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CORROSION ASSESSMENT GUIDANCE FOR HIGH STRENGTH STEELS

(PHASE 1)

Advantica Restricted

Restricted to :US DOT PHMSA, PRCI & Advantica

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EXECUTIVE SUMMARY

The continuing worldwide demand for natural gas presents major challenges to pipeline operators. There is increasing need to construct long distance, high capacity transmission pipelines, particularly in the more remote areas of Arctic North America, Asia, Africa and South America. To achieve satisfactory economic returns on the investment, operators are focusing attention on the use of increasing material strength (pipe grade) that allows for higher operating pressures and smaller pipe diameters, thus reducing the total steel tonnage, transportation costs and the volume of weld metal needed to be applied during pipe installation. Steel making and pipe manufacturing developments during the 1970's and 1980's resulted in the progressive evolution of API 5L Grade X65 to X70 and X80. In North America and Europe, Grade X80 pipelines have gained general acceptance. The economic benefits of further increases in strength have focused attention on the next step increase to Grade X100 and even X120. In the US two major operators have recently announced a joint venture to build a major pipeline using Grade X100 pipe.

Extensive experimental and numerical work has been undertaken to develop methods for assessing the remaining strength of corroded transmission pipelines. These methods, embodied in documents such as ASME B31G, RSTRENG and BS 7910 have, however, only been validated for pipeline materials of grades up to and including X65. The method detailed in BS 7910 is based on the output of a Group Sponsored Project (GSP) led by Advantica in the late 1990's. The method is often referred to as the Line Pipe Corrosion (LPC) method. The output from the GSP also forms the basis of the assessment method described in DNV RP-F101.

As operators start to use higher material strengths, there will be an increasing need to assess the integrity of high strength corroded pipelines. Use of existing assessment methods may be inappropriate for higher strength pipelines. A particular concern is the high yield to tensile (Y/T) ratio of high strength steels; early development Grade X100 materials had (Y/T) values up to 0.98. Although more recent materials have reduced this to some extent, there is still a concern that high strength steels may not have sufficient work hardening capacity, or strain to failure, to ensure that existing assessment methods are appropriate.

This report describes a program of work to extend existing methods to material strengths up to grade X100 using finite element (FE) analyses and validation using full scale testing.

Conclusions

1. For the burst tests on high strength line pipe investigated in this report, standard assessment methods used by the pipeline industry generally give conservative failure predictions. For a small number of test points the ASME B31G, Modified ASME B31G and the LPC-1 methods gave non-conservative failure predictions when used to assess defect depths greater than 50% of the pipe wall. However, for machined defects, particularly those that are rectangular flat bottomed patches the use of ASME B31G and Modified ASME B31G to predict failure pressures may be inappropriate because the area of

metal loss can be underestimated. Therefore the results need to be treated with caution.

2. The RSTRENG method is the most reliable and conservative method for predicting the failure pressure of corroded pipelines. RSTRENG predicts conservative failure pressures for defect depths up to 80% of the pipe wall in line pipe of strength grades up to X100.
3. Modifying the flow stress to equal the arithmetic mean of the specified minimum yield strength and the ultimate tensile strength adds conservatism to the calculated failure predictions.
4. The non-linear FE method gives failure predictions within a scatter band of ±10%, although in a number of cases the failure predictions are non-conservative. This level of scatter is typical. More accurate modeling of the geometry and material properties, to take into account of any through wall variation, should reduce the observed scatter.

Recommendations

1. Burst tests on higher strength pipe have to date only been conducted using machined defects to simulate volumetric corrosion. Predictions of failure pressures using the ASME B31G and Modified ASME B31G methods for machined defects, particularly those that are rectangular flat bottomed patches may be inappropriate because the area of metal loss can be underestimated. It is recommended that a focused program of burst tests are conducted on grade X80 and X100 pipe with corrosion defects that are more representative of those found in the field. Failure pressure predictions using ASME B31G, Modified ASME B31G and RSTRENG should then be compared to the recorded burst test pressures.
2. The results and conclusions described in this report should be reviewed following completion of the work in Phase 2 of Project #153H and when the results from the BP Exploration X100 Operational Trial become available.

CONTENTS

1 INTRODUCTION

The continuing worldwide demand for natural gas presents major challenges to pipeline operators. There is increasing need to construct long distance, high capacity transmission pipelines, particularly in the more remote areas of Arctic North America, Asia, Africa and South America. To achieve satisfactory economic returns on the investment, operators are focusing attention on the use of increasing material strength (pipe grade) that allows for higher operating pressures and smaller pipe diameters, thus reducing the total steel tonnage, transportation costs and the volume of weld metal needed to be applied during pipe installation. Steel making and pipe manufacturing developments during the 1970's and 1980's resulted in the progressive evolution of API 5L Grade X65 to X70 and X80. In North America and Europe, Grade X80 pipelines have gained general acceptance. The economic benefits of further increases in strength have focused attention on the next step increase to Grade X100 and even X120. In the US two major operators have recently announced a joint venture to build a major pipeline using Grade X100 pipe [1].

Extensive experimental and numerical work has been undertaken to develop methods for assessing the remaining strength of corroded transmission pipelines. These methods, embodied in documents such as ASME B31G [2], RSTRENG [3], [4] and BS 7910 [5] have, however, only been validated for pipeline materials of grades up to and including X65. The method detailed in BS 7910 is based on the output of a Group Sponsored Project (GSP) led by Advantica in the late 1990's. The method is often referred to as the Line Pipe Corrosion (LPC) method [6]. The output from the GSP also forms the basis of the assessment method described in DNV RP-F101 [7].

As operators start to use higher material strengths, there will be an increasing need to assess the integrity of high strength corroded pipelines. Use of existing assessment methods may be inappropriate for higher strength pipelines. A particular concern is the high yield to tensile (Y/T) ratio of high strength steels. For cold expanded pipe, API 5L/ISO 3183 [21] states that the (Y/T) ratio should not exceed 0.93 for Grade X80 pipe and 0.97 for Grade X100 pipe. Early development Grade X100 materials had Y/T values up to 0.98. Although more recent materials have reduced this to some extent, there is still a concern that high strength steels may not have sufficient work hardening capacity, or strain to failure, to ensure that existing assessment methods are appropriate.

This report describes a program of work to extend existing methods to material strengths up to grade X100 using burst tests, ring expansion tests and finite element (FE) analyses.

2 ASSESSMENT METHODS USED BY THE PIPELINE INDUSTRY

Existing assessment methods regularly used by the pipeline industry are ASME B31G, Modified ASME B31G, RSTRENG, LPC, BS 7910 and DNV RP-F101. The refinery and petrochemical industry also use API 579-1/ASME FFS-1 [8]. These methods have been developed from the results of a large number of full-scale burst tests on ring expansion and vessel specimens. Some researchers have supplemented their database of full-scale test results with finite element (FE) analyses. A wide range of material properties and pipeline geometries has been investigated. Most of the experimental work considered volumetric corrosion defects, predominantly longitudinally orientated, subject only to internal pressure. Some investigations have been undertaken to study the effect of in-plane bending and axial loading on pipelines. Some tests have also been undertaken on pipes with circumferentially or helically orientated corrosion defects. In the US, the Federal Regulations, CFR 192 [9] and 195 [10] recommend using ASME B31G or RSTRENG.

A brief background to the development of the main assessment methods described above is given in [11].

3 APPROACH

The non-linear finite element (FE) method described in BS 7910 and PRCI's Guidance Document [12] has been routinely used by Advantica to predict the failure pressure of corroded pipelines [13], [14]. The method was also used to develop the LPC method which forms the basis of the assessment methods described in BS 7910 and DNV RP-F101.

The general approach is consistent with a Level 3 assessment described in API 579-1/ASME FFS-1. In agreement with the PRCI project team, the approach taken on this project was as follows:

1. Validate the failure pressures predicted from the FE analyses against available burst test data. It is to be noted that burst test data for Grade X80 and X100 materials is generally not available in the public domain. Advantica has undertaken 8 vessel tests on Grade X80 line pipe for a PRCI member company (National Grid plc). The tests were conducted on 1219.2mm (48-inch) diameter Grade X80 line pipe. Basic details of the test results are given in [11] and are reproduced in Table 1 of this report. In addition, Advantica has undertaken a project on behalf of BP Exploration to investigate the failure behavior of corroded 1320.8mm (52-inch) diameter Grade X100 line pipe, see section 4 below. BP Exploration has agreed to release the burst test results in support of Project #153H. Basic details of the test results are given in [11] and are reproduced in Tables 2 and 3 of this report.

2. Compare the burst test data with failure predictions obtained from the FE analyses and existing methods such as ASME B31G, Modified ASME B31G, RSTRENG and LPC.

3. Based on the above, make recommendations for assessing the remaining strength of corroded pipe up to grade X100.

4 BURST TESTS ON GRADE X80 AND X100 LINE PIPE

Both grade X80 and X100 pipe with real corrosion defects was not available for conducting burst tests. Therefore a series of burst tests were undertaken by Advantica using linepipe with machined defects to simulate volumetric corrosion defects. Tests on 1219.2mm (48-inch) diameter grade X80 line pipe were conducted using 8 full-scale vessels. Two pipe wall thicknesses were tested, 19.89mm (0.783-inch) and 13.79mm (0.543-inch). The test report and interpretation is described in

[15][1]. Basic details of the tests and the recorded failure pressures are summarized in Table 1. The numbering terminology used to identify each test is consistent with that used in [11].

In addition to the burst test program on grade X80 pipe, Advantica has also completed a series of burst tests for BP Exploration to investigate the corrosion defect tolerance of 1320.8mm (52-inch) diameter grade X100 line pipe. Two pipe wall thicknesses were tested, 20.6mm (0.811-inch) and 22.9mm (0.902-inch). Tests were undertaken using both ring expansion specimens and full-scale vessels. The test report and interpretation is described in [16][2]. Briefly, the test program comprised 39 ring expansion tests and 4 full-scale vessel tests. Defects were machined on the external surface of the pipe defects to simulate areas of metal loss. Patch[3], groove[4] and slit[5] type defects were investigated. Basic details of the tests and the recorded failure pressures are summarized in Tables 2 and 3. Once again the numbering terminology used to identify each test is consistent with that used in [11].

5 FAILURE PREDICTIONS USING NON-LINEAR FINITE ELEMENT ANALYSIS

The non-linear FE analysis method described in Annex G of BS 7910 was used to predict the failure pressure of grade X100 line pipe with a single volumetric corrosion defect. A description of the defect dimensions and nomenclature is illustrated in Figure 1. To validate the results of the FE analyses, a selection of the burst tests from the BP Exploration test program described in section 4 was modeled. Due to budget and time constraints the validation was undertaken using a selection of grade X100 tests, primarily because they exhibited high yield to tensile (Y/T) ratios. The validation was undertaken using the results from 4 vessel and 10 ring expansion tests, see Tables 2 and 3. In addition to the comparing failure pressures obtained using the FE method, a comparison of the predicted failure pressures was also made using standard assessment methods such as ASME B31G, Modified ASME B31G, RSTRENG and LPC.

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[1] This is a confidential Advantica report for National Grid and is not available in the public domain.

[2] This is a confidential Advantica report for BP Exploration report and is not available in the public domain.

[3] Patch defects are defined as areas of general metal loss resulting from corrosion, erosion or a combination of both. The area of metal loss is uniformly distributed in the axial and circumferential directions.

[4] Grooves defects are defined as long elongated areas of metal loss caused by directional corrosion and/or erosion. The length of the groove is much greater than the width.

[5] Slit defects are much narrower than the groove or patch defects. They are machined using a wire feed electro-discharge machine (EDM). The diameter of the wire used was 0.1mm (~3.9 mil), giving a final slit width of approximately 0.15mm (5.9 mil).

5.1 Method

Volumetric metal loss corrosion defects in pipelines are generally present as smooth profiled areas with a reduced ligament of the pipe wall. The failure mechanism of this type of defect is dominated by plastic collapse at the remaining ligament. The failure pressure of internally pressurized ductile steel pipe with either local or general metal loss defects, such as corrosion, can be predicted by numerical analysis using the non-linear FE method and a validated failure criterion. Complex flaw shapes and combined loading conditions can be considered in the analysis. This method is described in BS 7910 Annex G [5] and the PRCI Corrosion Assessment Guidance Document [12]. Briefly, the method consists of four major steps as follows:

- Create a finite element model of the corroded pipe or vessel, using information on the flaws detected, the measured material properties, and the structural constraints and applied loads.
- Perform a non-linear, large deformation stress analysis using an appropriate finite element analysis software package and a validated analysis procedure.
- Examine analysis results obtained from the stress analysis.
- Determine the failure or critical pressure value based on the variation of local stress or strain states with reference to a validated failure criterion or test work.

As with any FE simulation, the results obtained are highly dependent upon the assumptions made in the generation of the model, material properties and the prescribed boundary conditions.

5.2 Model Generation

For the vessel models, quarter symmetry, three-dimensional (3D) non-linear FE models were created as shown in Figure 2. This approach takes advantage of symmetry to reduce the size of the FE model, thereby reducing computer run/post-processing times. The models were created using the mesh generating software MSC PATRAN [17] and analyzed using the commercially available finite element code, ABAQUS/Standard [18]. The 3D models were constructed using twenty noded, reduced integration brick elements (ABAQUS type C3D20R). As recommended in Annex G of BS 7910 care was taken to ensure that at least four layers of elements were used through the remaining ligament of each corrosion defect. This was to ensure that the high stress gradients could be predicted with sufficient accuracy in the areas of interest. To ensure that the mesh was fine enough a mesh convergence study was conducted to confirm that the FE model was sufficiently fine. All groove defects were modeled to be round bottomed with spherical ends, the radius of which is equal to the wall thickness, t, so each defect was modeled with a width equal to 2t.

The ring expansion specimens were modeled using two-dimensional (2D), 4 noded plane strain solid elements (ABAQUS type CPE4) with one plane of symmetry, see Figure 3. Patch defects were modeled with a spherical radius to give a circumferential surface width, W, of approximately 4 times the pipe wall thickness. The groove defects were modeled to be round bottomed with spherical ends, the radius of which is equal to the required defect depth, as shown in Figure 1. The slits were modeled with a rounded bottom of radius equal to half the width.

5.3 Loading and Boundary Conditions

Failure pressures were investigated for internal pressure loading only. For each model the load was applied as a monotonically increasing internal pressure, where pressure loads remain normal to the pipe surface throughout the analysis. External loading was not considered.

For the 3D models, symmetry boundary conditions were used to reduce the size of the FE models. Two axes of symmetry were applied to the quarter models, in the x=0 and z=0 planes (see Figure 2). The model was not allowed to rotate, or to expand or contract axially. This simulates a buried pipe in which axial expansion and contraction is restricted by the soil. The model was, however, allowed to expand and contract radially. Rigid body motion was prevented by restraining nodes in the axial direction at the end of the cylinder furthest away from the area of interest. The cylindrical shell was extended sufficiently far away to ensure the application of boundary conditions did not affect stresses in the area of interest.

In order to represent the pipe sections being capped off (as in the full-scale tests, pressure end loads were applied to the unrestrained end of the model.

For the 2D plane strain models, one axis of symmetry was applied in the x=0 plane (see Figure 3). Rigid body motion was prevented by restraining one node in the y direction at the bottom center of the ring, furthest away from the area of interest.

5.4 Material Properties

Stress versus strain curves were obtained for grade X80 and X100 line pipe material. Data from round bar tests was used in preference to data from flattened strap tests. For FE analyses, data from round bar tests is considered more reliable as the Bauschinger effect can influence stress versus strain data from flattened strap tests. The Data for each material grade was obtained as follows:

- **Grade X80**

FE simulations of the burst tests were not conducted for grade X80 pipe. However, for completeness and to aid with comparison with grade X100 materials, stress versus strain curves for X80 material was obtained. Data was obtained from the public domain and from PRCI member companies [15], [20]. The data was obtained from four 812.8mm (32-inch) diameter by 19.05mm (0.75-inch) thick and four 1219.2mm (48-inch) diameter by 15.9mm (5/8-inch); 19.89mm (0.783-inch); 13.79mm (0.534-inch) thick line pipe specimens.

- **Grade X100**

Stress versus strain data for 1320.8mm (52-inch) diameter grade X100 line pipe was available from the BP Exploration test program, see section 4. Data was also available from a Joint Industry Project (JIP) on X100 [19] that was led by Advantica and from published work, primarily from the 2004 ASME International Pipeline Conference (IPC) proceedings [20].

The specified minimum yield strength (SMYS) and tensile strength (SMTS) for Grade X100 pipe is quoted in [21] as 690MPa (100ksi) and 760MPa (110ksi) respectively, with a maximum yield to tensile strength ratio of 0.93. Yield strength is quoted at a total strain of 0.5%, designated as $R_{t0.5}$.

Figure 4 shows a compilation of nominal stress versus strain curves obtained from the sources described above. When defining plasticity data in FE codes such as ABAQUS/Standard, true stress versus true strain data must be used, where zero plastic strain corresponds to the yield point of the material. The equations for true stress and true strain are valid only up to the onset of necking, i.e. the tensile strength of the material. Hence the engineering stress versus strain data used was truncated at this value before being converted to true stress versus true strain data. The data is input into ABAQUS/Standard as a piecewise linear representation. A rate-independent plasticity model using the von Mises yield criterion and isotropic hardening rule was adopted. An isotropic hardening rule is generally used for assessing structures subject to a monotonically increasing load. The ABAQUS documentation recommends use of a kinematic hardening rule when cyclic loading is modeled.

A comparison of the true stress versus true strain curves used for grade X65, X80 and X100 material are shown in Figure 5.

All the analyses were undertaken using a Young's Modulus of 210000 MPa (30460 ksi) and a Poisson's ratio of 0.3.

5.5 Method of Predicting Failure Pressures

The method of predicting failure pressure of corroded pipelines using FE analysis is described in Annex G of BS 7910.

For each model analyzed, the von Mises equivalent stress was monitored at three points through the highest stress portion of the ligament of each defect as the internal pressure in the pipe was increased. As shown in Figure 6, the stress variation with increasing internal pressure exhibits three distinct stages. The first stage is a linear response progressing to a point when the elastic limit is reached. As the pressure continues to increase, a second stage is evident as plasticity spreads through the ligament. The von Mises equivalent stress increases very slowly because of the constraint provided by the surrounding pipe wall. The third phase is dominated by material hardening and begins when the von Mises equivalent stress in the entire ligament exceeds the material's yield strength. Once this stage is reached, the whole ligament deforms plastically but failure does not occur immediately due to strain hardening. Figure 7 shows a typical von Mises equivalent stress contour plot of a pipe with an axially orientated groove defect.

For the analyses described in this report, the failure pressure was determined as that corresponding to the point at which the average von Mises equivalent stress at the ligament was equal to the true ultimate tensile strength of the material; this is consistent with the approach described in Annex G of BS 7910.

6 COMPARISON OF TEST AND FAILURE PRESSURE PREDICTIONS

6.1 Failure Predictions with Flow Stress Unmodified

Figures 8 to 12 show a comparison of the actual failure pressure (P_A) versus the predicted failure pressure (P_f) using the ASME B31G, Modified ASME B31G, RSTRENG, LPC-1 and the non-linear finite element analysis methods. In each case the flow stress is calculated using the specified minimum yield strength or the specified ultimate tensile strength as appropriate. The results are presented in a non-dimensional form. Values of the ratio (P_A/P_f) less than unity indicate a non-conservative failure prediction. Tabulated values of the assessment points are given in Tables 4 to 6.

The following is concluded from the assessments:

1. ASME B31G is conservative for 36 out of the 40 valid[6] test points. Non-conservative predictions are obtained for a relatively deep defect (77.5%) in grade X80 pipe. The remaining three non-conservative predictions are for defects that are for depths 50% and above. One of these test points (INDEX 300) is for a machined slit defect. As discussed in [11], it is debatable whether standard methods for assessing corrosion damage in pipelines are suitable for slit type defects. As also discussed in [11], for machined defects, particularly those that are rectangular flat bottomed patches the use of ASME B31G to predict failure pressures may be inappropriate because the area of metal loss can be underestimated.
2. Modified ASME B31G is conservative for 32 out of the 40 valid test points. Non-conservative predictions for 2 tests on grade X80 pipe. It is also to be noted that for 3 of these points (INDEX 277, 292 and 299), ring expansion testing was used. As discussed in section 4 of [11], the Modified ASME B31G method uses an arbitrary shape factor of 0.85 for the corrosion defect. For tests conducted using ring expansion specimens, where the defect length is infinitely long, use of a shape correction is inappropriate. Therefore, the comparison of burst pressure and predicted failure pressures should be treated with caution. For the cases where non-conservative predictions are obtained, the defect depth is approximately 50% of the wall or deeper.
3. RSTRENG is conservative for 39 out of 40 valid test points. For the one test point (INDEX 299) where a non-conservative failure prediction was obtained, this was for a deep (77% of the pipe wall) machined slit defect, i.e. similar to a sharp crack-like defect. It is debatable whether existing assessment methods for assessing corrosion damage in pipelines are suitable for this type of defect.

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[6] Validity of the test points is based on the defect depth. The ASME B31G, Modified ASME B31G and RSTRENG methods are valid for assessing defect depths up to 80% of the pipe wall. The LPC-1 method is valid for assessing defect depths up to 85% of the pipe wall.

4. LPC-1 is conservative for 45 out of the 49 valid test points. One of these test points is for a relatively deep defect (78.2% of the pipe wall) in grade X80 pipe. Out of the three remaining points, one is very close to unity; another point is for INDEX 299, see above and should be discounted. The final test point is for a 50% deep groove defect in grade X100 pipe.
5. The non-linear FE method is conservative for 6 out of the 14 tests that were modeled. However, in the majority of cases the failure predictions are only marginally non-conservative. 3 of most marked non-conservative predictions are obtained for slit defects (INDEX 289, 294 and 298) and as discussed previously it is debatable whether standard methods for assessing corrosion damage in pipelines are suitable for slit type defects. The comparison of tests with slit defects should therefore be discounted. The remaining failure predictions are within ±10% of the actual failure pressure. This is consistent with the level of scatter observed for lower strength grades and can be explained by the fact that the FE method is based on an idealized geometry, both of the pipe and the defect. In reality, there may be some ovality in the test pipe and/or local variation in the wall thickness. There may also be local variations in material properties, around the circumference and through the pipe wall. A through wall variation in tensile properties is not unexpected for high strength steels due to the potential differences in cooling rates during plate manufacture. Variations in strain during the U and O stages of the pipe forming process may also add to these variations. An investigation of the variation in tensile properties of grade X100 pipe is the subject of the study in Phase 2 of Project #153H. Once these factors have been taken into account, it is judged that failure predictions, for smooth groove and patch like defects, using the FE method will be in very good agreement with actual burst pressures.

6.2 Failure Predictions with Flow Stress Modified

As discussed in [11][7], the flow stress is not a precisely defined parameter; its magnitude lies somewhere between the yield strength and ultimate tensile strength of the material. Some operators impose additional requirements on the material properties for higher strength line pipe. For example if the (Y/T) ratio is limited to 0.9 for grade X80 line pipe, then the minimum tensile strength is equal to 1.11 times the specified minimum yield strength. Using the definitions of flow stress as appropriate for each assessment method, the following is obtained for grade X80 line pipe:

Assessment Method	**Yield Strength (ksi)**	**Tensile Strength (ksi)**	**Flow Stress (ksi)**
ASME B31G	80	89	88

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[7] More details regarding the concept of the flow stress and the definitions used for the ASME B31G, Modified ASME B31G, RSTRENG, LPC, SHELL92 and PCORRC assessment methods is given in [11].

Mod ASME B31G	80	89	90
RSTRENG	80	89	90
LPC-1	80	89	89

In this example, the flow stress is calculated to be greater than the tensile strength for the Modified ASME B31G and RSTRENG methods. Care is therefore required in how the methods are used when assessing corrosion defects in higher strength pipelines. In the fitness-for-purpose standard, BS 7910 [5], the flow stress is defined as the arithmetic mean of the yield strength and tensile strength up to a value of 1.2 times the yield strength. The effect of the modification is that the flow stress will always be calculated to be less than the tensile strength. To investigate the sensitivity of the failure predictions, the flow stress definition was modified to that recommended in BS 7910.

Figures 13 to 16 show a comparison of the actual failure pressure (P_A) versus the predicted failure pressure (P_f) using the ASME B31G, Modified ASME B31G, RSTRENG and LPC-1 methods. The main conclusion drawn from the study is that the calculated failure predictions are more conservative when the flow stress is modified according to that given in BS 7910.

7 DISCUSSION

The results of the study described in this report have shown that for the majority of cases, existing methods used by the pipeline industry can be used to assess volumetric corrosion defects in pipelines of strength grades up to X100. However, for a small number of tests, non-conservative failure predictions were obtained. In particular, the ASME B31G, Modified ASME B31G and the LPC-1 methods gave non-conservative failure predictions when assessing defect depths greater than 50% of the pipe wall. As discussed in [11], for machined defects, particularly those that are rectangular flat bottomed patches the use of ASME B31G and Modified ASME B31G to predict failure pressures may be inappropriate because the area of metal loss can be underestimated. Therefore these results need to be treated with caution. It is recommended that a focused program of full-scale burst tests are conducted using high strength pipe (Grade X80 and X100) with simulated defects that represent real corrosion damage in the field. More realistic corrosion defects could be produced by a number of methods. Starting with a flat bottomed machined defect, corrosion features could be produced by either treating an area of the pipe with a mineral acid such as hydrochloric acid (HCl) or by accelerating corrosion by simulated ground water (e.g. NS4 solution) using electrochemical methods. In either case a realistic corroded surface would be produced which would better simulate an actual service defect compared to a machined defect. Failure pressure predictions using ASME B31G, Modified ASME B31G and RSTRENG should then be compared to the recorded burst test pressures.

The non-linear FE method generally gave failure predictions within a scatter band of ±10%, although it is noted that in the majority of the cases the failure predictions are marginally non-conservative. The most marked non-conservative failure predictions were obtained for relatively deep slit defects. It is debatable whether standard methods for assessing corrosion damage in pipelines are suitable for slit type defects and these results should be discounted.

More accurate modeling of the geometry and material properties, possibly to take into account the through wall variation, should reduce the observed scatter in the failure predictions. In Phase 2 of Project #153H, the through wall variation of material properties in grade X100 pipe will be investigated. It is recommended that once the outcome of this work is known and when the results of the BP X100 Operational Trial [22], [23] become available, failure predictions described in this report using the FE method are revisited.

A further concern is that for higher strength steels, the (Y/T) ratio starts to rise. API 5L/ISO 3183 stipulates limits of 0.93 and 0.97 for Grade X80 and X100 respectively. Depending on the assessment method used, the flow stress definition when applied to assessing higher strength steels can exceed the tensile strength. When the flow stress is modified to equal the arithmetic mean of the specified minimum yield strength and the specified minimum tensile strength, the calculated failure pressure is more conservative.

The RSTRENG method proved to be the most reliable and conservative method. This conclusion is consistent with that obtained for the much larger test database of material grades from A25 to X100 investigated in [11]. As discussed in [11], the SHELL92 method[8] [24], which is a modified version of the ASME B31G method, conservatively predicts failure pressures for corrosion defects up to 80% deep in line pipe of strength grade up to X100.

8 CONCLUSIONS

1. For the burst tests on high strength line pipe investigated in this report, standard assessment methods used by the pipeline industry generally give conservative failure predictions. For a small number of test points the ASME B31G, Modified ASME B31G and the LPC-1 methods gave non-conservative failure predictions when used to assess defect depths greater than 50% of the pipe wall. However, for machined defects, particularly those that are rectangular flat bottomed patches the use of ASME B31G and Modified ASME B31G to predict failure pressures may be inappropriate because the area of metal loss can be underestimated. Therefore the results need to be treated with caution.
2. The RSTRENG method is the most reliable and conservative method for predicting the failure pressure of corroded pipelines. RSTRENG predicts conservative failure pressures for defect depths up to 80% of the pipe wall in line pipe of strength grades up to X100.

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[8] The SHELL92 method uses the same Folias (bulging correction) factor as that used by ASME B31G. The shape of the defect is modified from parabolic to rectangular and the flow stress is modified to equal 0.9 times the specified minimum tensile strength.

3. Modifying the flow stress to equal the arithmetic mean of the specified minimum yield strength and the ultimate tensile strength adds conservatism to the calculated failure predictions.
4. The non-linear FE method gives failure predictions within a scatter band of ±10%, although in a number of cases the failure predictions are non-conservative. This level of scatter is typical. More accurate modeling of the geometry and material properties, to take into account of any through wall variation, should reduce the observed scatter.

9 RECOMMENDATIONS

1. Burst tests on higher strength pipe have to date only been conducted using machined defects to simulate volumetric corrosion. Predictions of failure pressures using the ASME B31G and Modified ASME B31G methods for machined defects, particularly those that are rectangular flat bottomed patches may be inappropriate because the area of metal loss can be underestimated. It is recommended that a focused program of burst tests are conducted on grade X80 and X100 pipe with corrosion defects that are more representative of those found in the field. Failure pressure predictions using ASME B31G, Modified ASME B31G and RSTRENG should then be compared to the recorded burst test pressures.
2. The results and conclusions described in this report should be reviewed following completion of the work in Phase 2 of Project #153H and when the results from the BP Exploration X100 Operational Trial become available.

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INDEX	Source Reference	Grade	D/t	Defect Type	$\frac{L}{\sqrt{Dt}}$	$\frac{d}{t}$	$\frac{\text{YS}}{\text{SMYS}}$	$\frac{\text{UTS}}{\text{SMTS}}$	$\frac{\text{YS}}{\text{UTS}}$	Failure Mode	Failure Pressure (MPa)
INDEX 255	ADVANTICA P1V1A	X80	60.1	Machined (AG)	3.890	0.775	1.060	1.166	0.808	R	7.6
INDEX 256	ADVANTICA P1V1B	X80	60.1	Machined (AS)	3.877	0.207	1.060	1.166	0.808	R	21.4
INDEX 257	ADVANTICA P1V2A	X80	60.1	Machined (AG)	3.890	0.374	1.073	1.179	0.809	R	17.7
INDEX 258	ADVANTICA P1V2B	X80	60.1	Machined (AG)	3.903	0.089	1.073	1.179	0.809	R	23.3
INDEX 259	ADVANTICA P2V1A	X80	81.8	Machined (AG)	4.538	0.782	1.030	1.149	0.797	R	4.7
INDEX 260	ADVANTICA P2V1B	X80	81.8	Machined (AS)	4.450	0.167	1.030	1.149	0.797	R	15.3
INDEX 261	ADVANTICA P2V2A	X80	81.8	Machined (AG)	4.546	0.395	1.068	1.191	0.797	R	12.0
INDEX 262	ADVANTICA P2V2B	X80	81.8	Machined (AG)	4.523	0.112	1.068	1.191	0.797	R	16.1

Table 1. Test Results on Grade X80 Line Pipe

Notes

1. INDEX numbers are consistent with those used in Reference [11].
2. AG = axial groove and AS = axial slit

INDEX	Source Reference	Grade	D/t	Defect Type	$\frac{L}{\sqrt{Dt}}$	$\frac{d}{t}$	$\frac{\mathrm{YS}}{\mathrm{SMYS}}$	$\frac{\mathrm{UTS}}{\mathrm{SMTS}}$	$\frac{\mathrm{YS}}{\mathrm{UTS}}$	Failure Mode	Failure Pressure (MPa)
INDEX 263	ADVANTICA HKL-R03	X100	57.7	Machined (P)	146.332	0.111	1.134	1.057	0.976	R	27.0
INDEX 264	ADVANTICA HKL-R04	X100	57.7	Machined (P)	146.332	0.099	1.134	1.057	0.976	N/A	27.7
INDEX 265	ADVANTICA HKL-R05	X100	57.7	Machined (P)	146.396	0.101	1.134	1.057	0.976	R	27.5
INDEX 266	ADVANTICA HKL-R06	X100	57.6	Machined (P)	146.300	0.294	1.134	1.057	0.976	R	21.3
INDEX 267	ADVANTICA HKL-R07	X100	57.9	Machined (P)	146.588	0.294	1.134	1.057	0.976	R	21.8
INDEX 268	ADVANTICA HKL-R08	X100	57.9	Machined (P)	146.588	0.287	1.134	1.057	0.976	R	22.0
INDEX 269	ADVANTICA HKL-R09	X100	57.8	Machined (P)	146.372	0.502	1.134	1.057	0.976	R	15.9
INDEX 270	ADVANTICA HKL-R10	X100	57.8	Machined (P)	146.404	0.497	1.134	1.057	0.976	R	15.7
INDEX 271	ADVANTICA HKL-R11	X100	57.8	Machined (P)	146.460	0.502	1.134	1.057	0.976	R	15.9
INDEX 272	ADVANTICA HKL-R12	X100	57.7	Machined (P)	146.308	0.809	1.134	1.057	0.976	R	6.2
INDEX 273	ADVANTICA HKL-R13	X100	57.8	Machined (P)	146.492	0.833	1.134	1.057	0.976	R	5.5
INDEX 274	ADVANTICA HKL-R14	X100	57.8	Machined (P)	146.372	0.814	1.134	1.057	0.976	R	6.4
INDEX 275	ADVANTICA HKB-R01	X100	63.9	Machined (P)	154.075	0.102	1.134	1.057	0.976	R	23.2
INDEX 276	ADVANTICA HKB-R02	X100	63.9	Machined (P)	154.171	0.286	1.134	1.057	0.976	R	18.9
INDEX 277	ADVANTICA HKB-R03	X100	63.9	Machined (P)	154.075	0.503	1.134	1.057	0.976	R	13.2
INDEX 278	ADVANTICA HKB-R04	X100	63.9	Machined (P)	154.075	0.807	1.134	1.057	0.976	R	5.1
INDEX 279	ADVANTICA HKL-R15	X100	57.9	Machined (AG)	146.620	0.204	1.134	1.057	0.976	R	25.0
INDEX 280	ADVANTICA HKL-R16	X100	58.0	Machined (AG)	146.597	0.204	1.134	1.057	0.976	R	25.7
INDEX 281	ADVANTICA HKL-R17	X100	57.8	Machined (AG)	146.492	0.508	1.134	1.057	0.976	R	16.0
INDEX 282	ADVANTICA HKL-R18	X100	57.9	Machined (AG)	146.588	0.499	1.134	1.057	0.976	R	16.2

Table 2. Test Results on Grade X100 Line Pipe

Notes

1. INDEX numbers are consistent with those used in Reference [11].
2. P = Patch and AG = axial groove.
3. All results obtained using ring expansion testing.

INDEX	Source Reference	Grade	D/t	Defect Type	$\frac{L}{\sqrt{Dt}}$	$\frac{d}{t}$	$\frac{\mathrm{YS}}{\mathrm{SMYS}}$	$\frac{\mathrm{UTS}}{\mathrm{SMTS}}$	$\frac{\mathrm{YS}}{\mathrm{UTS}}$	Failure Mode	Failure Pressure (MPa)
INDEX 283	ADVANTICA HKL-R19	X100	57.8	Machined(AG)	146.524	0.810	1.134	1.057	0.976	R	6.3
INDEX 284	ADVANTICA HKL-R20	X100	57.9	Machined(AG)	146.468	0.811	1.134	1.057	0.976	R	6.3
INDEX 285	ADVANTICA HKB-R05	X100	63.8	Machined(AG)	154.096	0.207	1.134	1.057	0.976	R	21.8
INDEX 286	ADVANTICA HKB-R06	X100	63.8	Machined(AG)	153.888	0.504	1.134	1.057	0.976	R	14.3
INDEX 287	ADVANTICA HKB-R07	X100	63.9	Machined(AG)	154.075	0.818	1.134	1.057	0.976	R	5.1
INDEX 288	ADVANTICA HKL-R21	X100	57.7	Machined(AS)	146.276	0.099	1.134	1.057	0.976	L	28.6
INDEX 289	ADVANTICA HKL-R22	X100	57.7	Machined(AS)	146.340	0.102	1.134	1.057	0.976	L	28.2
INDEX 290	ADVANTICA HKL-R23	X100	57.7	Machined(AS)	146.332	0.301	1.134	1.057	0.976	L	22.5
INDEX 291	ADVANTICA HKL-R24	X100	57.7	Machined(AS)	146.396	0.306	1.134	1.057	0.976	L	22.1
INDEX 292	ADVANTICA HKL-R25	X100	57.7	Machined(AS)	146.332	0.488	1.134	1.057	0.976	R	15.1
INDEX 293	ADVANTICA HKL-R26	X100	57.8	Machined(AS)	146.492	0.507	1.134	1.057	0.976	R	15.5
INDEX 294	ADVANTICA HKL-R27	X100	57.7	Machined(AS)	146.308	0.804	1.134	1.057	0.976	R	5.6
INDEX 295	ADVANTICA HKL-R28	X100	57.7	Machined(AS)	146.244	0.808	1.134	1.057	0.976	R	5.7
INDEX 296	ADVANTICA HKB-R08	X100	63.7	Machined(AS)	153.851	0.111	1.134	1.057	0.976	L	24.6
INDEX 297	ADVANTICA HKB-R09	X100	63.8	Machined(AS)	154.059	0.309	1.134	1.057	0.976	L	19.4
INDEX 298	ADVANTICA HKB-R10	X100	63.4	Machined(AS)	153.444	0.493	1.134	1.057	0.976	R	14.2
INDEX 299	ADVANTICA HKB-R11	X100	63.8	Machined(AS)	153.888	0.769	1.134	1.057	0.976	R	5.1
INDEX 300	ADVANTICA HKL V01	X100	57.9	Machined (P)	3.503	0.496	1.134	1.057	0.976	R	18.1
INDEX 301	ADVANTICA HKK V01	X100	57.9	Machined (P)	6.384	0.500	1.134	1.057	0.976	R	15.4
INDEX 302	ADVANTICA HKL V02	X100	57.9	Machined(AG)	2.962	0.503	1.134	1.057	0.976	R	17.9
INDEX 303	ADVANTICA HKK V02	X100	57.8	Machined(AG)	5.825	0.500	1.134	1.057	0.976	R	15.0

Table 3. Test Results on Grade X100 Line Pipe

Notes

1. INDEX numbers are consistent with those used in Reference [11].
2. P = Patch; AG = axial groove; and AS = axial slit.
3. INDEX 300, 301, 302 and 303 results obtained using vessel tests. The remaining results obtained using ring expansion testing.

INDEX	Source Reference	Grade	D/t	Defect Type	$\frac{L}{\sqrt{Dt}}$	d/t (actual)	ASME B31G P_A/P_f	Mod ASME B31G P_A/P_f	RSTRENG P_A/P_f	LPC-1 P_A/P_f	FE P_A/P_f
INDEX 255	ADVANTICA P1V1A	X80	60.1	Machined	3.890	0.775	0.670	0.853	1.232	1.088	-
INDEX 256	ADVANTICA P1V1B	X80	60.1	Machined	3.877	0.207	1.183	1.186	1.220	1.173	-
INDEX 257	ADVANTICA P1V2A	X80	60.1	Machined	3.890	0.374	1.090	1.131	1.208	1.138	-
INDEX 258	ADVANTICA P1V2B	X80	60.1	Machined	3.903	0.089	1.210	1.195	1.207	1.176	-
INDEX 259	ADVANTICA P2V1A	X80	81.8	Machined	4.538	0.782	1.443	0.745	1.099	0.993	-
INDEX 260	ADVANTICA P2V1B	X80	81.8	Machined	4.450	0.167	1.128	1.127	1.152	1.120	-
INDEX 261	ADVANTICA P2V2A	X80	81.8	Machined	4.546	0.395	1.340	1.080	1.164	1.106	-
INDEX 262	ADVANTICA P2V2B	X80	81.8	Machined	4.523	0.112	1.221	1.139	1.155	1.130	-

Table 4. Comparison of Failure Predictions for the Grade X80 Tests

Notes

1. INDEX numbers are consistent with those used in Reference [11].

INDEX	Source Reference	Grade	D/t	Defect Type	$\frac{L}{\sqrt{Dt}}$	d/t	ASME B31G	Mod ASME B31G	RSTRENG	LPC-1	FE
						(actual)	P_A/P_f	P_A/P_f	P_A/P_f	P_A/P_f	P_A/P_f
INDEX 263	ADVANTICA HKL-R03	X100	57.7	Machined	146.332	0.111	1.164	1.141	1.162	1.142	-
INDEX 264	ADVANTICA HKL-R04	X100	57.7	Machined	146.332	0.099	1.168	1.147	1.166	1.146	-
INDEX 265	ADVANTICA HKL-R05	X100	57.7	Machined	146.396	0.101	1.165	1.144	1.164	1.144	-
INDEX 266	ADVANTICA HKL-R06	X100	57.6	Machined	146.300	0.294	1.146	1.077	1.145	1.122	0.922
INDEX 267	ADVANTICA HKL-R07	X100	57.9	Machined	146.588	0.294	1.179	1.108	1.177	1.154	-
INDEX 268	ADVANTICA HKL-R08	X100	57.9	Machined	146.588	0.287	1.178	1.109	1.176	1.153	-
INDEX 269	ADVANTICA HKL-R09	X100	57.8	Machined	146.372	0.502	1.217	1.056	1.216	1.188	-
INDEX 270	ADVANTICA HKL-R10	X100	57.8	Machined	146.404	0.497	1.192	1.037	1.191	1.164	-
INDEX 271	ADVANTICA HKL-R11	X100	57.8	Machined	146.460	0.502	1.215	1.055	1.215	1.187	-
INDEX 272	ADVANTICA HKL-R12	X100	57.7	Machined	146.308	0.809	Invalid	Invalid	Invalid	1.196	1.028
INDEX 273	ADVANTICA HKL-R13	X100	57.8	Machined	146.492	0.833	Invalid	Invalid	Invalid	1.220	-
INDEX 274	ADVANTICA HKL-R14	X100	57.8	Machined	146.372	0.814	Invalid	Invalid	Invalid	1.265	-
INDEX 275	ADVANTICA HKB-R01	X100	63.9	Machined	154.075	0.102	1.091	1.071	1.089	1.072	0.989
INDEX 276	ADVANTICA HKB-R02	X100	63.9	Machined	154.171	0.286	1.114	1.050	1.113	1.093	-
INDEX 277	ADVANTICA HKB-R03	X100	63.9	Machined	154.075	0.503	1.118	0.970	1.117	1.094	0.950
INDEX 278	ADVANTICA HKB-R04	X100	63.9	Machined	154.075	0.807	Invalid	Invalid	Invalid	1.086	-
INDEX 279	ADVANTICA HKL-R15	X100	57.9	Machined	146.620	0.204	1.199	1.153	1.198	1.175	0.951
INDEX 280	ADVANTICA HKL-R16	X100	58.0	Machined	146.597	0.204	1.235	1.188	1.234	1.211	-
INDEX 281	ADVANTICA HKL-R17	X100	57.8	Machined	146.492	0.508	1.238	1.071	1.237	1.209	-
INDEX 282	ADVANTICA HKL-R18	X100	57.9	Machined	146.588	0.499	1.230	1.069	1.229	1.201	-

Table 5. Comparison of Failure Predictions for the Grade X100 Tests

Notes

1. INDEX numbers are consistent with those used in Reference [11].

INDEX	Source Reference	Grade	D/t	Defect Type	$\frac{L}{\sqrt{Dt}}$	d/t	ASME B31G	Mod ASME B31G	RSTRENG	LPC-1	FE
						(actual)	P_A/P_f	P_A/P_f	P_A/P_f	P_A/P_f	P_A/P_f
INDEX 283	ADVANTICA HKL-R19	X100	57.8	Machined	146.524	0.810	Invalid	Invalid	Invalid	1.235	1.005
INDEX 284	ADVANTICA HKL-R20	X100	57.9	Machined	146.468	0.811	Invalid	Invalid	Invalid	1.235	-
INDEX 285	ADVANTICA HKB-R05	X100	63.8	Machined	154.096	0.207	1.156	1.111	1.154	1.135	-
INDEX 286	ADVANTICA HKB-R06	X100	63.8	Machined	153.888	0.504	1.212	1.051	1.212	1.186	0.984
INDEX 287	ADVANTICA HKB-R07	X100	63.9	Machined	154.075	0.818	Invalid	Invalid	Invalid	1.155	-
INDEX 288	ADVANTICA HKL-R21	X100	57.7	Machined	146.276	0.099	1.206	1.185	1.205	1.184	-
INDEX 289	ADVANTICA HKL-R22	X100	57.7	Machined	146.340	0.102	1.196	1.174	1.194	1.174	0.966
INDEX 290	ADVANTICA HKL-R23	X100	57.7	Machined	146.332	0.301	1.223	1.148	1.222	1.198	-
INDEX 291	ADVANTICA HKL-R24	X100	57.7	Machined	146.396	0.306	1.213	1.136	1.212	1.187	-
INDEX 292	ADVANTICA HKL-R25	X100	57.7	Machined	146.332	0.488	1.118	0.978	1.118	1.092	-
INDEX 293	ADVANTICA HKL-R26	X100	57.8	Machined	146.492	0.507	1.197	1.036	1.196	1.169	-
INDEX 294	ADVANTICA HKL-R27	X100	57.7	Machined	146.308	0.804	Invalid	Invalid	Invalid	1.058	0.863
INDEX 295	ADVANTICA HKL-R28	X100	57.7	Machined	146.244	0.808	Invalid	Invalid	Invalid	1.090	-
INDEX 296	ADVANTICA HKB-R08	X100	63.7	Machined	153.851	0.111	1.163	1.140	1.161	1.143	-
INDEX 297	ADVANTICA HKB-R09	X100	63.8	Machined	154.059	0.309	1.182	1.107	1.181	1.159	-
INDEX 298	ADVANTICA HKB-R10	X100	63.4	Machined	153.444	0.493	1.169	1.020	1.169	1.144	0.896
INDEX 299	ADVANTICA HKB-R11	X100	63.8	Machined	153.888	0.769	0.931	0.621	0.931	0.909	-
INDEX 300	ADVANTICA HKL V01	X100	57.9	Machined	3.503	0.496	0.931	1.021	1.136	1.045	1.027
INDEX 301	ADVANTICA HKK V01	X100	57.9	Machined	6.384	0.500	1.175	0.927	1.047	0.999	1.048
INDEX 302	ADVANTICA HKL V02	X100	57.9	Machined	2.962	0.503	0.909	0.992	1.101	1.001	1.299
INDEX 303	ADVANTICA HKK V02	X100	57.8	Machined	5.825	0.500	1.145	0.897	1.012	0.960	1.087

Table 6. Comparison of Failure Predictions for the Grade X100 Tests

Notes

1. INDEX numbers are consistent with those used in Reference [11].

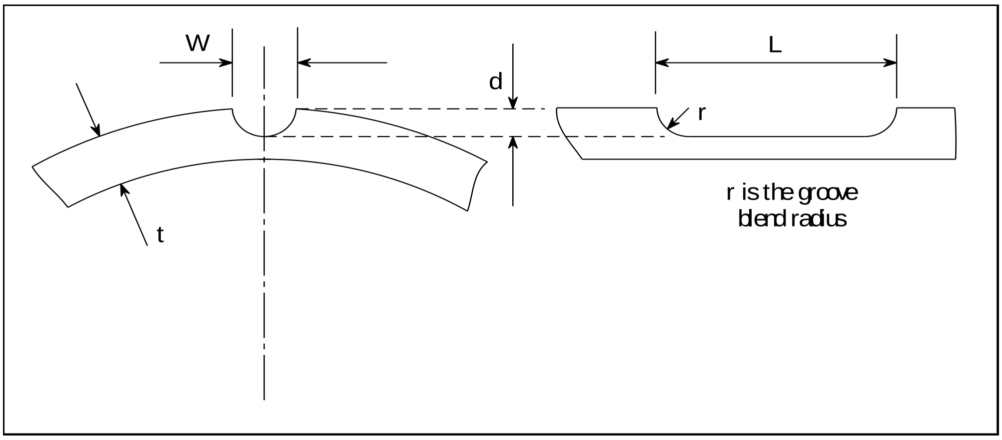


Figure 1. Defect Dimensions

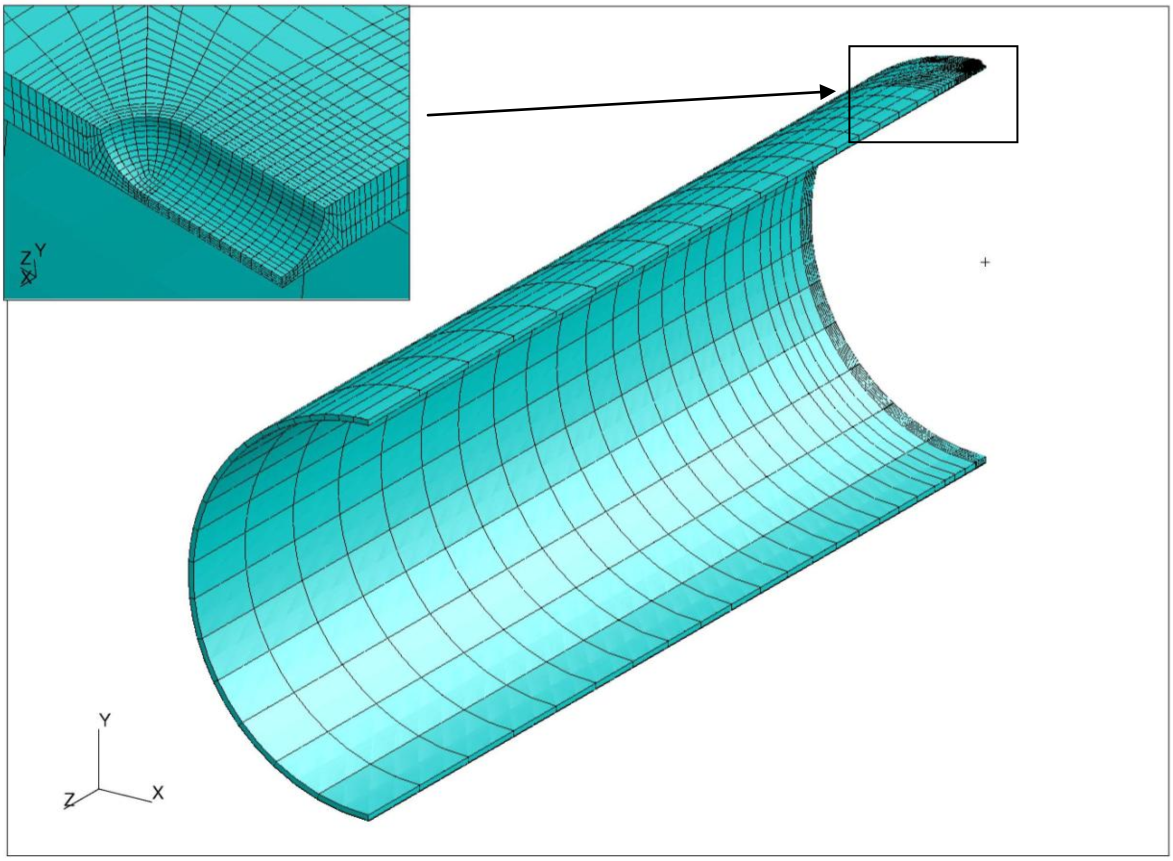
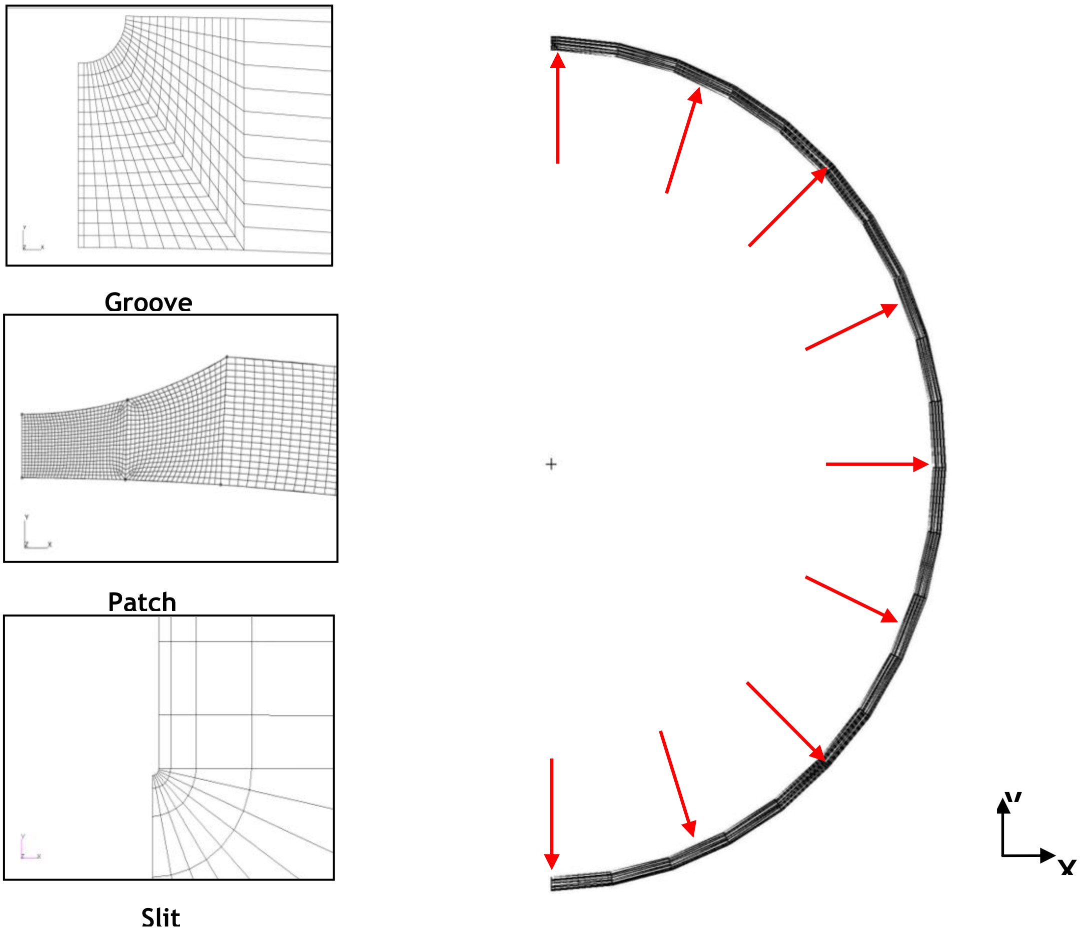


Figure 2. Typical 3D Quarter Symmetry FE Model of a Pipeline with an Axial Groove Defect


Groove

Patch

Slit

Figure 3. 2D Plane Strain FE Models of the Ring Expansion Tests

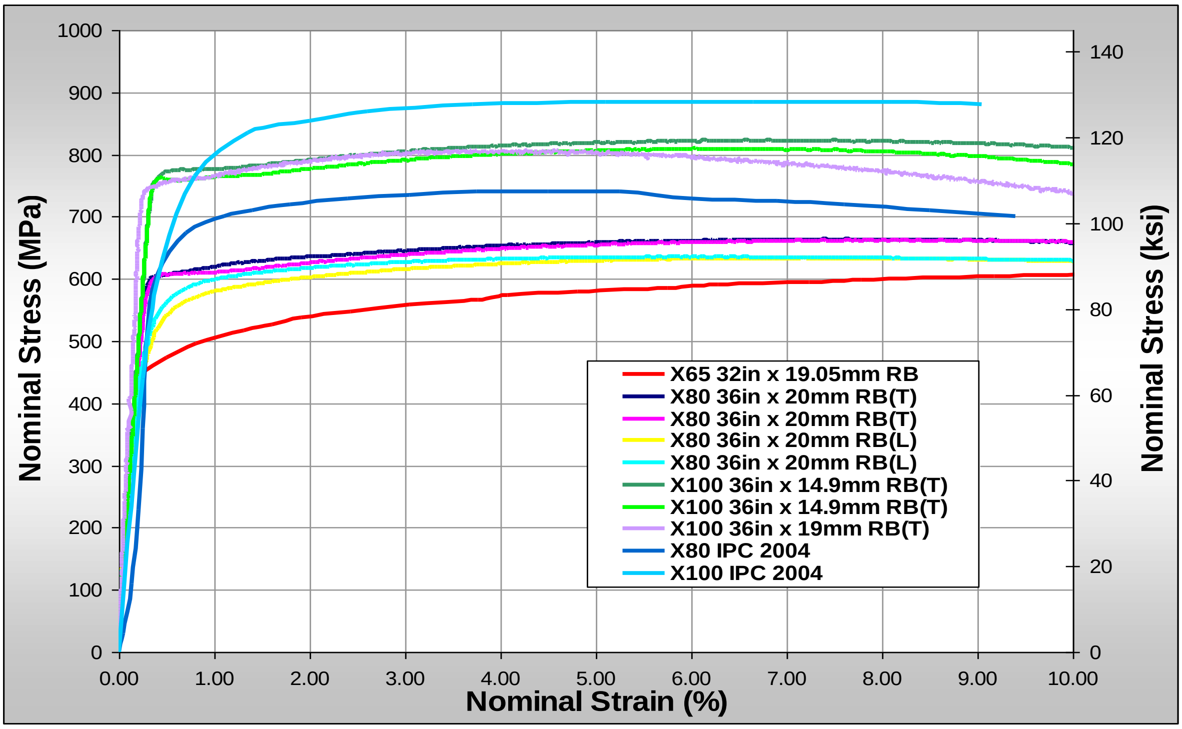


Figure 4. Stress versus Strain Curves for Grade X65, X80 and X100 Line Pipe

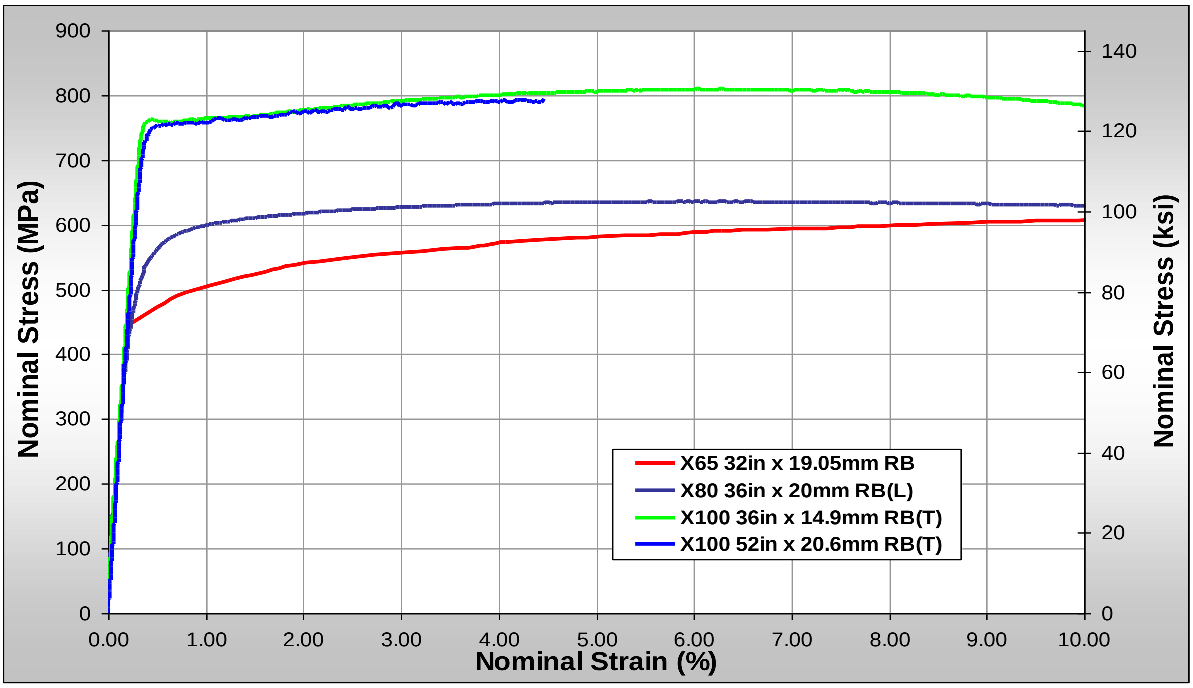


Figure 5. True Stress versus True Strain Curves for Grade X65, X80 and X100 Line Pipe

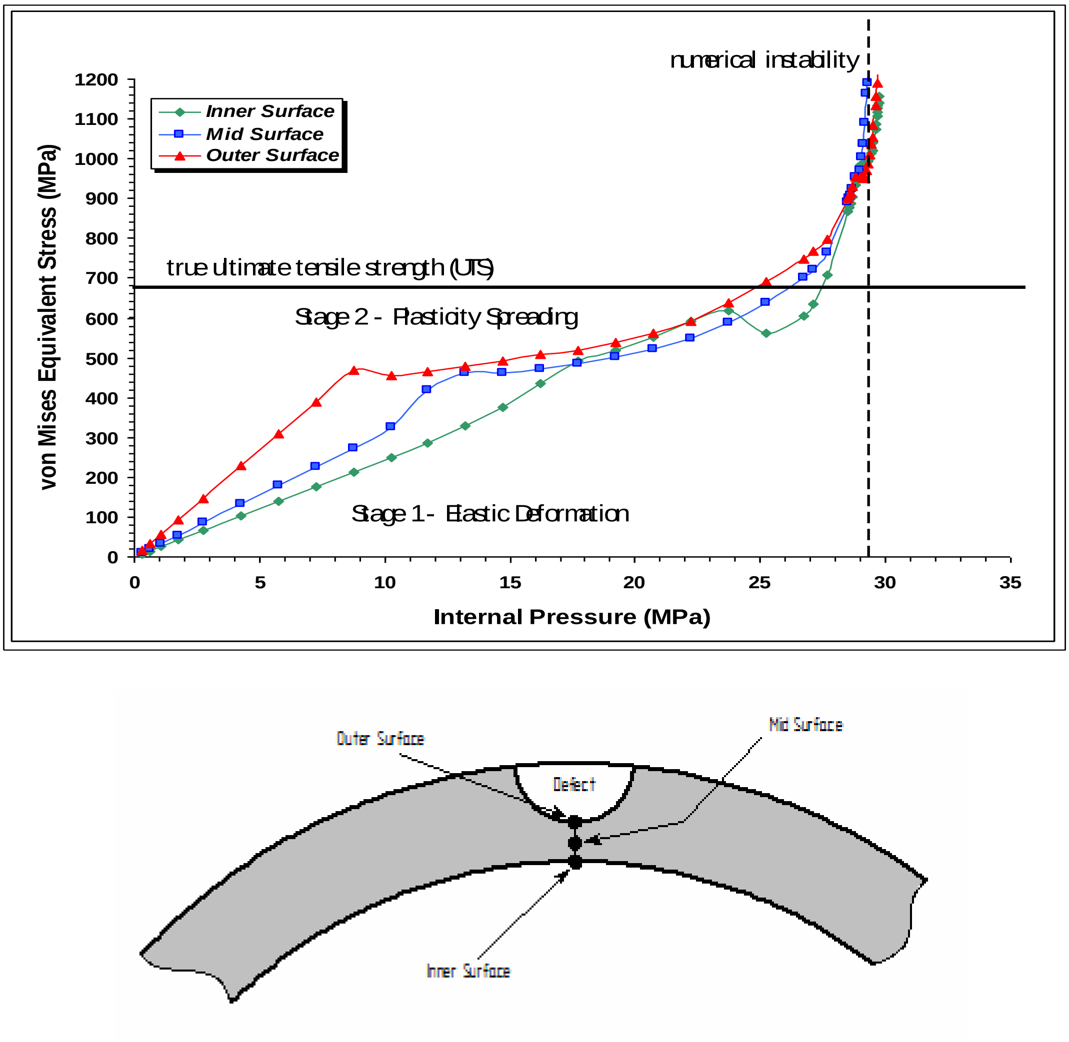


Figure 6. von Mises Equivalent Stress Variation Through Ligament with Increasing Internal Pressure

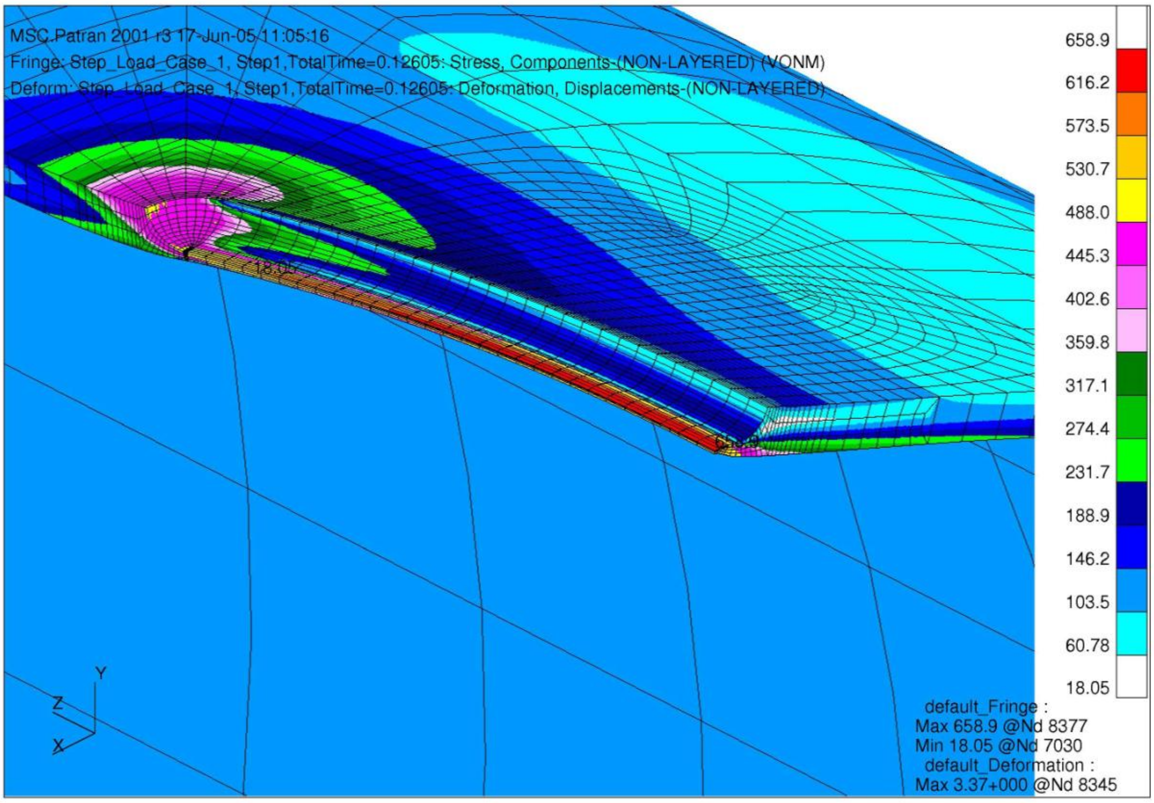


Figure 7. Typical von Mises Equivalent Stress Contour Plot for a Pipe with an Axially Orientated Groove Defect

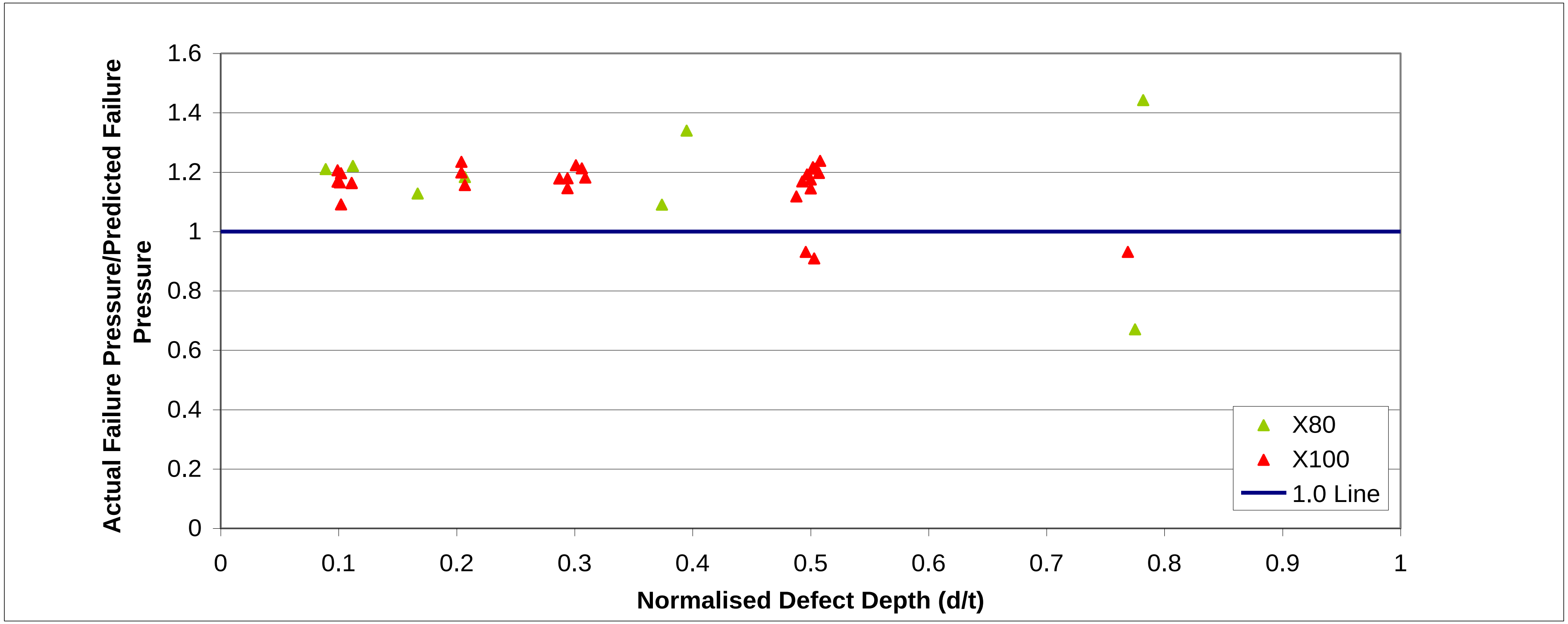


Figure 8. Comparison of Actual and Predicted Failure Pressures using the ASME B31G Method

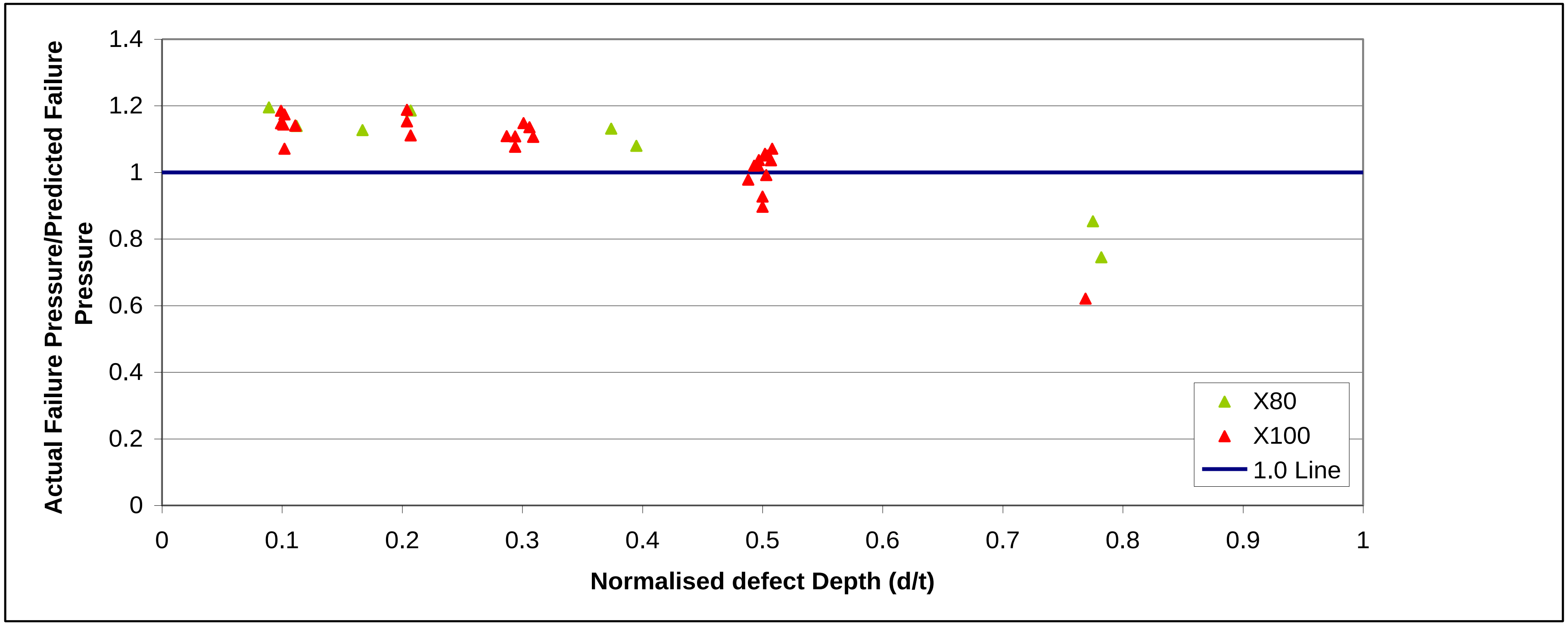


Figure 9. Comparison of Actual and Predicted Failure Pressures using the Modified ASME B31G Method

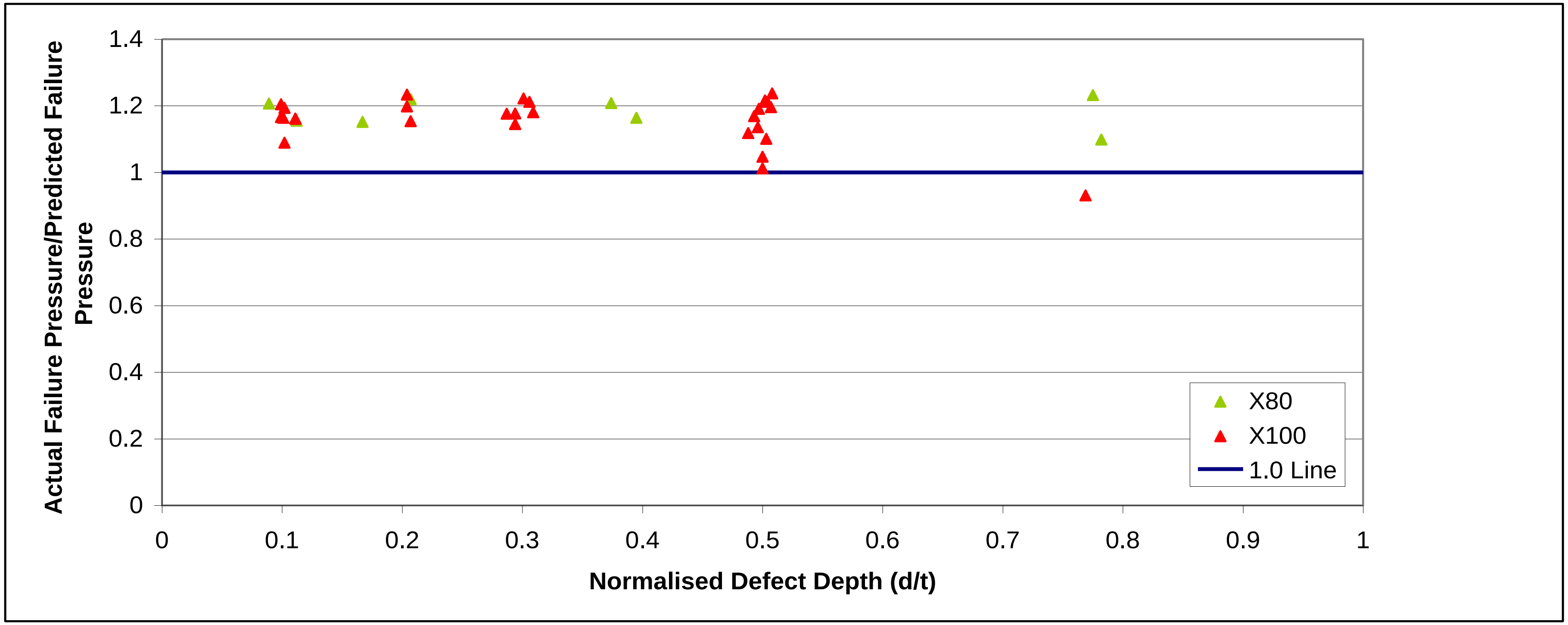


Figure 10. Comparison of Actual and Predicted Failure Pressures using the RSTRENG Method

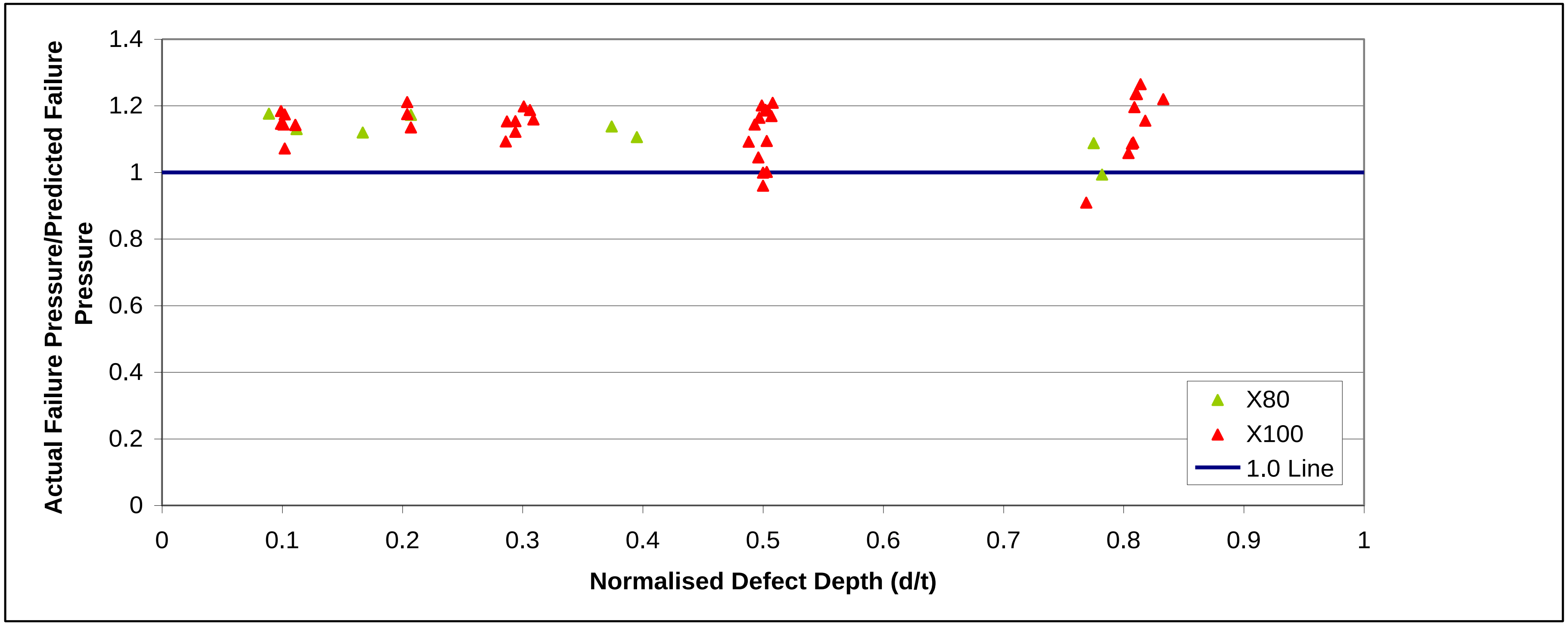


Figure 11. Comparison of Actual and Predicted Failure Pressures using the LPC-1 Method

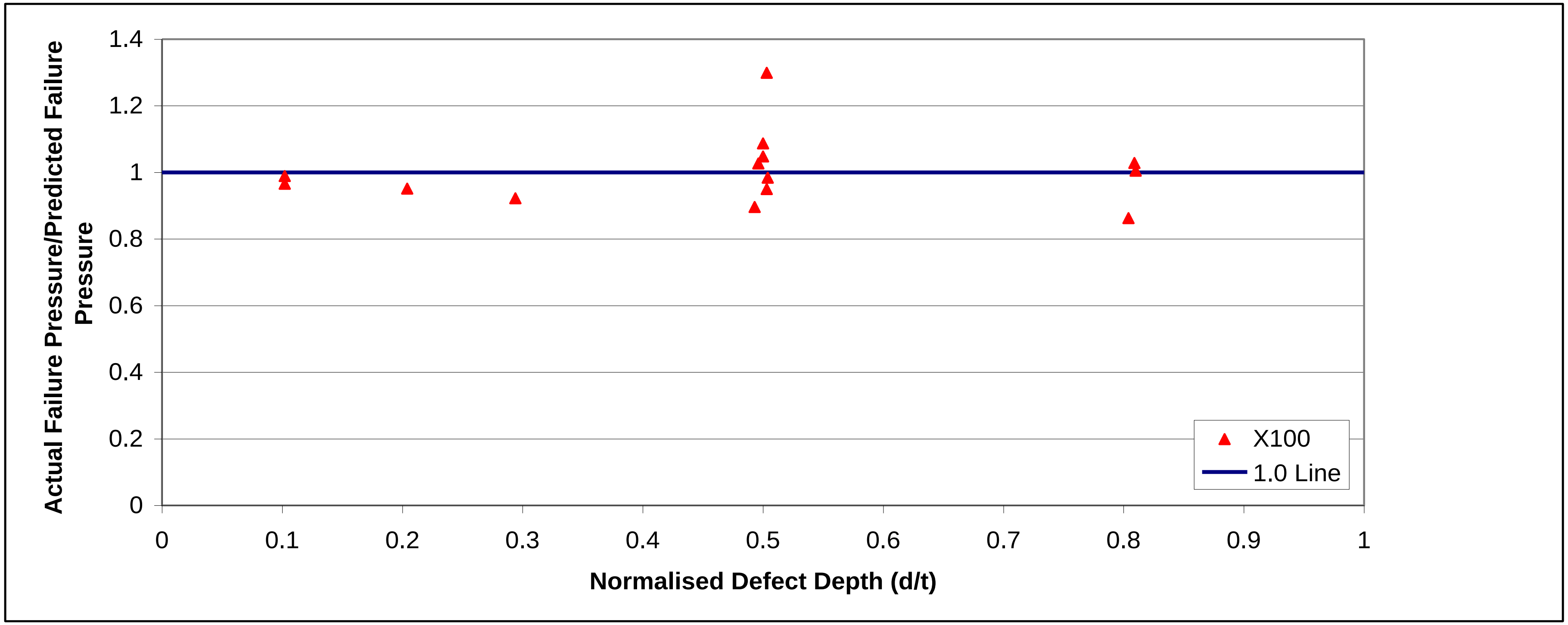


Figure 12. Comparison of Actual and Predicted Failure Pressures using the Non-Linear Finite Element Method (Grade X100 Test Points)

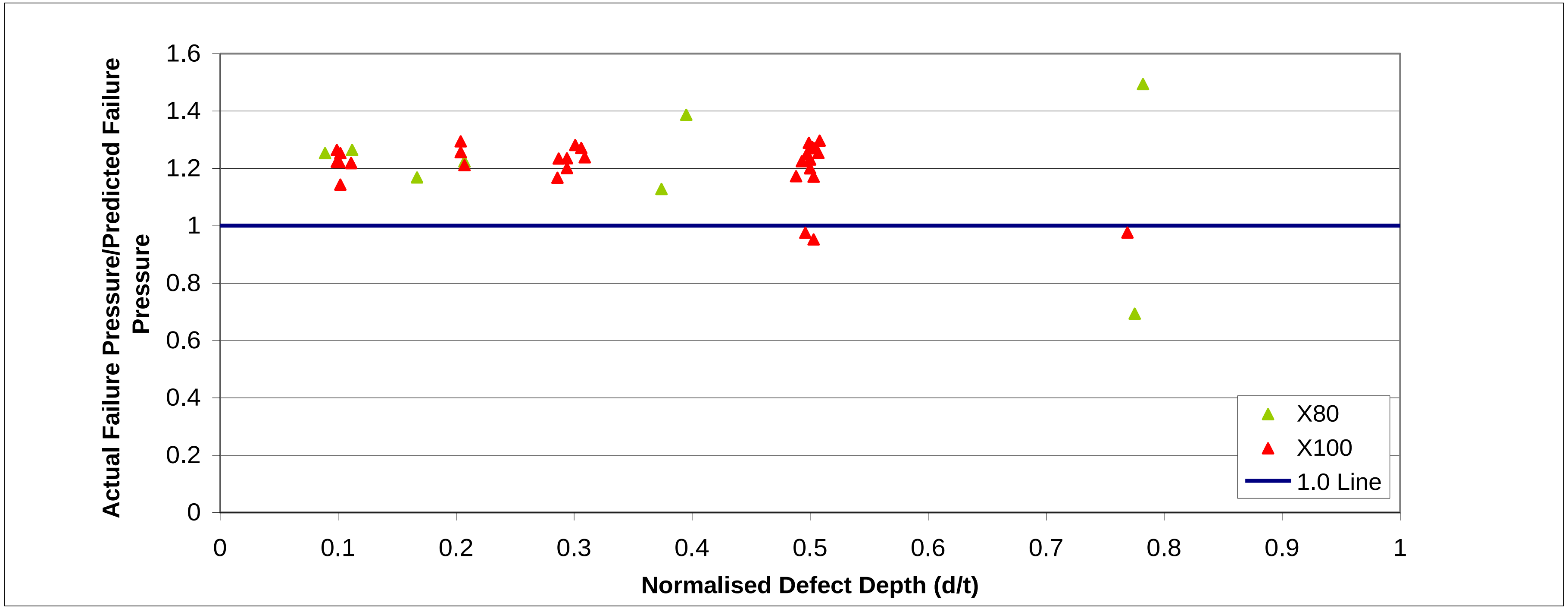


Figure 13. Comparison of Actual and Predicted Failure Pressures using the ASME B31G Method (Flow Stress Modified to Equal the Mean of the Specified Minimum Yield Strength and the Specified Minimum Ultimate Tensile Strength)

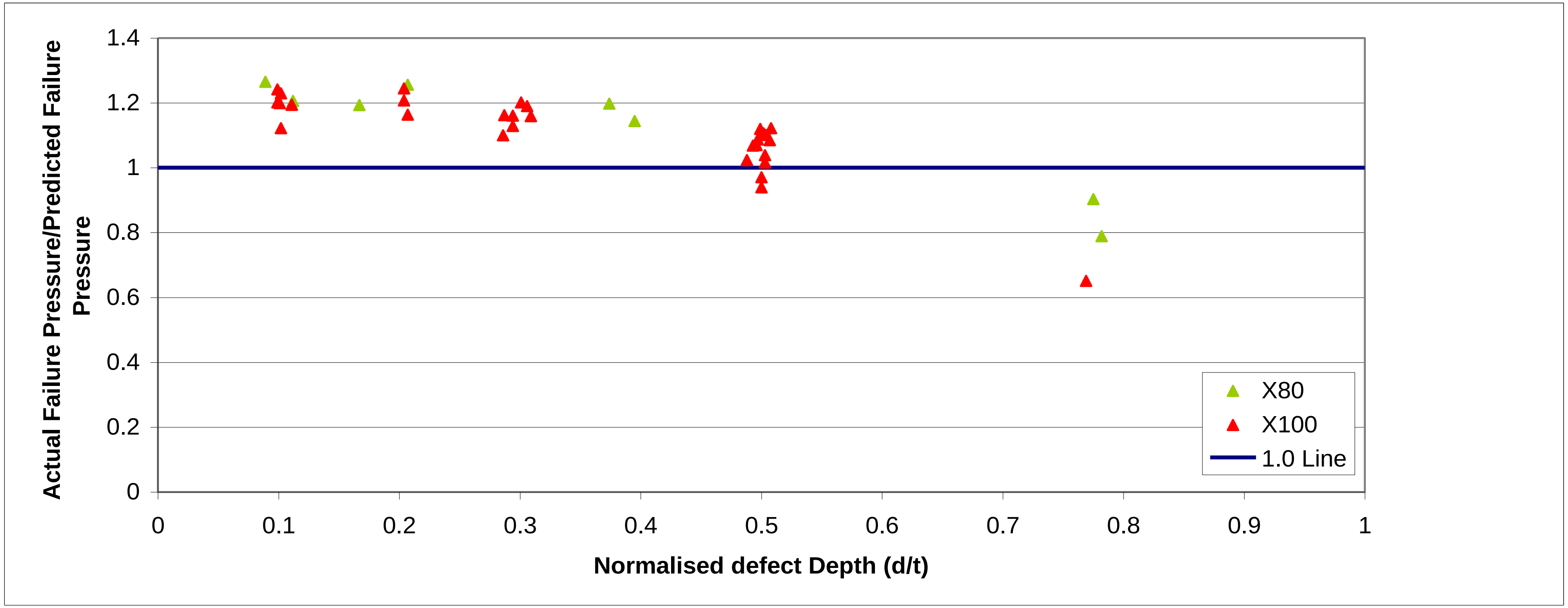


Figure 14. Comparison of Actual and Predicted Failure Pressures using the Modified ASME B31G Method (Flow Stress Modified to Equal the Mean of the Specified Minimum Yield Strength and the Specified Minimum Ultimate Tensile Strength)

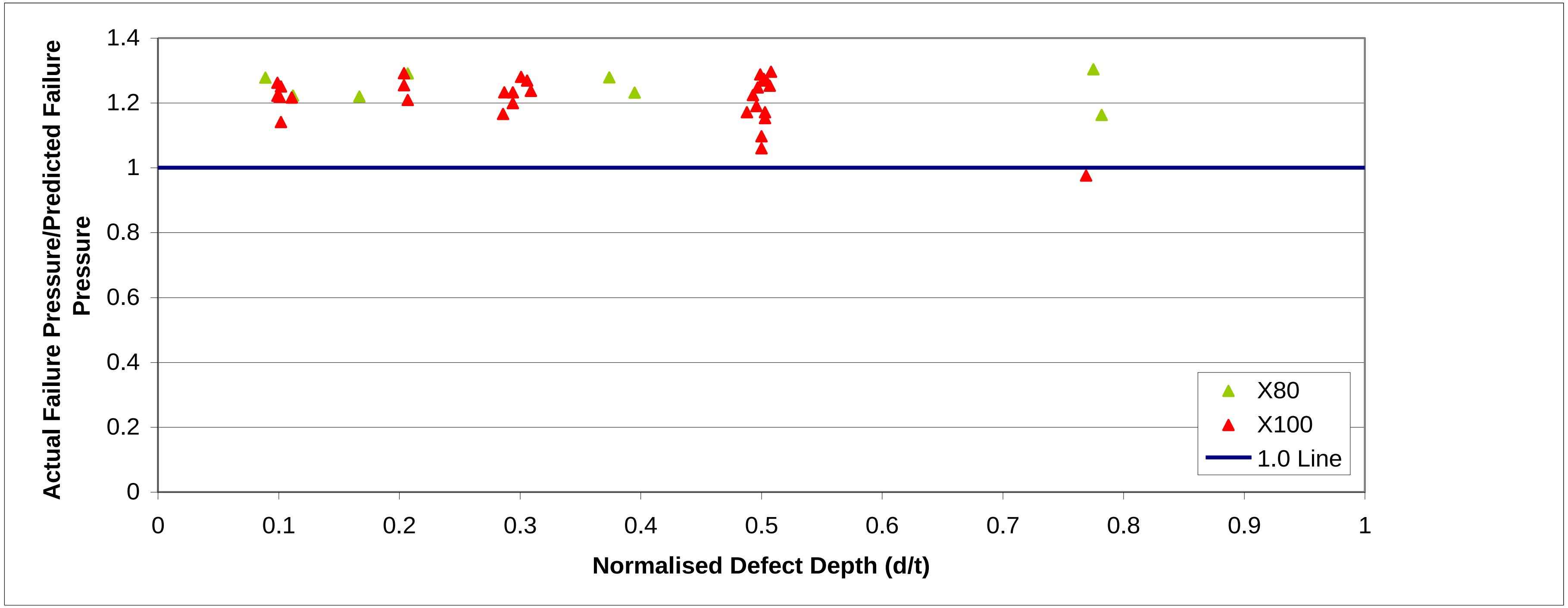


Figure 15. Comparison of Actual and Predicted Failure Pressures using the RSTRENG Method (Flow Stress Modified to Equal the Mean of the Specified Minimum Yield Strength and the Specified Minimum Ultimate Tensile Strength)

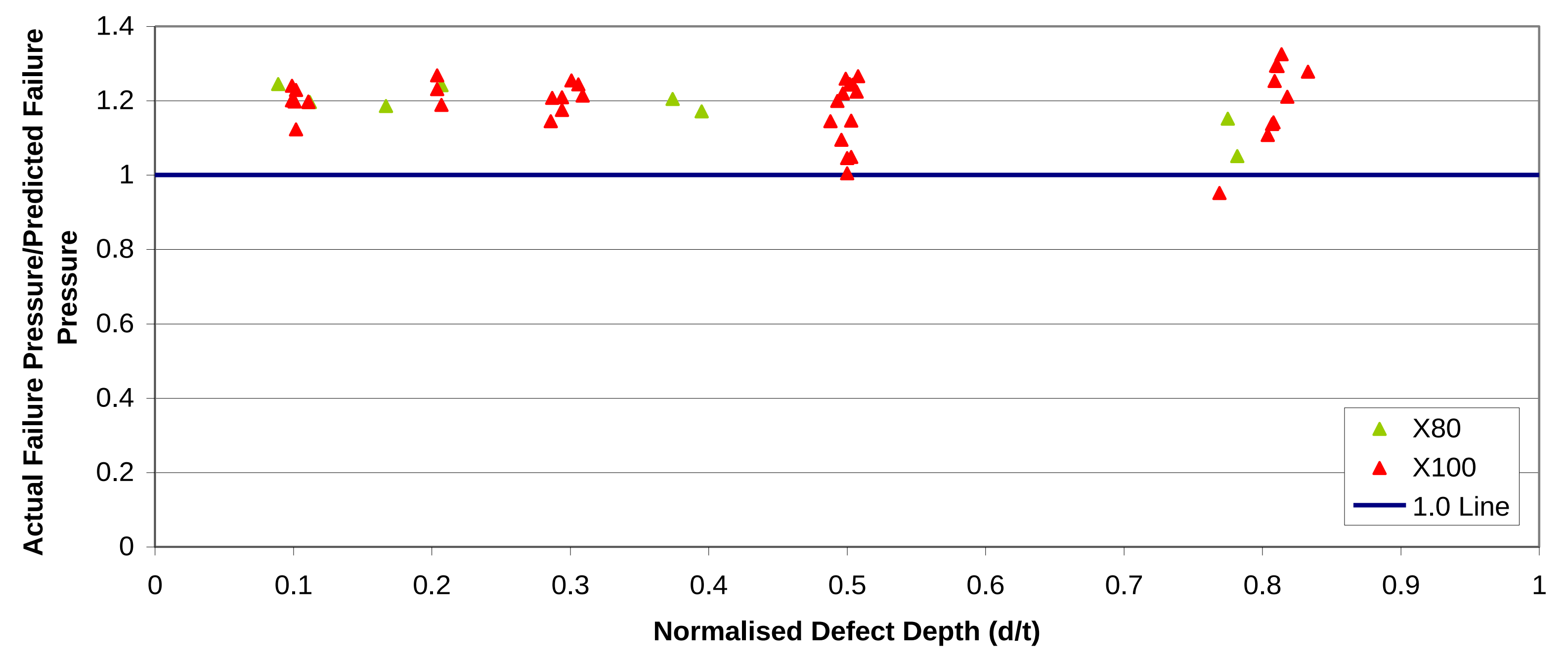


Figure 16. Comparison of Actual and Predicted Failure Pressures using the LPC-1 Method (Flow Stress Modified to Equal the Mean of the Specified Minimum Yield Strength and the Specified Minimum Ultimate Tensile Strength)