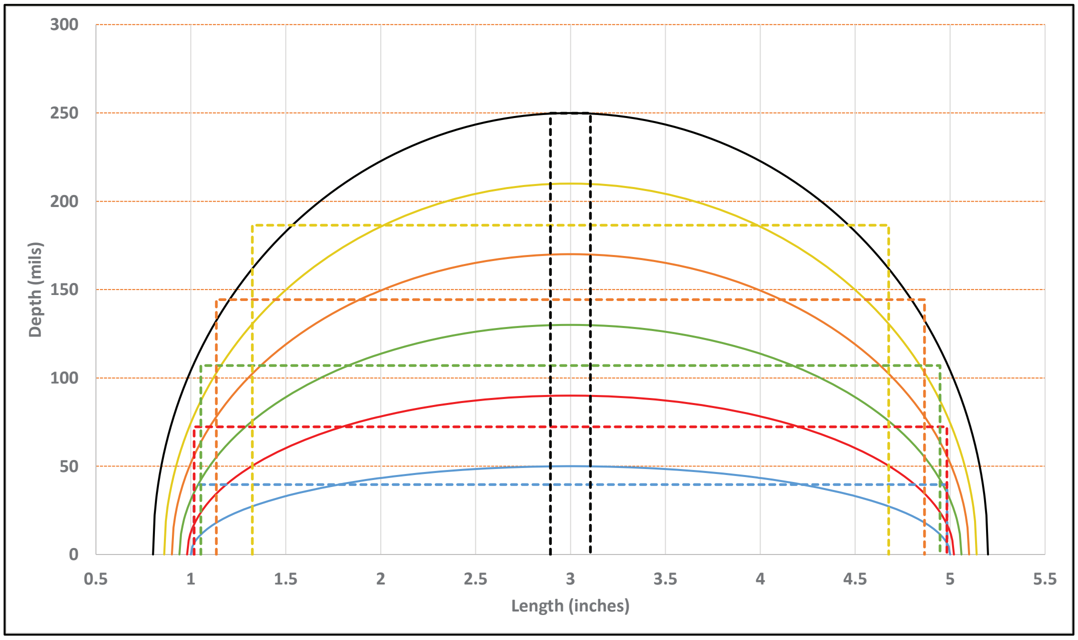

Figure 2. Profile and effective length example with growth rate proportional to depth

The pipeline represented in Figure 2 is 24-inches (610 mm) in diameter, made of X52 steel (359 MPa) with a wall thickness of 250 mils (6.4 mm). It has a maximum allowable operating pressure (MAOP) of 780 psig (5.38 MPa), which represents 72% of the specified minimum yield stress (SMYS). The initial aggregate (shallowest [blue]) semi-elliptical cluster is 4 inches (102 mm) long with a maximum depth of 20% of the wall thickness. The final (deepest [black]) cluster is 4.4 inches (112 mm) long with a maximum depth of 100% of the wall thickness.

Figure 2 also shows the effective length of each cluster as vertical dashed lines of a rectangular that represents the effective area. At a shallow cluster depth, the effective area covers nearly the full semi-ellipse, but it changes as the semi-ellipse depth increases. Initially, the effective length increases slightly as the cluster's depth and length increase, then it decreases as depth approaches the full wall thickness. The effective areas are always centered on the maximum depth, as expected. When the maximum depth approaches the full wall thickness, the effective length approaches zero.†

The growth rates of the individual anomalies that comprise each cluster are proportional to the initial depth of each anomaly. Therefore, the clusters maintain their semi-elliptical shape as they grow. Each axial end of the cluster grows in length at the same rate as the maximum growth rate of the anomalies, as shown in the figure. The growth rate between each curve in Figure 2 represents a change in

† Theoretically, the effective length at failure for a 100% deep semi-elliptical anomaly is zero. That is, it requires no length to fail once the depth reaches 100% of the wall thickness. The effective length shown in Figure 2 corresponds to a depth near but not equal to 100%.

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maximum depth of 0.04 inches (1 mm). For a growth rate of 20 mils per year (mpy) (0.5 mm per year), each curve would represent a time period of two years.

Impact on Effective Lengths and Critical Depths

Figure 3 shows the effective length of the semi-ellipses as a function of their maximum depth, expanded beyond the six shown in Figure 2. As reflected by the dashed vertical lines in Figure 2, the effective length drops as the maximum depth increases, approaching zero when the depth approaches the full wall thickness.

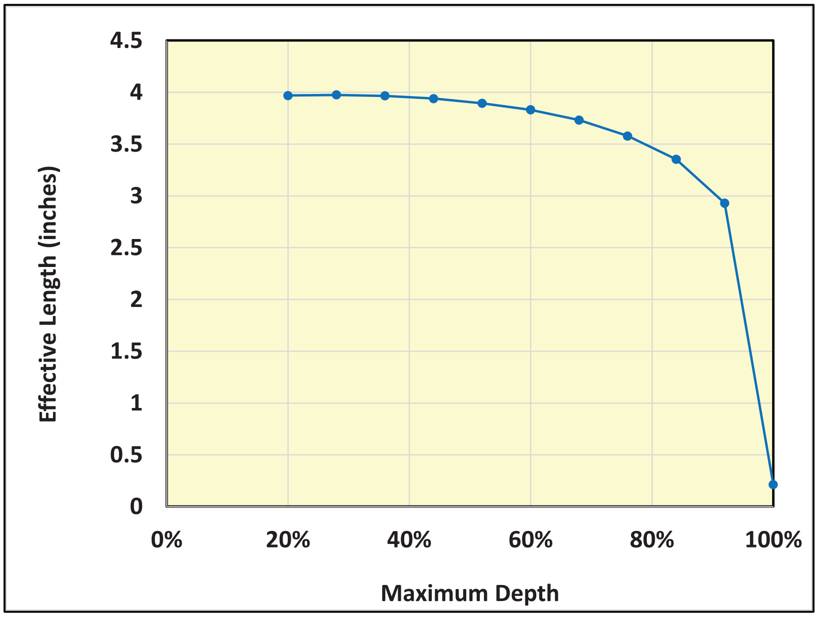

Figure 3. Effective length versus maximum depth example with growth rate proportional to depth

Figure 4 shows the corresponding burst pressures (P_{burst}) calculated using the RSTRENG method based on the effective areas shown in Figure 2 and via Equation 2.[1] They are plotted against the respective effective lengths of the semi-ellipses. As can be seen, the estimated burst pressures decrease as effective lengths decrease due to the increase in maximum depth, which controls failure. The plot is used to determine the effective length of the cluster at a specified failure pressure.

$$P_{burst} = \left(\frac{2\sigma_{flow}t}{D}\right)\left[\frac{1-\frac{A}{A_0}}{1-\frac{A}{A_0 M}}\right] \quad (2)$$

Here,

σ_{flow} = flow stress of the pipe, psi
t = pipe wall thickness, in
D = pipe diameter, in
A = effective area, in^2
A_0 =original area, in^2
M = Folias factor

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The effective length at the operating pressure of 780 psig (5.38 MPa) represents the potential failure condition, while the initial effective length is that based on the initial depth of the semi-elliptical cluster. At the initial dimensions, the effective length that contributes to failure (at approximately 1,200 psig) is just under 4 inches (102 mm). For failure at the operating pressure, the corresponding effective length is approximately 3.6 inches (91 mm). When this value is used in Figure 3, the maximum depth of the growing cluster that fails at 780 psig is 75.6%.

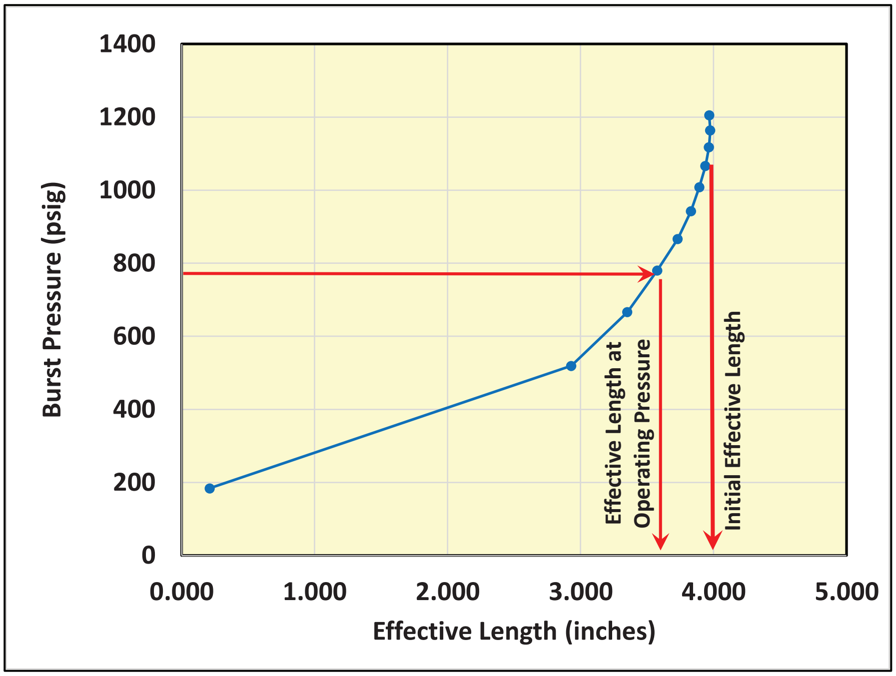

Figure 4. Burst pressure versus effective length example with growth rate proportional to depth

At the extremes of the growth scenario shown in Figure 2, the maximum cluster depth is equal to the effective depth. The initial cluster (blue curve) has an effective length equal to the semi-ellipse. Therefore, the group of anomalies that contribute to failure can be modelled as a perfect semi-ellipse with effective depth equal to the maximum depth. Similarly, a cluster that reaches 100% of the wall thickness (black curve) can be modelled as a rectangle with the effective depth equal to the maximum depth. These two shapes are easy to navigate when calculating a critical depth from Equation 1 at a specified failure pressure for a remaining life analysis.

Unfortunately, for growth periods between these two timeframes, the effective area of anomalies that contribute to the failure will be a non-ideal shape (i.e., a portion of a semi-ellipse). One approach is to assume the shape is a rectangle with a depth equal to the average depth (like those shown in Figure 2), but this is likely to produce smaller critical depths and conservative remaining life estimates because the average depths of the rectangles are below the maximum cluster depths. Therefore, an iterative process was performed on numerous initial cluster sizes to develop a critical flaw curve at 780 psig (5.38 MPa) relating effective length and maximum cluster depth.

Figure 5 shows this trend and the effect of the changing effective length on the critical cluster depth at the operating pressure. The curved line represents critical flaw dimensions at the operating pressure of 780 psig (5.38 MPa). The critical cluster depth using the initial effective length of 4 inches (102 mm) is 72.8% deep. The critical depth at the operating pressure using an effective length of 3.6

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inches (91 mm) is 75.6% deep, a difference of 3.3%. While modest, the 3.3% change in critical depth affects the calculated remaining life.

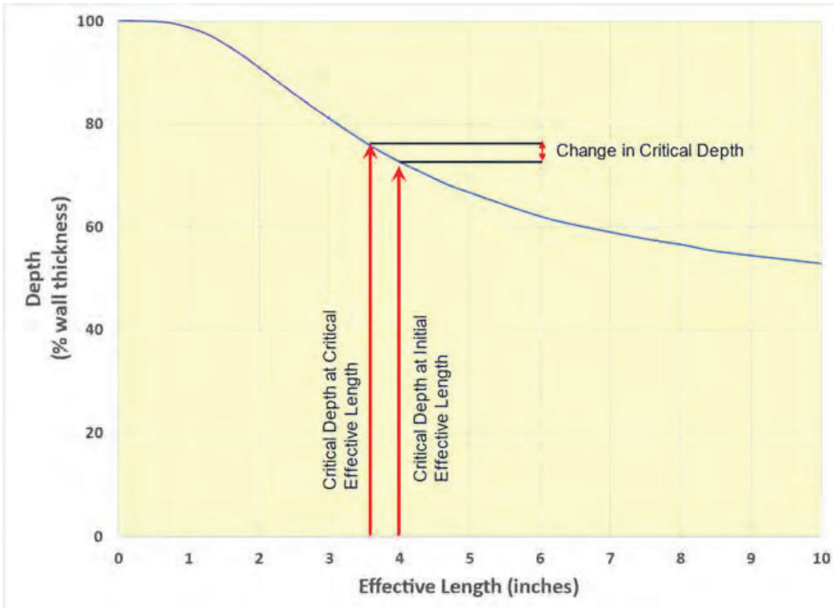

Figure 5. Maximum cluster depth versus effective length considering failure at 780 psig

As shown in Figures 2 through 5, the effective length of an anomaly that is predicted to fail at the operating pressure can be less than the effective length of the initial flaw. Consequently, the critical depth of the cluster that would fail at the operating pressure is larger than the critical depth based on the initial effective length of the cluster.

The prior example highlights three factors that can be important in determining the projected critical depth at failure (i.e., the depth at the operating pressure or MAOP) of clusters reported by ILI:

- The effective length of a cluster is not constant as the cluster depth grows. Calculated effective lengths can decrease as the maximum depth of a cluster grows. The most important effective length is the length that corresponds to potential failure at the local operating pressure of a pipeline.

- The change in effective length depends on assumptions made about how the growth rate varies along the cluster length. Different growth rate assumptions can lead to different effective lengths at the local operating pressure.[2]

- There is a corresponding change in critical (maximum) depth as the effective length changes. The critical depth increases as the effective length decreases. This leads to longer predicted remaining lives when changes in effective length are considered and can have ramifications on how reassessment intervals are established.

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Example

When applying the above method to real-world clusters, it is important to evaluate assumptions regarding the growth rates of the individual anomalies that comprise the cluster. It seems reasonable to assume that very long clusters fail when a portion of the profile reaches a critical state (i.e., when the effective length and depth of some portion of the profile becomes critical). Will the effective length of actual clusters follow the same trends seen for the semi-elliptical cluster discussed earlier?

To partially answer this question, Figure 6 shows an example for a real-world cluster that measured approximately 18 inches (457 mm) in the axial direction and 37% of the wall thickness deep. As before, the pipeline has an MAOP of 780 psig (5.38 MPa or 72% SMYS) and was constructed from X52 steel (359 MPa) steel with a diameter of 24 inches (610 mm) and a wall thickness of 0.250 inches (250 mils or 6.4 mm) (this diameter and wall thickness are used for illustration only and are not the actual diameter and wall thickness).

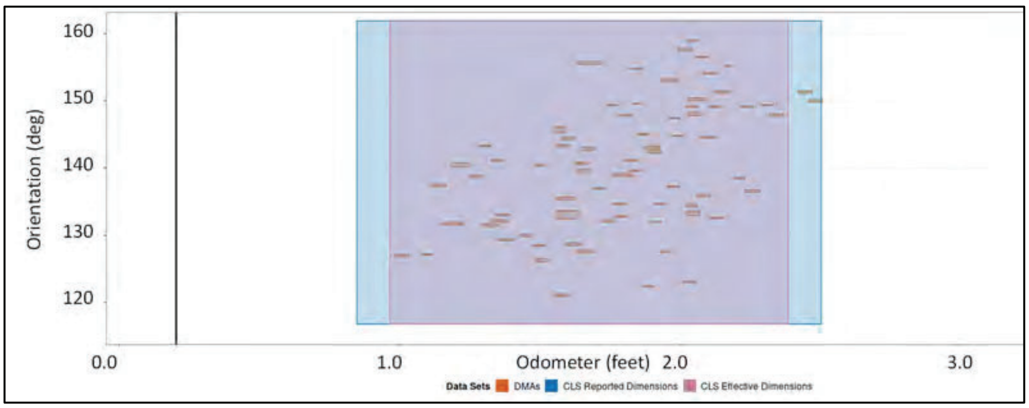

Figure 6. Analysis cluster boxit plot

Figure 7 gives the river-bottom profile for the cluster represented in Figure 6. The initial river-bottom profile is shown in blue near the bottom of the plot. The green (midway) river-bottom profile represents a case where the depth is partway between the initial depth and full wall thickness, and the red river-bottom profile represents the case where the deepest part of the cluster has just reached full wall thickness. In this example, the overall length of the cluster is not growing with depth.

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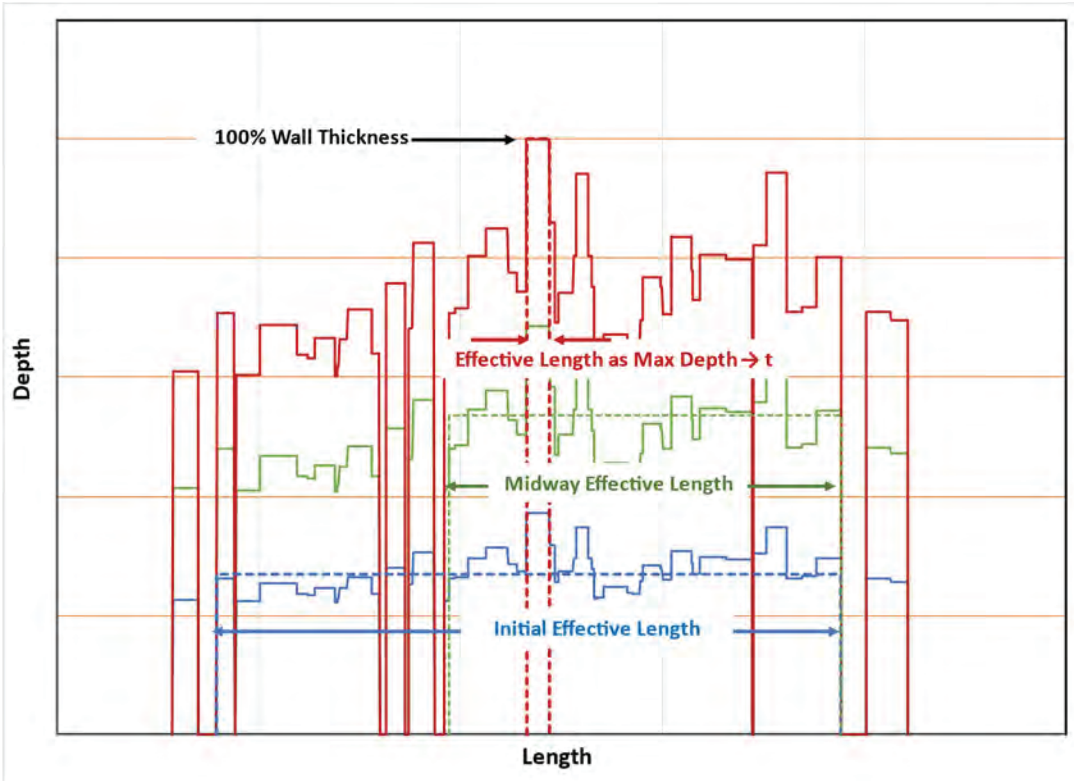

Figure 7. Profiles and effective lengths for 18-inch long cluster, with proportional growth along the cluster length

Figure 7 also shows the effective lengths of each cluster as vertical deashed lines. The effective length decreases from the initial value near the full length to a much shorter value that encompasses only the deepest part of the cluster at the time the depth breaches the wall thickness. As expected, and unlike the semi-ellipse discussed earlier, the change in effective length is not symmetric about the center of the cluster because the cluster itself is not symmetric.

Figure 8 shows the relationship between the maximum depth of the cluster, its effective length, and burst pressure assuming proportional growth (where the growth rate of each anomaly in the cluster increases in proportion to its initial reported depth). Critical flaw sizes were determined at the local MAOP of 780 psig (5.38 MPa). At this pressure, the maximum depth at failure is approximately 63% of the wall thickness with an effective length of 9.7 inches (246 mm). The initial effective length, which corresponds to the reported maximum depth of 37% of the wall thickness, is 15.5 inches (394 mm). Figure 8 also shows how the effective length of the cluster does not always change as growth occurs. This is because the effective length will only change when individual anomalies become added or removed from the group that contributes to failure.

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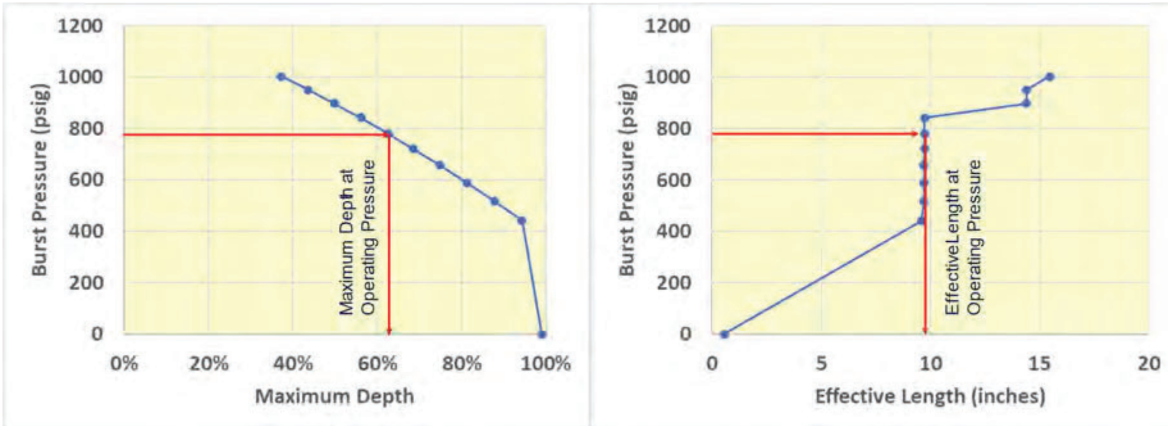

Figure 8. Effective length versus maximum depth example with real-world cluster

Figure 9 compares the critical depth of the effective-length cluster shown above. Here, the y-axis refers to the <u>average</u> depth of the effective area rather than the maximum depth. As mentioned previously, assuming a rectangular shape and using the average depth in remaining life calculations is generally conservative. However, for real-world clusters like this example, a critical flaw curve can only be constructed for idealized shapes.

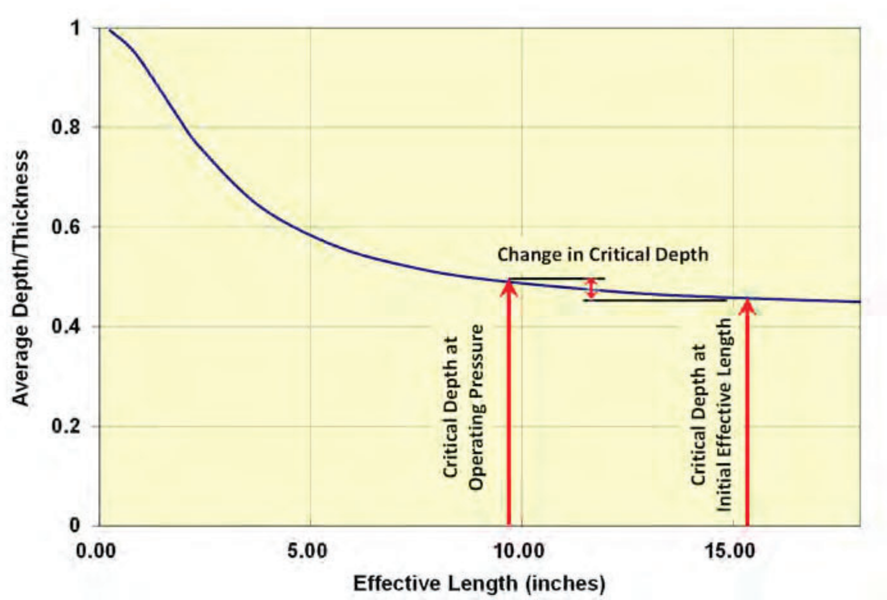

Figure 9. Critical flaw curve at two effective lengths

The average cluster depth assuming proportional growth and an effective length of 15.5 inches (394 mm) is 46%. This cluster has a burst pressure equal to the local MAOP of 780 psig (5.38 MPa). The corresponding average cluster depth at an effective length of 9.7 inches (246 mm) corresponds to an average depth of 49%. Therefore, even taking the conservative approach of assuming a rectangular flaw shape, the critical depth increased by 3% of the wall thickness when considering a decreasing effective length.

Studies are underway to examine the effects of changing effective lengths on more real-world clusters. This will provide insight on how the maximum depths change with decreasing effective lengths,

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similar to the semi-ellipse example above. Real-world clusters can be comprised of as few as two individual metal-loss anomalies to hundreds or thousands of anomalies, and they can range in length from under an inch to hundreds of inches long. Changes in effective lengths, critical depths, and remaining lives are being evaluated. Other areas to be evaluated include assessing the impact of changes in length and width of individual anomalies that comprise the clusters and the impact these changes have on interactions between other nearby clusters or anomalies.

Conclusions

The anomalies comprising a cluster that contribute to failure are not constant as the cluster grows. Consequently, the critical length of the cluster changes, which in turn affects calculated remaining lives. Pipeline operators should consider determining the effective length of a cluster at the operating pressure to more accurately represent conditions under which the pipeline might fail. Reassessment intervals based on effective lengths calculated at local operating pressures should better represent potential future conditions than effective lengths based on current (as found) effective lengths.

Acknowledgments

Thanks to DNV GL USA for its continued support of the developments discussed in this paper.

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https://doi.org/10.52202/072781-0081