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TOWARDS A VALIDATED PIPELINE DENT INTEGRITY ASSESSMENT MODEL

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ABSTRACT

Detectable dents in buried pipelines can occur due to a number of potential causes; the pipe resting on rock, third party machinery strike, rock strikes during backfilling. The integrity of a dented pipeline segment is a complex function of a variety of parameters, including pipe geometry, indenter shape, dent depth, indenter support and pressure history at and following indentation. In order to estimate the safe remaining operational life of a dented pipeline, all of these factors must be accounted for in the analysis.

The following paper summarizes ongoing efforts to develop a validated pipeline dent integrity assessment model. The model under development makes use of experimental tests to validate a finite element model of the denting and re-rounding process for a variety of dent scenarios (i.e. depths, restraints, indenter sizes). The results of the finite element model are then used in conjunction with the estimated pressure-time history in an integrity assessment procedure to estimate the safe remaining operational life of the pipe segment. The paper presents a discussion of the full scale fatigue tests carried out on dented pipeline segments and the efforts under way to develop and validate a finite element model of the experimental specimens with the goal of estimating the experimental fatigue life.

INTRODUCTION AND SCOPE

In order to develop a mechanistic based model to characterize the severity of a dent on the integrity of a pipeline system, there must first be sufficient information available describing the behaviour of the deformed pipe when subjected to typical loading scenarios. While there have been a number of full scale test programs that have been used to develop general trends in the behaviour of dented pipe subjected to cyclic pressure loads [1,2,3,4], these programs have not produced sufficiently detailed information in terms of material properties and pipe behaviour, to form the basis of a severity assessment criterion [5].

In an effort to generate data necessary to develop and evaluate both empirical and mechanistic models capable of predicting cyclic internal pressure related failures of a pipe segment, BMT Fleet Technology Limited, with the support of PRCI, has began a multi-year full scale pipeline dent test program. The program will generate and provide detailed experimental data for cyclic pressure failures of pipe segments subjected to:

- Unrestrained plain dents located in the pipe body
- Restrained plain dents located in the pipe body
- Dents interacting with an ERW longitudinal seam weld
- Dents interacting with a typical pipeline girth weld
- Dents interacting with metal loss typical of external surface corrosion

The focus of the current paper is to present an overview of Year 1 of the test program which included the testing of 12 plain dent specimens. In addition the paper discusses the on-going efforts being carried out at BMT to develop and validate a finite element model capable of predicting the stress-strain histories in the vicinity of the dent which are required for a mechanistic based cyclic failure prediction methodology.

FULL SCALE DENT TEST PROGRAM

The purpose of the full scale testing program was to develop a database of detailed experimental data that could be used to develop mechanistic based models to characterize the severity of a dent on the integrity of a pipeline [6]. Therefore the development of the initial test program focused on selecting test parameters that would be representative of real world scenarios and identifying experimental data that would be required in developing and assessing failure models.

The key test parameters considered included the number of specimens, pipe specification, dent depths and interactions, indenter sizes, dent restraint and the applied pressure histories. The key experimental data required as output of the full scale test program included the indentation force, applied internal pressure, pipe wall strains and the number of cycles to failure.

In addition to the full scale data requirements, it was recognized that detailed material property data is also required in order to develop and assess mechanistic based failure models. As such the test program included a detailed material characterization phase concerned with recording the material properties most likely required during the development of a failure criteria (i.e. complete monotonic stress-strain curves, fracture toughness data, Charpy data, etc).

The complete test matrix for the full scale test program included 24 individual scenarios (i.e. combinations of pipe spec, indenter size, dent depth, dent restraint etc). Due to the variability inherent in fatigue testing, two specimens for each configuration are included in the matrix, for a total of 48 test specimens.

Based on availability, the two pipe specifications identified and selected for use at the beginning of the test program were:

- Batch A: NPS 24, t_w = 7.9mm, X52
- Batch B: NPS 24, t_w = 8.9mm, X70

The diameters of the round indenters selected for the program were 60.3mm (2.375 inches) and 114.3mm (4.5 inches), with dent depths ranging from 5% to 15% of the pipe outer diameter (OD).

TEST PROGRAM – YEAR 1

Year 1 of the full scale test program was focused on the following two primary aspects of the overall project:

1. Detail material testing to characterize the material properties of the pipes chosen for the full scale test program.
2. Carrying out 12 plain dent scenarios as summarized in Table 1.

The detailed material testing was carried out by BMT while the full scale testing portion of the program was carried out by Stress Engineering Services in Houston, Texas.

Material Characterization

The purpose of the material characterization phase of the testing program was to develop and record a database of material properties that may be required during the development of a mechanistic approach to estimating the fatigue life of a dented pipeline segment. The data developed and recorded during detailed testing included:.

- Yield and Ultimate tensile strengths.
- Complete monotonic and cyclic stress vs strain curves.
- Microhardness readings and chemistries.
- Charpy Impact testing curves.
- Fracture toughness (CTOD) values.

The results of the testing are summarized in Tables 2 and 3 for both flattened strap and round bar tensile tests.

Table 1: Summary of Year 1 Plain Dent Specimens

#	Pipe	Rest.*	Indent Diam.	Initial Dent Depth	Max Pres Initial	Pres Cycle Range
			(in)	(OD)	(SMYS)	(SMYS)
1	A	Yes	60.3	7.5%	100%	10%-80%
2	A	Yes	60.3	7.5%	100%	10%-80%
3	B	Yes	114.3	10%	100%	10%-80%
4	B	Yes	114.3	10%	100%	10%-80%
5	B	Yes	114.3	10%	80%	10%-80%
6	B	Yes	114.3	10%	80%	10%-80%
7	A	No	60.3	15%	100%	10%-80%
8	A	No	60.3	15%	100%	10%-80%
9	A	No	60.3	15%	80%	10%-80%
10	A	No	60.3	15%	80%	10%-80%
11	A	No	114.3	15%	100%	10%-80%
12	A	No	114.3	15%	100%	10%-80%

*Restrained or unrestrained dent

Table 2: Flattened Strap Tensile Test Results

Batch	Orient	0.5% Yield Strength (MPa)	Ultimate Strength (MPa)	Elong (%)
1	Transverse	437	518	36
2	Longitudinal	441	516	35
3	Transverse	457	512	34
4	Longitudinal	450	503	34
5	Transverse	506	667	23
6	Longitudinal	530	675	25
7	Transverse	552	653	30
8	Transverse	546	652	30

Table 3: Round Bar Tensile Test Results

Batch	Orient	0.5% Yield Strength (MPa)	Ultimate Strength (MPa)	Elong (%)
1	Transverse	445	503	34
2	Longitudinal	441	494	N/A
3	Transverse	397	464	36
4	Longitudinal	419	483	31
5	Transverse	476	653	26
6	Longitudinal	496	661	30
7	Transverse	517	595	27
8	Longitudinal	552	638	N/A

Full Scale Test – Plain Dents

Year 1 of the test program focused on completing the twelve plain dent test summarized in Table 1.

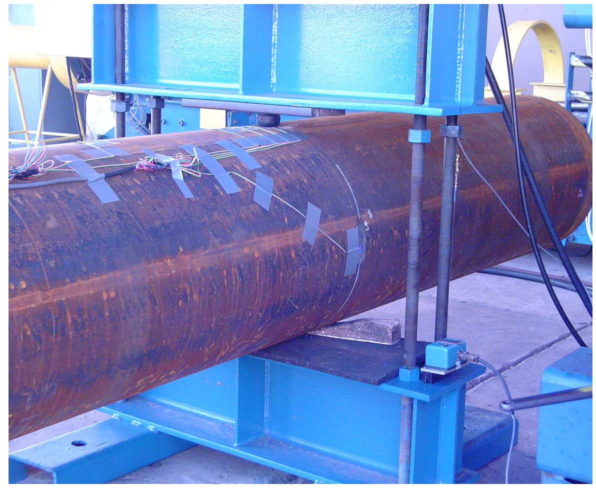
Although the exact details for each of the test specimens differ slightly, they all followed the same basic test protocol which is summarized below:

1. Indent un-pressurized pipe to target depth.
2. For restrained dents restrain indenter at desired depths. For unrestrained dents remove indenter and allow pipe to elastically rebound.
3. Increase internal pressure to initial maximum pressure (either 80% or 100% SMYS) in 10% increments, holding at each increment.
4. Reduce internal pressure to 0.
5. Increase internal pressure to 80% SMYS in 10% increments.
6. Reduce internal pressure to 10% SMYS.
7. Cycle internal pressure between 10% and 80% SMYS until failure occurs.

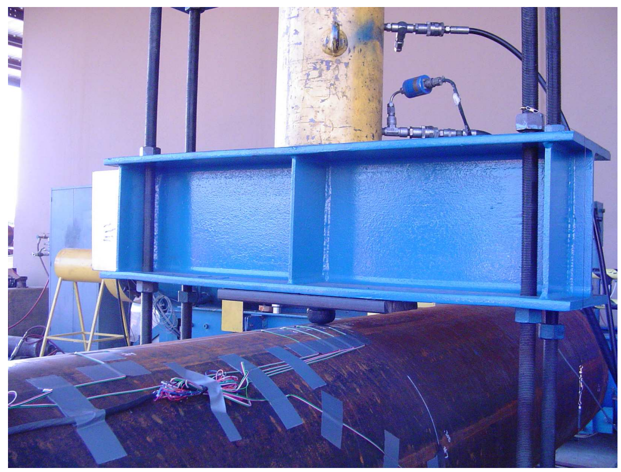
The typical experimental test set-up used during full scale testing of the restrained dent specimens is presented in Figure 1. Specimens were mounted in the test frame with a rigid beam directly over and underneath the longitudinal centre of the pipe. Indentation was accomplished using a hydraulic ram to force the upper beam into the specimen until the required dent depth was reached.

Pressure cycling was accomplished using water as the filling medium where the applied pressure was controlled using a pressure transducer and an electronic control box.

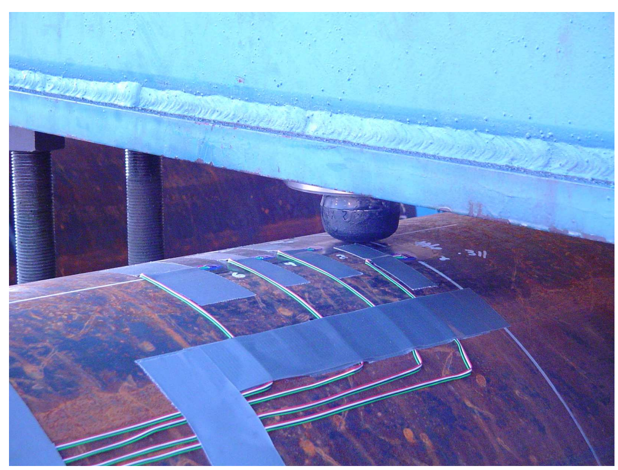
Specimens highlighted in grey in Table 1 included seven strains gauges at various locations on the OD surface of the pipe. Along the longitudinal centreline of the pipe, bi-axial strain gauges were located at distances of 50.8, 101.6, 152.4, 609.6 and 1219.2 mm from the centre of the indenter. In addition, along the circumferential direction, bi-axial strain gauges were located at 50.4 mm and 90^{o} from the indenter.



(a) Test Specimen in Test Frame



(b) Hydraulic Ram used during Indentation



(c) Close-up of Indenter

Figure 1: Full Scale Experimental Test Setup

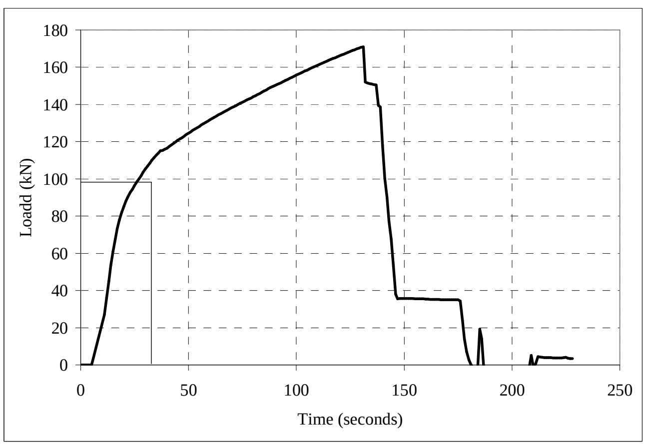
FULL SCALE TEST RESULTS

Detailed results gathered during the full scale tests included:

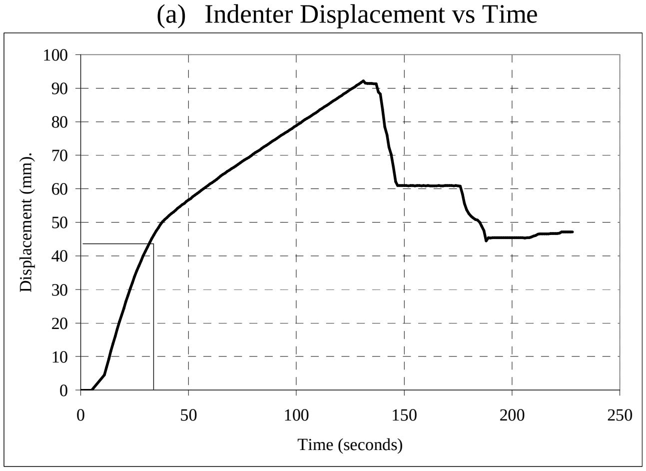
- Load vs displacement data during the indentation phase.
- Applied pressures for the initial maximum pressure cycles.
- Detailed pipe wall strains during the indentation phase and initial maximum pressure cycles.
- Detailed pipe wall strains and applied pressures during the initial five cyclic pressure cycles and at various stages throughout the duration of the test (i.e. after 500, 1000, 2000 cycles, etc).

A brief sample of the experimental data gathered for each of the specimens is presented in Figures 2 - 8. Note that the example data is presented for a variety of specimens.

Figure 2 presents the indenter displacement and load vs time curves for Specimen 8.



(a) Indenter Displacement vs Time



(b) Indenter Displacement vs Time

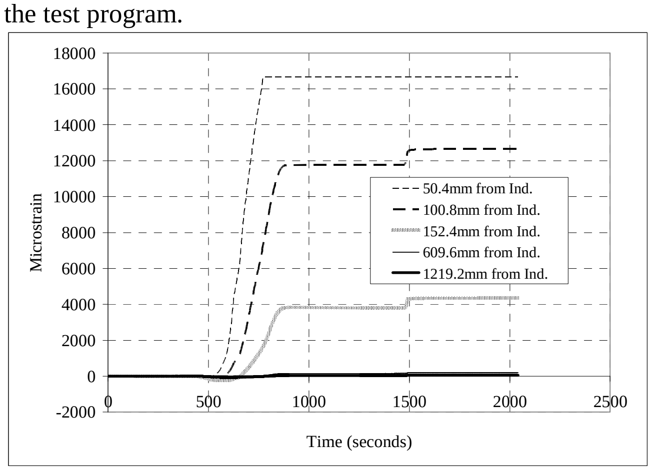
Figure 2: Indenter Displacement and Load vs Time for Indentation Phase

Figure 3 presents the axial and circumferential OD strains time histories for the gauges located along the length of the pipe during the indentation phase of Specimen 1.

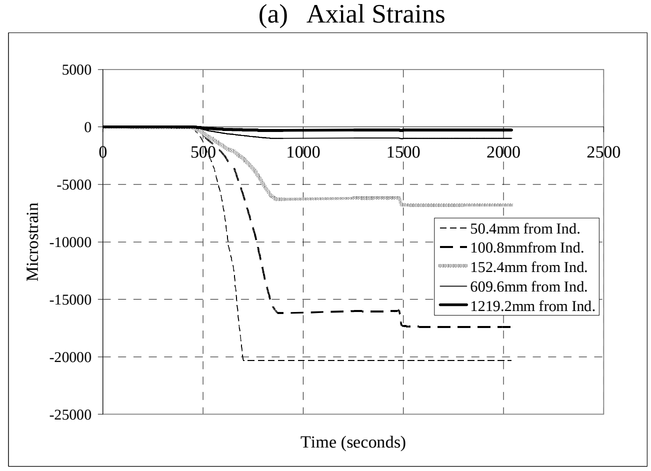
Figure 4 presents the pressure time history and the resulting axial and circumferential strains during the initial maximum pressure (re-rounding) cycles for Specimen 1. Similar data was captured and recorded for various steps throughout the duration of the test.

Figure 5 presents the initial and re-rounded dent profiles for Specimen 1, while Figure 6 presents axial strain vs internal pressure plots, for a two gauge locations after various stages of internal pressure loading.

The results of the Year 1 of the testing program are summarized in Table 4 in terms of the number of cycles to failure and the location of the observed failure (i.e. leak). The results presented in Table 4 indicate the range of experimental fatigue lives that can occur for nominally the same conditions. For example for Specimens 3 and 4 which both developed leaks in the shoulders of the dent region, the experimental fatigue lives vary by a factor of 2.4. This potential variation in fatigue life for similar specimens would not be evident if duplicate testing was not included in the test program.



(a) Axial Strains



(b) Circumferential Strains

Figure 3: Strains – Indentation Phase

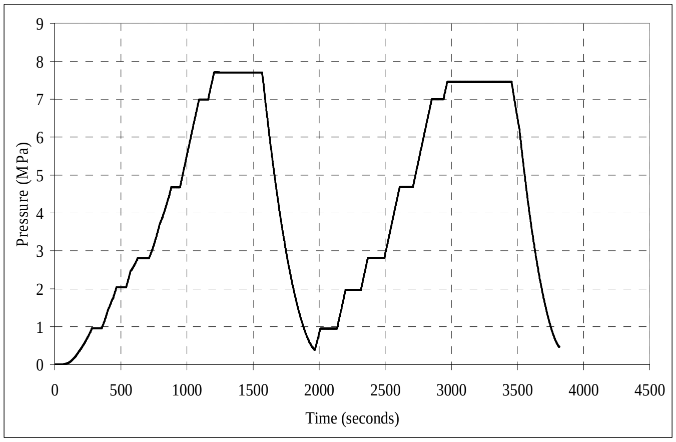


Figure 4: Internal Pressure vs Time – Rerounding Phase

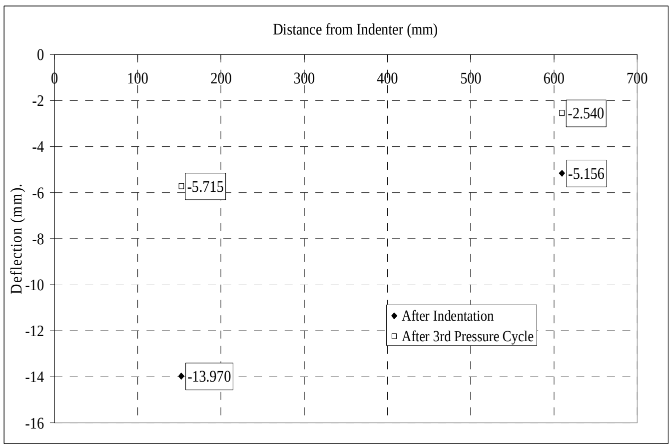
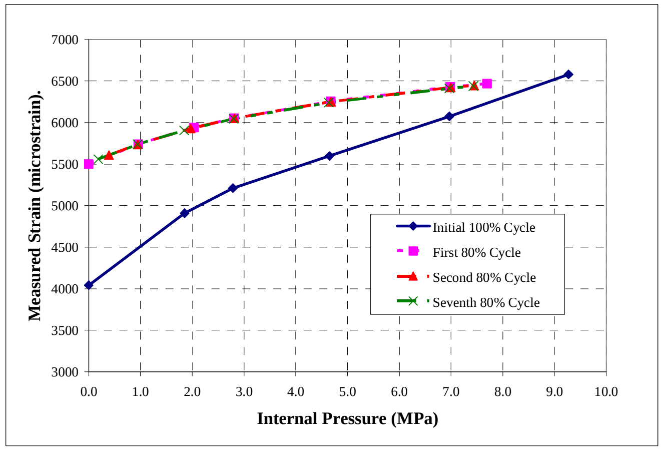
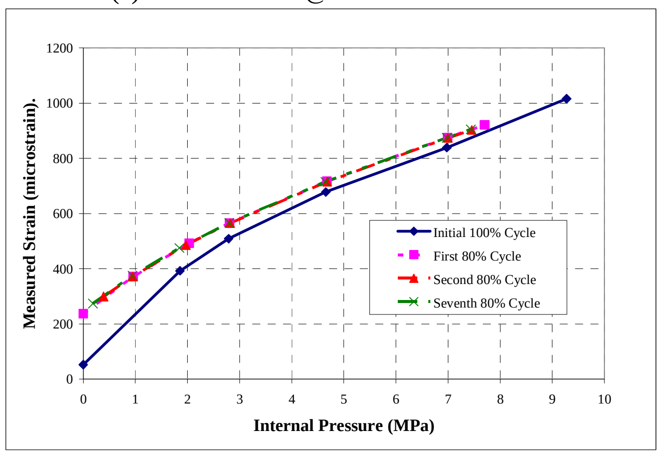


Figure 5: Initial and Re-rounded Dent Shapes



(a) Axial Strains @ 152.4mm from Indenter



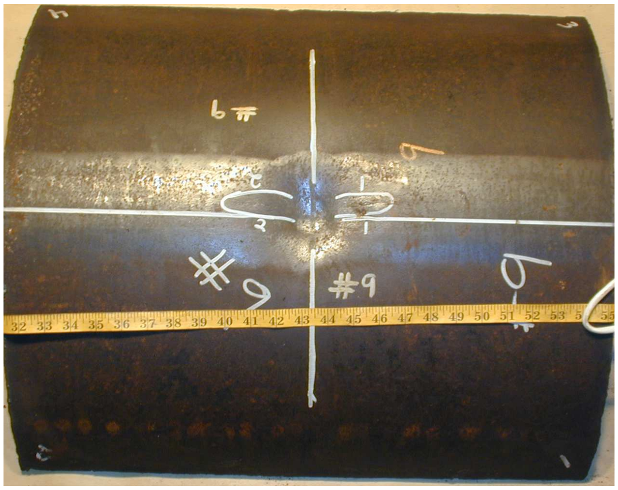
(b) Axial Strains @ 609.6mm from Indenter

Figure 6: Pipe Wall Strain vs Internal Pressure after Various Stages of Loading

Table 4: Summary of Year 1 Test Results

Spec. #	Cycles	Failure Location
1	6 948	Leak in dent shoulder
2	38 685	Leak in bosset and end cap
3	6 886	Leak in dent shoulder
4	16 234	Leak in dent shoulder
5	2 531	Leak in dent shoulder
6	3 359	Leak in dent shoulder
7	21 103	Leak in bosset
8	28 211	Leak in dent shoulder
9	6 825	Leak in dent shoulder
10	9 116	Leak in dent shoulder
11	15 063	Leak in dent shoulder
12	27 575	Leak in dent shoulder

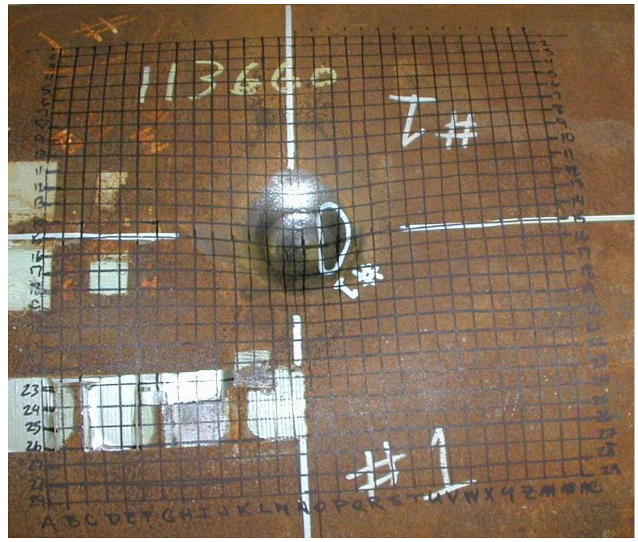
In addition to the data gathered during the test, detailed data regarding the dent shapes and failure locations (i.e. locations of leaks) were gathered and documented during the experimental program. An example of the post failure photos (for Specimen 1) used to document the results of the test are shown in Figure 7. An example of the post failure dent shape measurements are shown in Figure 8.



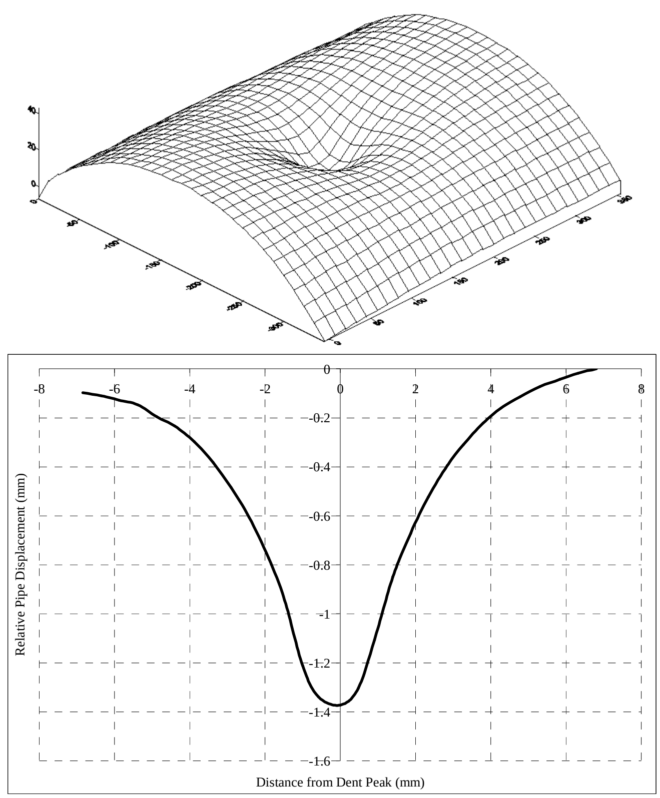
(a) General dent region

(b) Crack resulting in leak

Figure 7: Post Failure Photograph of Specimen 1 Dent Region and Failure Location



(a) Measurement Grid



(b) Surface contour and longitudinal dent profile through deepest point

Figure 8: Post Failure Dent Shape Measurements

FULL SCALE FINITE ELEMENT MODELING

For several years BMT has been involved in developing a mechanistic based failure prediction methodology for estimating the cyclic fatigue life of dented pipeline segments. The methodology has been developed based on the use of a finite element analysis to predict the stress and strains in a dented pipeline segment. Some of the previous development work at BMT has focused on investigating the effects of various finite element parameters on the local predicted stress-strain state in the dented region. Although the results of the investigations allowed for relative comparison between different analysis results, due to a lack of detailed experimental data, comparison to actual results were not possible. Current efforts at BMT are focused on using the results of the full scale dent testing program to further refine and develop both the finite element model of dented pipelines and the failure prediction methodology.

The finite element model used to predict the local stress-strain response of a pipeline has been developed using ANSYS and utilizes fully non-linear elasto-plastic shell elements with advanced non-linear material models.

The finite element analysis of the full scale dent specimen utilized a ½ symmetry model of the specimen, as shown in Figure 9, and accounted for all the detailed support restraints used in the experimental test set up. The model included the indenter as an infinitely rigid sphere and utilized contact elements to transfer the load between the indenter and the shell elements used to model the pipe wall.

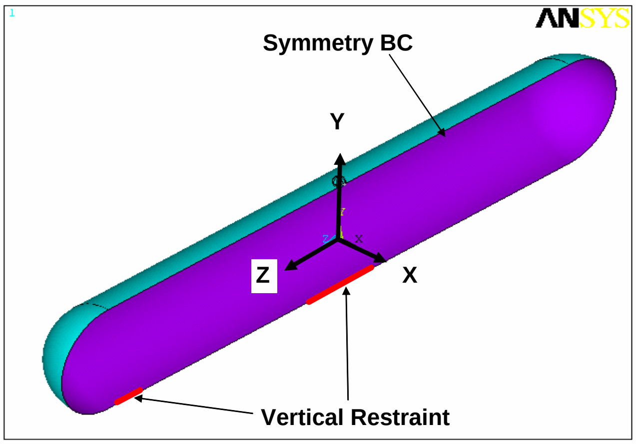


Figure 9: Geometry of FE Pipe Model

Development of the finite element model included examining the effects of various parameters on both the computational time and the accuracy of the results compared to the experimental data. The parameters investigated include:

- mesh density
- number of integration points through the thickness of the shell element used to model the pipe wall
- contact element stiffness
- allowable contact penetration
- nonlinear time stepping algorithm settings

A comparison of the finite element analysis results and the experimental test results for Specimen 1 is presented in Figures 10 and 11. Figure 10 shows the level of agreement between the experimental and FE load vs displacement curves for the indentation phase of the test. As can be seen, the finite element results are in relatively good agreement with the experimental curve with some divergence occurring after 6×10^4 N. The effect of the various finite element analysis parameters on the predicted load vs displacement curve was considered negligible therefore no immediate reason for the divergence is evident. Comparison with additional experimental specimens will be carried out to further investigate the finite element results.

Figure 11 compares the experimental and FE pipe wall profiles during indentation and after the 3rd pressure cycle. Again the FE results are in fairly good agreement with the experimental results. Although the FE result under predicts the experimental depth at a distance of 6 inches during the initial indentation phase, the difference of 0.15 inches is considered inside the experimental error associated with the measurement technique used during the experiment (i.e. a string stretched across the dent and measurements made manually). As with the load vs displacement curve, the effect of the various finite element analysis parameters on the predicted dent shapes was considered negligible.

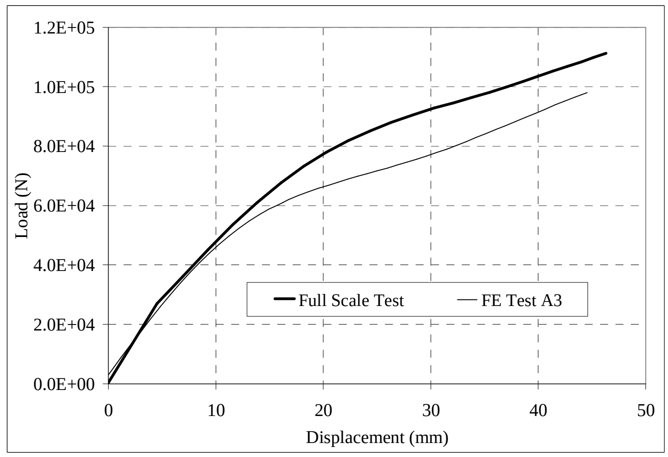


Figure 10: Experimental and FE Load vs Displacement Curves – Indentation Phase

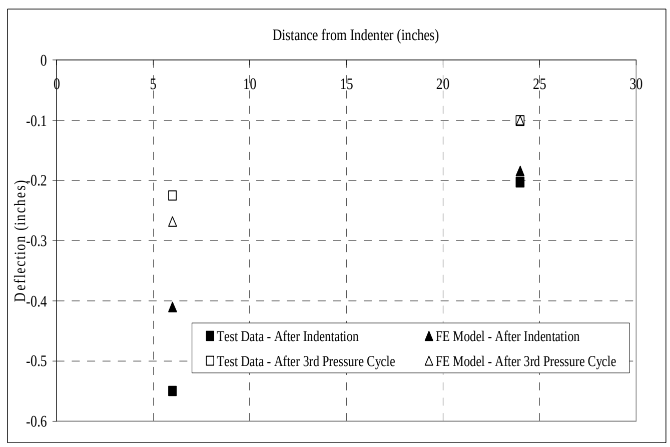


Figure 11: Experimental and FE Pipe Wall Profiles

More detailed comparisons between the experimental and FE results are presented in Figures 12 and 13 which illustrate the circumferential (hoop) and axial strain on the OD surface of the pipe wall after the indentation phase. Results from three different FE analyses are presented, where each analysis varied in the contact and solution parameters assumed. As can be seen, for locations where experimental strains are available, there is good agreement between the experimental and predicted strains for all the FE analyses considered.

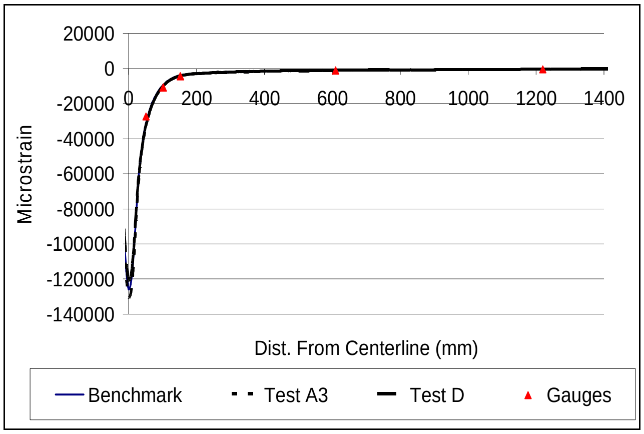


Figure 12: Outer Surface Hoop Strain Along Axial Centerline

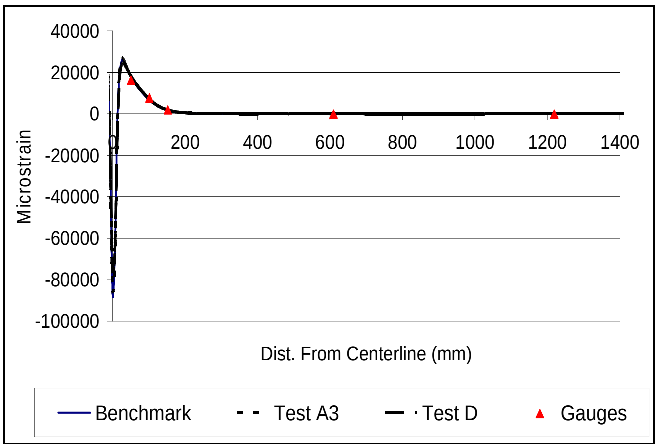


Figure 13: Outer Surface Axial Strain Along Axial Centerline

Typically, many dented pipeline fatigue failures occur in the shoulder region of the dent, thus the closer to the peak of the dent reliable data can be extracted the better the chance of accurately estimating the fatigue life. Therefore, Figures 14 and 15 present the FE strain results 50mm either side of the centre of the indenter, after the indentation. (Unfortunately, the experimental strain gauges closest to the dent peak were placed 2 inches from the centerline, and failed at approximately 85% of the target dent depth). As illustrated there is relatively good agreement between the various finite element analyses in terms of the predicted axial and hoop strains, with variations of approximately 10-15% for the various finite element analysis parameters considered in the development phase.

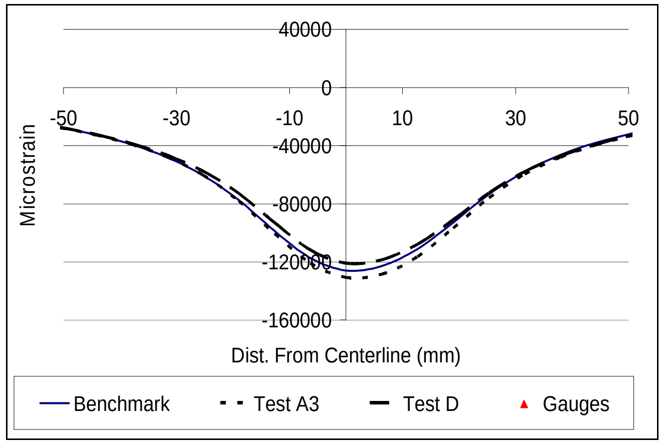


Figure 14: Outer Surface Hoop Strain Along Axial Centerline – 50mm From Transverse CL

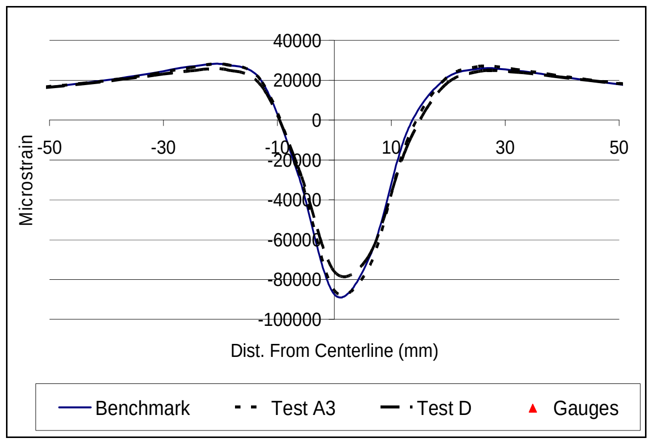


Figure 15: Outer Surface Axial Strain Along Axial Centerline – 50mm From Transverse CL

Figures 16 and 17 present the FE hoop and axial stress plots 50mm either side of the indenter. As can be seen, in contrast to the strain results presented in Figures 14 and 15, the predicted stresses exhibit a wide range of variation between the various finite element analyses. This could potentially be a concern for stress based failure prediction methodologies.

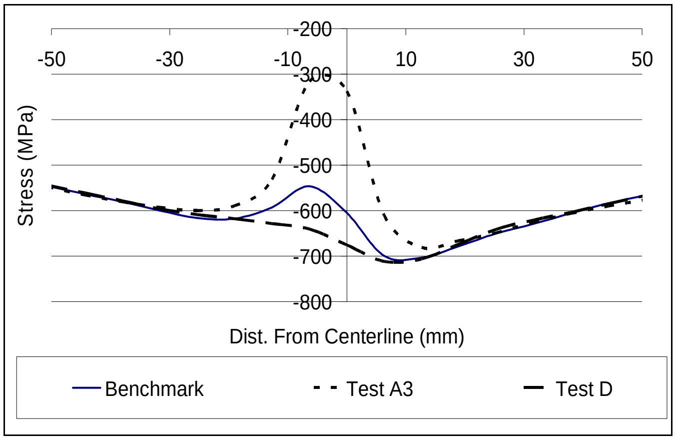


Figure 16: Outer Surface Hoop Stress Along Axial Centerline – 50mm From Transverse CL

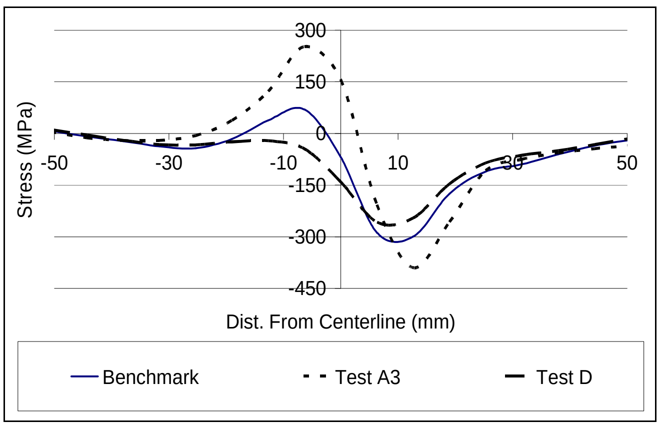
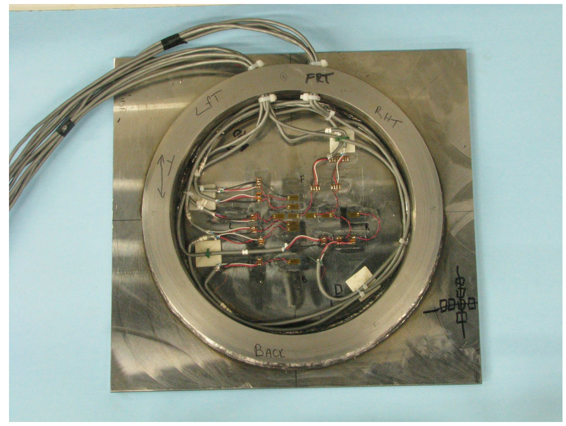


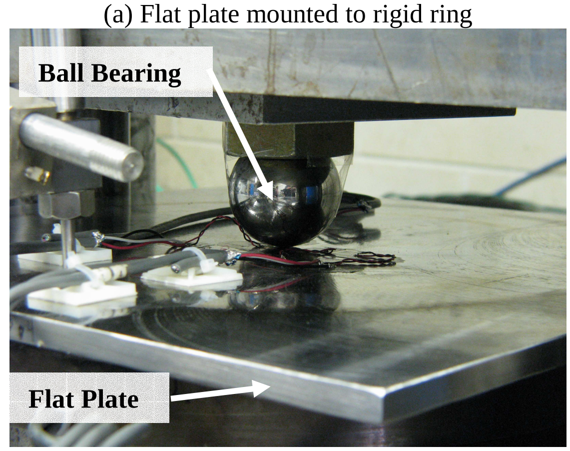
Figure 17: Outer Surface Axial Stress Along Axial Centerline – 50mm From Transverse CL

SMALL SCALE DENT TEST

In an effort to investigate and further understand the stresses and strains in the region of the dent peak, a small scale dent test was developed by BMT. The small scale dent test set-up, shown in Figure 18, utilized a flat plate (10mm thick) mounted to a rigid ring (OD = 323mm, tw = 30.5mm, height = 43mm), where a dent was formed in the middle of the flat plate using a 50.4mm diameter solid steel ball bearing.



(a) Flat plate mounted to rigid ring



(b) Experimental set-up

Figure 18: Small Scale Dent Test

Detailed experimental strain measurements were gathered using a total of 14 strain gauges mounted on both the upper and lower surfaces of the flat plate.

A variety of finite element models of the small scale dent test were developed in conjunction with carrying out the experimental test. Models were developed which utilized both shell and solid elements to model the dented flat plate. A sample ¼ symmetry finite element model of the test is shown in Figure 19 where the flat plate is modelled using four noded non-linear shell elements.

The material models used in all of the analyses were developed using the same philosophy used during the development of the full scale dented pipe finite element models, using tensile stress-strain curves generated experimentally in the BMT laboratories.

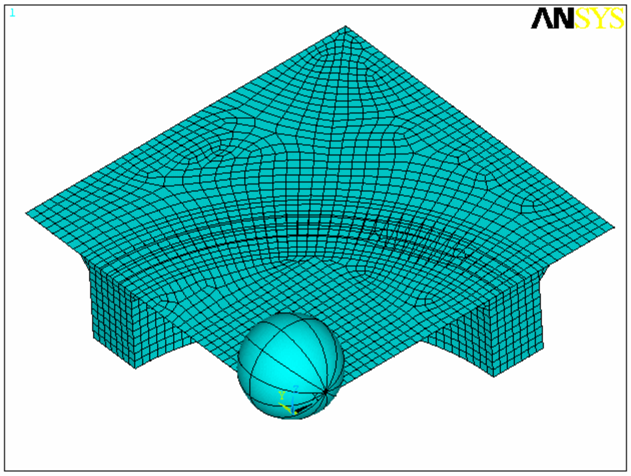


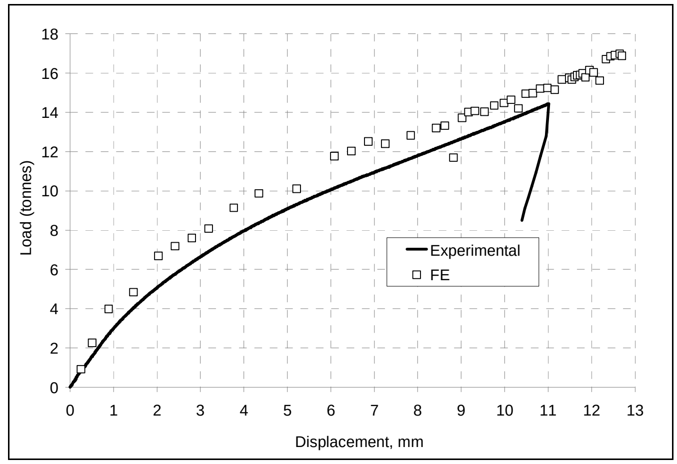
Figure 19: Example of Small Scale Dent FE Model

The primary objective of the small scale test program is to investigate the effect of finite element analysis parameters on the stresses and strains in and adjacent to the dent peak with the goal of thoroughly validating a finite element modeling approach.

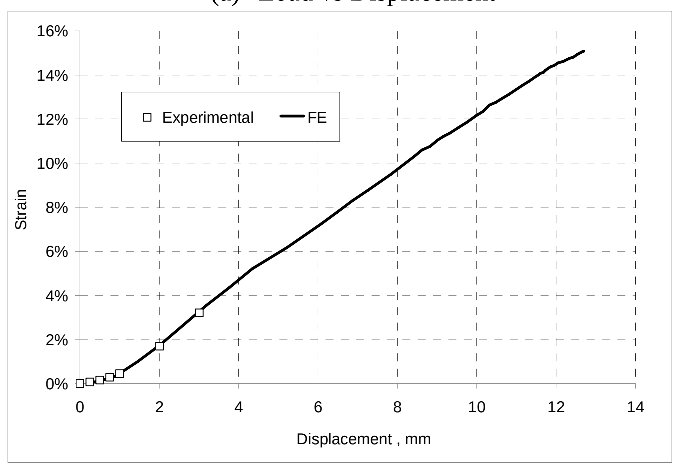
A comparison of the experimental and the initial finite element analysis results are presented in Figure 20. The finite element analysis results have been generated using eight noded solid brick elements to model the flat plate. Figure 20(a) compares the experimental and the predicted load vs displacement curves. Figure 20(b) compares the experimental and the predicted strain vs displacement curves for the gauge located on the lower surface of the plate directly under the indenter. Figure 20(c) compares the experimental and predicted strains for a location on the upper surface approximately 15mm from the indenter.

The comparison of the experimental and predicted load displacement curve indicates that the finite element model over predicts the indentation load when compared to the experimental curve. Some of the error in the prediction can be attributed to some elastic and plastic deformation that occurred in the fixture used to seat the indenter. This deformation also affects the accuracy of the experimental strain vs displacement plots. Additional experimental testing and FE modeling will be conducted to verify and rectify the discrepancy.

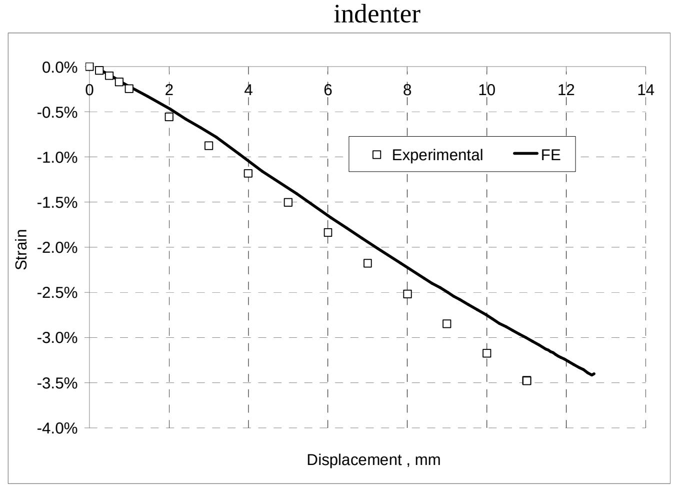
The example strain comparisons presented in Figures 20(b) and 20(c) indicate fairly good agreement between the experimental and predicted strain measurements where the estimated strains are with in approximately 10-15% of the experimental strains.



(a) Load vs Displacement



(b) Strains on lower surface of plate directly under indenter



(c) Strains on upper surface of plate 15mm from indenter

Figure 20: Example of Small Scale Dent FE Model

The next phase of development work to be carried out by BMT will focus on conducting additional small scale dent test and refining the finite element model in order to improve the strain estimates in the dent region. Once refined additional finite element modeling will be conducted to investigate and quantify the effects of varying finite element analysis parameters on the stresses and strains in the dent region. The lessons learned and the parameters developed using the small scale dent test results will then be applied to the finite element analysis of the full scale dented pipeline experiments with the objective of accurately predicting the stresses and strains in the dent region. These results will then be used to further refine and improve the dented pipeline cyclic failure prediction methodology being developed by BMT.

CONCLUDING REMARKS

The full scale experimental test program discussed in this paper, carried out on behalf of PRCI, represents an on-going effort to provide detailed experimental data for use in developing and validating empirical and mechanistic based models capable of characterizing the severity of a dent on the integrity of a pipeline system. The work completed to date includes the detailed material property characterization for the pipes batches used during full scale testing. In addition, 12 plain dent tests have been completed and documented. The remaining phase of the full scale test program will see an additional 60 tests being completed, where additional pipeline materials will be included (representative of older vintage pipe) and where the specimens will include the interaction effects between dents and girth welds, long seam welds and metal loss. Further work could include documenting the effects of other indenter shapes such as long bar or elliptical indenters.

The paper also described on-going efforts at BMT to use the full scale test results to further develop and validate a mechanistic approach to predicting the impact of dents on the fatigue life of dented pipelines. The efforts to date have focused on developing validated finite element models capable of predicting the detailed stress and strains in the vicinity of the dent peak. Included in the development effort is a small scale dent test where more detailed experimental data can be gathered for a wider range of applied strain levels, thus further validating the finite element modeling approach used in predicting the stresses and strains in the full scale experimental specimens.

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