QUARTERLY REPORT
Project WP#339: Structural Significance of Mechanical Damage

For Period Ending: August 31, 2010

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Prepared For: United States Department of Transportation
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List of Activities and Deliverables

Task No.	Task	Scheduled Completion Date	Completed Date	Milestone
1	Project Kick Off Meeting and Subcontracting	8/31/2008	8/31/2008	
2	Purchase & Characterize Pipe Material	8/31/2010	Ongoing*	
3	Literature Review	11/30/2009	Completed	
4	Testing of Dents on Welds and Corrosion Features	2/28/2012	Ongoing	
5	Testing of Dents with Gouges	2/28/2012	Ongoing	
6	Demonstration of Mechanical Damage Model Performance	11/30/2011	Ongoing	
7	Industry Workshop	5/31/2012	Not Yet Started	
8	Project Management and Reporting	5/31/2012	Ongoing	MS

* Pipe 1 and 2 complete, work on Vintage Pipe 3 is on-going.

Technical Status

Technical activities undertaken through the ninth quarter focused on the following tasks:

- Task 2—Purchase & Characterize Pipe Material
- Task 4—Testing of Dents on Welds and Corrosion Features
- Task 5—Testing of Dents with Gouges
- Task 8 – Project Management and Reporting

A summary of the technical status and results to date are presented below for each tasks.

The technical group for this program has maintained close communication with other related research projects being conducted by PRCI and DOT to ensure program coordination. The team has forwarded any issues of concern to PRCI and DOT for their consideration.

Task 2: Purchase & Characterize Pipe Material

There are three currently different pipe steels in this program:

- Pipe 1 and 2 are modern IPSCO pipes manufactured between 2005 and 2006

- Pipe 3 is intended to be of older steel which was initially intended to be a manufactured pipe that replicates vintage pipe properties. Due to challenges identified with this initial approach, the project is now using vintage pipe from former in-service pipelines provided by PRCI member companies. This has resulted in use of several different pipes, one vintage material for dents and a separate material for dent+gouge.

GDF SUEZ has received three samples of Pipe 1 and two samples of Pipe 2 all with a length of 11.8 m. Pipe 1 is API X52 grade and has a 24 in diameter and 7.9 mm wall thickness. Pipe 2 is API X70 grade. It also has the same diameter but has a wall thickness of 9.0 mm. IPSCO manufactured the pipe using the electric resistance welding (ERW) process. GDF SUEZ material characterization for Pipes 1 and 2 is fully complete and results presented in previous reports.

The team removed a sample of vintage pipe (called SoCal or Pipe 3) from the field and delivered it to Stress Engineering Services (SES) facility near Houston, TX for inspection by the research team. Based on the inspection of the pipe conditions, they selected five pipe joints for preliminary material characterization to confirm that the material properties are consistent with standard vintage pipe materials. SES cut ring samples from each of the five pipe joints and sent them to BMT Fleet Technology's facilities in Kanata, ON (Canada) in June 2010. BMT Fleet Technology is nearing completion of the preliminary characterization, and they expect the results in early September 2010. If the material characterization confirms the suitability of the vintage pipe for the full-scale testing program, BMT Fleet Technology will proceed with detailed material characterization and full scale tests based upon a material property characterization plan, including full characterization of the samples from each of the five sections - tensile testing, chemistry, Charpy, microstructure and hardness measurements.

PRCI finalized arrangements and secured a second set of vintage pipes for the dent+gouge test samples. The pipe is 24 in. diameter and made of X50 steel that was manufactured in the early 1940 by A.O. Smith. The sections of pipe have been transported to SES, where the team will perform a preliminary visual inspection and catalogue this vintage pipe with respect to the locations of known anomalies such as existing girth welds, sleeves, metal loss, and other features that could have an impact on the full-scale test results. SES will cut ring samples from the three longest sections of pipe (i.e., the 24 ft. section and two 40 ft. sections) and send it to BMT for immediate preliminary material characterization which includes the same test parameters as the SoCal pipe.

The other vintage pipes recovered from service and provided by Williams Companies were previously shipped to SES and will also undergo preliminary testing of material properties to confirm their use as vintage pipes. SES will then cut ring samples from each of two 40 ft. sections of the 24 in. pipe for preliminary characterization of basic materials properties. The team will designate the most appropriate vintage pipe as Pipe 4 and GDF SUEZ will use it to perform tests on the dent+gouge defects.

Task 3: Literature Review

The literature review regarding cyclic fatigue dent assessment techniques is complete. A report summarizing the findings and demonstrating the performance of the identified assessment techniques will be available following the completion of the testing.

Task 4: Testing of Dents on Welds and Corrosion Features

BMT Fleet Technology has completed the testing of dents on welds and simulated corrosion features for Pipe 1 and 2 (modern steel). They are reviewing the detailed experimental data collected during the test and reformatting it into a common format suitable for dissemination. The researchers will commence full scale dent testing of the vintage pipe material scenarios next quarter.

Task 5: Testing of Dents with Gouges

GDF SUEZ is in charge of the creation, characterization, burst test, and fatigue test of realistic combined defects, i.e., "dents with gouges", and their program is described in the next table:

The defects are identified by three characters **X.Y.Z.** which are numbers:

- **X.**Y.Z.—**X** identifies the **Pipe X** material which is noted by 1, 2, or 3 in this program;

- X.**Y.**Z.—**Y** defines the **type of dent and gouge defect** characterized by its geometry notably in terms of dent depth and length, and gouge depth and length. This program is considering a maximum of three different kinds of defects per pipe material, and therefore, the value of Y can range from 1 to 3; two extreme aggression conditions are considered in this study: highly dynamic and slower aggression. The former corresponds to defect Types 1 and 2 for Pipe 1 (two different excavator teeth used) and Type 1 for Pipe 2, while the latter corresponds to Type 3 for Pipe 1 and Type 2 for Pipe 2.

- X.Y.**Z.**—**Z** is the **number of defect in the defined type of defect**. There are three similar defects per type of defect. The number 1 is for a detailed geometrical, mechanical and metallurgical in-depth defect characterization after its creation. Number 2 is a similar defect for the burst test to evaluate the defect behavior of under monotonic pressure load and number 3 is a similar defect for the fatigue test to evaluate the defect behavior under cyclic variation of the internal pressure.

In the previous quarterly reports, the following results were presented:

- Creation conditions and results for 16 defects (14 + 2 repeated ones): 1.1.1, 1.1.1b, 1.1.2, 1.1.3, 1.2.1, 1.2.1b, 1.2.2, 1.3.1, 1.3.2, 1.2.3, 2.1.1, 2.1.2, 2.1.3 , 2.2.1, 2.2.2 and 2.2.3;
- Burst test conditions and results for 3 defects in Pipe 1: "1.1.2, 1.2.2 and 1.3.2" and two in Pipe 2: "2.1.2 and 2.2.2".
- Fatigue test conditions and results for 2 defects in Pipe 1: "1.1.3 and 1.2.3" and one in Pipe 2: "2.1.3";
- Metallurgical Failure Investigation for 3 defects "1.1.2, 1.1.3, 1.2.2 and 2.1.3".

This report presents:

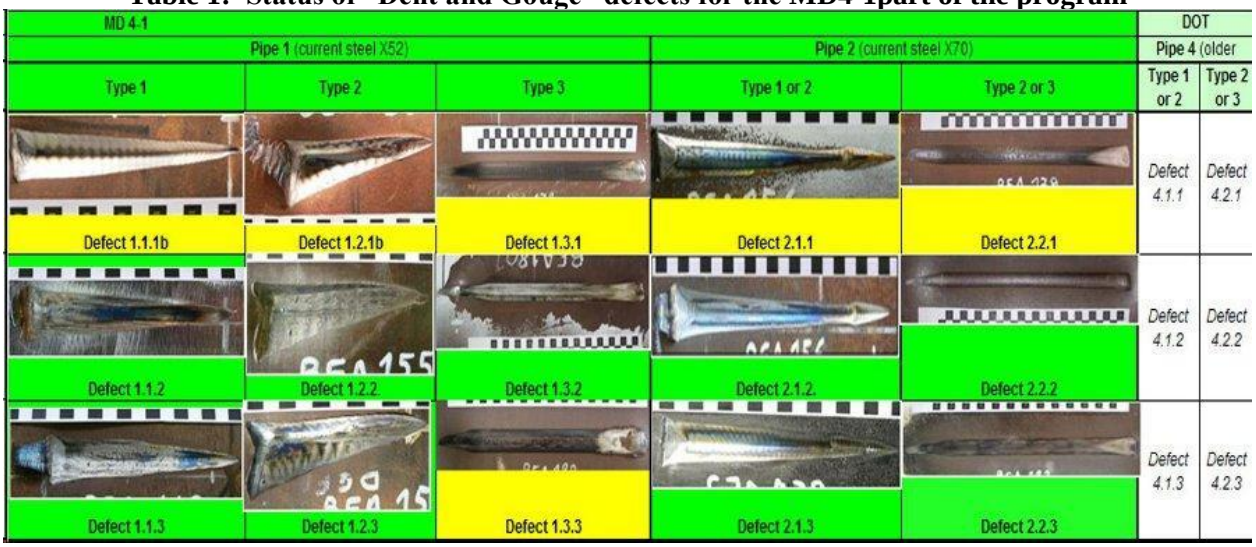
- Creation of defect 1.3.3;
- Fatigue tests of defect 2.2.3;
- Additional investigation by SEM of the hardened layer at the gouge bottom.

Table 1 below summarizes the progress of the task on "Dent and Gouge" defects for the MD4-1 part of the program. The background color in the table represents:

- White: Defects not yet created
- Yellow: Defects already created but not yet characterized/investigated or submitted to either burst or fatigue tests

- Green: Defects created and tests completed

Table 1: Status of "Dent and Gouge" defects for the MD4-1part of the program



Business Status

The project remains well coordinated with the pipeline industry through PRCI.

Funds Expended

The financial condition of the project is shown in Table 2 below. Please note that a contract modification was submitted to DOT which will affect the budget.

Table 2: Status of the budget for the Project

		Federal Funding			Cost Share Funding			
Task # per MS	**Task Description**	**Budget**	**Expended (Actuals) This Quarter**	**Expended (Actuals) to Date**	**Budget**	**Expended (Actuals) This Quarter**	**Expended (Actuals) to Date**	**% Task Work Completed**
1	Project Kick Off Meeting and Subcontracting	$9,335	$0	$9,335	$831	$0	$831	100%
2	Purchase & Characterize Pipe Material	$134,674	$15,107	$34,674	$146,108	$44,453	$68,769	67%
3	Literature Review	$11,549	$0	$11,549	$8,669	$0	$6,975	100%
4	Testing of Dents on Welds & Corrosion Features	$188,507	$0	$157,363	$599,632	$25,934	$438,065	75%
5	Testing of Dents with Gouges	$150,020	$0	$150,020	$254,404	$0	$71,336	60%
6	Demonstration of Mechanical Damage	$22,008	$0	$0	$10,930	$0	$0	30%

	Model Performance							
7	Industry Workshop	$12,030	$0	$0	$4,325	$0	$0	0%
8	Project Management and Reporting	$88,366	$1,834	$57,076	$43,959	$0	$1,450	On-going
	GRAND TOTAL	**$616,490**	**$16,941**	**$420,017**	**$1,068,858**	**$70,387**	**$587,425**	

Schedule

The project is generally on schedule, but as discussed in prior reports, Task 5 is impacted by the decision to add neutron diffraction testing of selected dent+gouge samples to the program. The facility initially selected to perform the neutron diffraction testing, the Canadian Neutron Beam Centre (CNBC) at Chalk River, ON, experienced a shutdown for an extended period and this has delayed the proposed additional testing. To help address the delay, the Program Team has coordinated with National Institute of Standards and Technology (NIST) Center for Neutron Research at Gaithersburg, MD to perform the testing. In April, NIST received defects 1.1.1b and 1.3.1, and NIST is finishing the experimental work and interpretation of the data this month. The reader should note that the analysis of the defect samples using neutron diffraction was not included in the original scope of work and was added to the program to capitalize on the availability of the neutron diffraction testing equipment and laboratories at no cost to the project. The data generated will be very beneficial to improving the understanding the behavior of dent+gouge defects and providing further input for improving the mechanical damage modeling projects.

Payable Milestones

Task status for this period is shown in **Table 3**.

Table 3: Status of Tasks for Project

Task No.	Task	Status	Scheduled Completion Date	Payable Milestone (Item No)
1	Project Kick Off Meeting and Subcontracting	100% Complete	8/31/2008	
2	Purchase & Characterize Pipe Material	67% Complete	8/31/2010	16
3	Literature Review – effect of pre-strain and dent-gouge defect from field feed-back	100% Complete	11/30/2009	
4	Testing of Dents on Welds and Corrosion Features	75% Complete	2/28/2012	32
5	Testing of Dents with Gouges	60% Complete	2/28/2012	
6	Demonstration of Mech. Damage Model Performance	30% Complete	11/30/2011	
7	Industry Workshop	0% Complete	5/31/2012	

8	Project Management and Reporting	On-Going	5/31/2012	

Results and Conclusions

A summary of the results are:

- Task 2—Material characterization are complete for Pipe 1 and Pipe 2;
- Task 3—The literature review of cyclic fatigue dent assessment techniques is complete;
- Task 4—The testing of dents interacting with girth welds is complete.
- Task 5—The team created a dent+gouge defect labeled 1.3.3 and performed a fatigue test on defect 2.2.3. They also used scanning electron microscope (SEM) to investigate a small surface crack in defect 1.1.3

Task 4: Testing of Dents on Welds and Corrosion Features

A summary of the full scale fatigue test results, for dents on Pipes 1 and 2 (i.e. all plain dents, dents interacting with welds and dents interacting with simulated corrosion features) is presented in the table below.

Table 4: Summary of Full Scale Dent Tests – Pipe Materials 1 and 2

Spec #	Pipe	Nominal Indenter Diameter	Indenter Travel	Rest.	Cond.	Initial Pressure Cycle	Weld Loc.	Metal Loss	Initial Dent Depth	Final Dent Depth	Cycles to Failure
		(in)	(%)			(%SMYS)			(%OD)	(%OD)	
1	1	2	7.5%	R	Plain	100%	N.A.	N.A.	N.A.	5.56%	6948
2	1	2	7.5%	R	Plain	100%	N.A.	N.A.	N.A.	5.51%	38685
3	2	4	10.0%	R	Plain	100%	N.A.	N.A.	N.A.	9.01%	6886
4	2	4	10.0%	R	Plain	100%	N.A.	N.A.	N.A.	8.28%	16234
5	2	4	10.0%	R	Plain	80%	N.A.	N.A.	N.A.	9.84%	2531
6	2	4	10.0%	R	Plain	80%	N.A.	N.A.	N.A.	9.84%	3359
7	1	2	15.0%	U	Plain	100%	N.A.	N.A.	5.21%	2.63%	21103
8	1	2	15.1%	U	Plain	100%	N.A.	N.A.	5.88%	2.48%	28211
9	1	2	15.1%	U	Plain	80%	N.A.	N.A.	5.89%	3.28%	6825
10	1	2	15.1%	U	Plain	80%	N.A.	N.A.	5.76%	2.69%	9116
11	1	4	15.0%	U	Plain	100%	N.A.	N.A.	7.99%	2.55%	15063
12	1	4	15.1%	U	Plain	100%	N.A.	N.A.	6.00%	2.28%	27575
13	2	2	15.0%	U	Plain	100%	N.A.	N.A.	5.81%	2.17%	13262
14	2	2	15.0%	U	Plain	100%	N.A.	N.A.	5.74%	2.21%	15065
15	2	2	15.0%	U	Plain	80%	N.A.	N.A.	5.52%	2.21%	4035
16	2	2	15.0%	U	Plain	80%	N.A.	N.A.	5.63%	2.22%	4684
17	2	4	15.0%	U	Plain	100%	N.A.	N.A.	5.41%	1.56%	11415
18	2	4	15.0%	U	Plain	100%	N.A.	N.A.	5.32%	1.69%	15949
19	1	2	5.1%	R	L.S.	100%	2" Off	N.A.	n/a	n/a	32282
20	1	2	5.1%	R	L.S.	100%	2" Off	N.A.	n/a	n/a	24919
21	1	2	5.0%	R	G.W.	100%	2" Off	N.A.	N.A.	2.78%	66871
22A	1	4	10.0%	R	G.W.	100%	2" Off	N.A.	N.A.	4.60%	66429
23	2	4	10.0%	R	G.W.	100%	2" Off	N.A.	N.A.	5.88%	12722
24	2	4	10.1%	R	G.W.	100%	2" Off	N.A.	N.A.	5.49%	16278
25	1	2	15.0%	U	G.W.	100%	C.L.	N.A.	6.28%	2.77%	19063

27	1	2	15.0%	U	G.W.	100%	2" Off	N.A.	6.93%	2.88%	18633
28	1	2	15.0%	U	G.W.	100%	2" Off	N.A.	6.85%	2.88%	16107
29	1	4	15.0%	U	G.W.	100%	2" Off	N.A.	6.35%	2.20%	14400
31	2	2	15.1%	U	G.W.	100%	2" Off	N.A.	6.03%	2.55%	9890
32	2	2	15.0%	U	G.W.	100%	2" Off	N.A.	5.97%	2.51%	9506
33	2	4	15.1%	U	G.W.	100%	2" Off	N.A.	5.82%	2.20%	9386
34	2	4	15.0%	U	G.W.	100%	2" Off	N.A.	5.87%	1.97%	9871
35	2	4	15.1%	U	G.W.	100%	C.L.	N.A.	5.28%	2.10%	19959
36	2	4	15.0%	U	G.W.	100%	C.L.	N.A.	5.03%	1.88%	15568
26*	1	4	10.0%	R	M.L.	100%	N.A.	1	10.0%	6.06%	40832
30	1	4	10.0%	R	M.L.	100%	N.A.	2	10.0%	6.08%	31179
37*	1	4	15.0%	R	M.L.	100%	N.A.	3	15.0%	3.41%	42159
38	1	4	15.0%	U	M.L.	100%	N.A.	1	15.0%	2.43%	32963
39	2	4	5.0%	R	M.L.	100%	N.A.	1	5.0%	2.81%	7559
40	2	4	15.0%	U	M.L.	100%	N.A.	1	15.0%	2.01%	6504

* Indentation carried out under 30% pressure.

Task 5: Testing dents with gouges: Creation of defect 1.3.3, fatigue test of defect 2.2.3 and microscopic examination of small crack in hardened layer of defect 1.1.3.

The team created defect 1.3.3 using a slower aggression procedure, similar to defects 1.3.1 and 1.3.2. They created it under an internal pressure of 30 bar in order to ensure the process would produce a deep dent. The force versus displacement is plotted below in **Figure 1**. The value of total absorbed energy for the creation of defect 1.3.3 is 23973 J. This value is aligned with the energy levels of 34930 Joules and 28312 Joules for the similar defects, which in turn were high compared to the absorbed energy below 10000 J for other defects created with dynamic impact aggression. This difference is due to the defect length, almost three times longer in the former case.

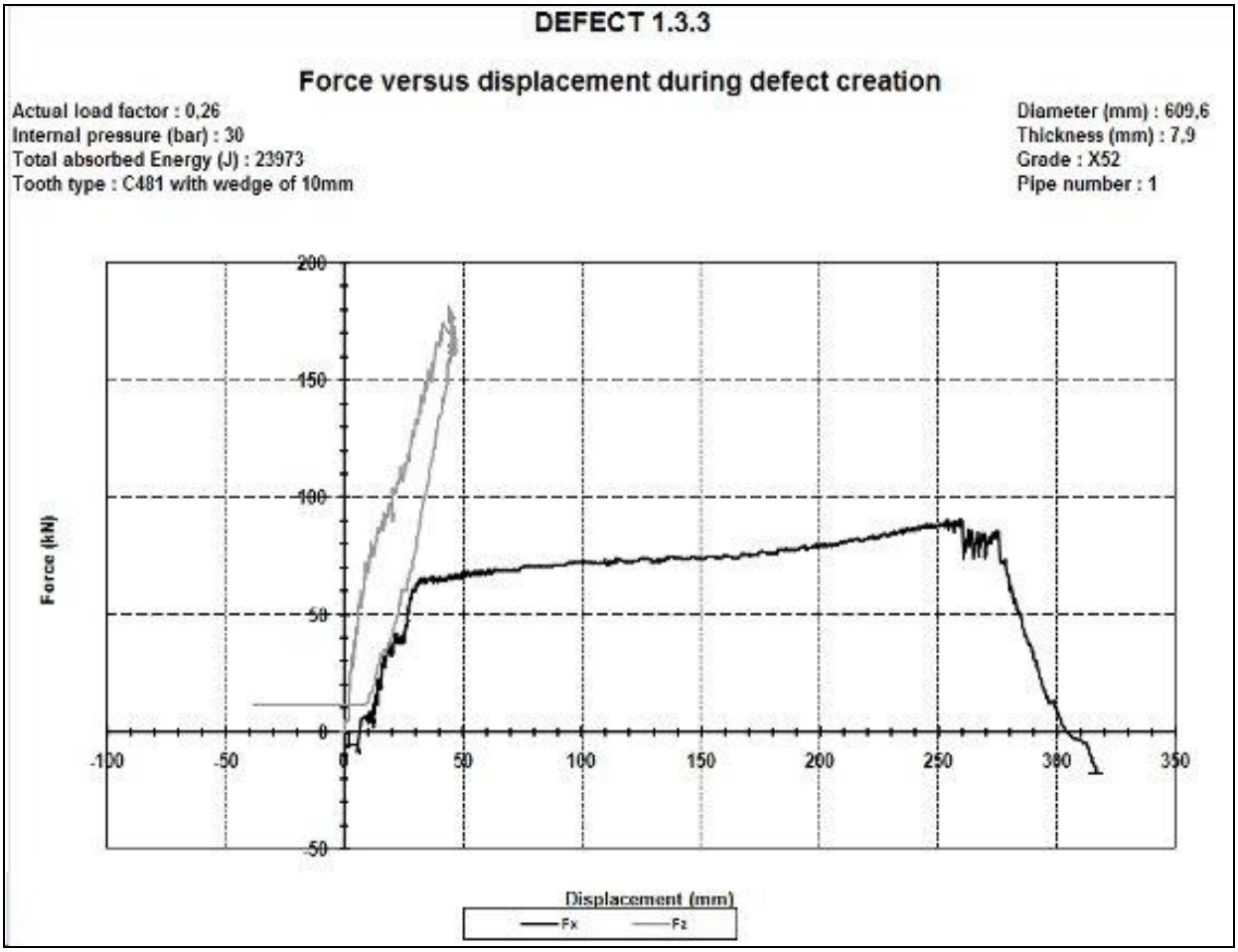


Figure 1: Force-displacement curve for creation of defect 1.3.3

After the defect creation, the team did not detect any cracks at the bottom of the gouge using MPI (Magnetic Particles Inspection).

The dent depth is 5.8% and the gouge depth is 20%. For comparison the values of dent depth for respectively defects 1.3.1 and 1.3.2 were 5.3% and 5.7% and the values of gouge depth 28% and 29%., respectively. **Figure 2** shows the longitudinal profile of defect 1.3.3 passing by the deepest point.

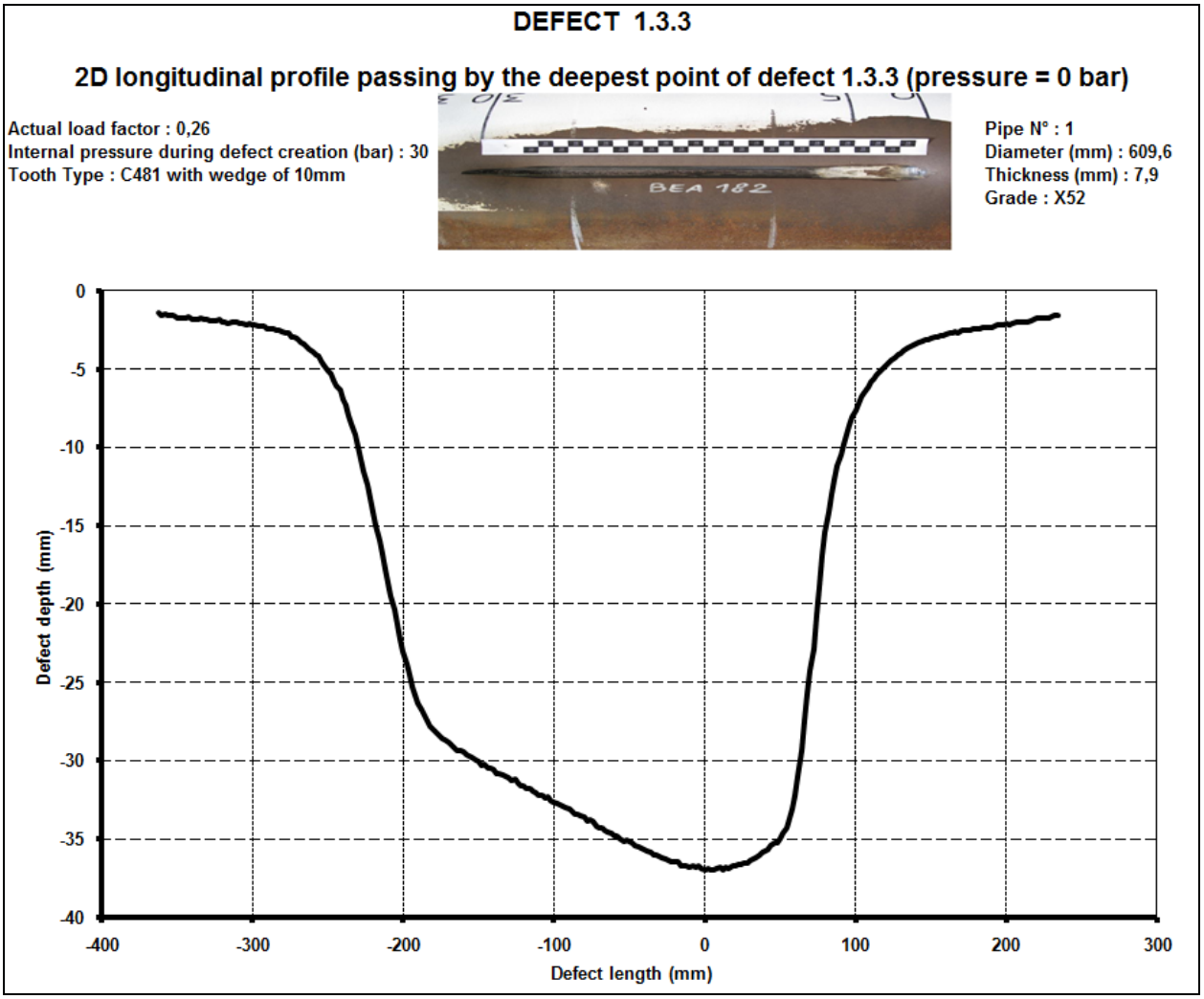


Figure 2: **Longitudinal profile passing by the deepest point of defect 1.3.3**

GDF SUEZ performed fatigue test on defect 2.2.3. They equipped the sample with one clip gauge, rosettes at the edge of the gouge, one hoop uni-axial strain gauge at the gouge bottom, and two vertical displacement sensors in the gouge. For reference, the researchers placed strain gauges and one vertical displacement sensor on the pipe body. They also adhered targets at the edge of the gouge on each side to measure the displacements of targets with a camera during the test. Finally, the team used acoustic emission sensors to detect with accuracy the failure onset and also to estimate the number of cycles of crack initiation. **Figure 3** gives a view of instrumentation (after fatigue failure).

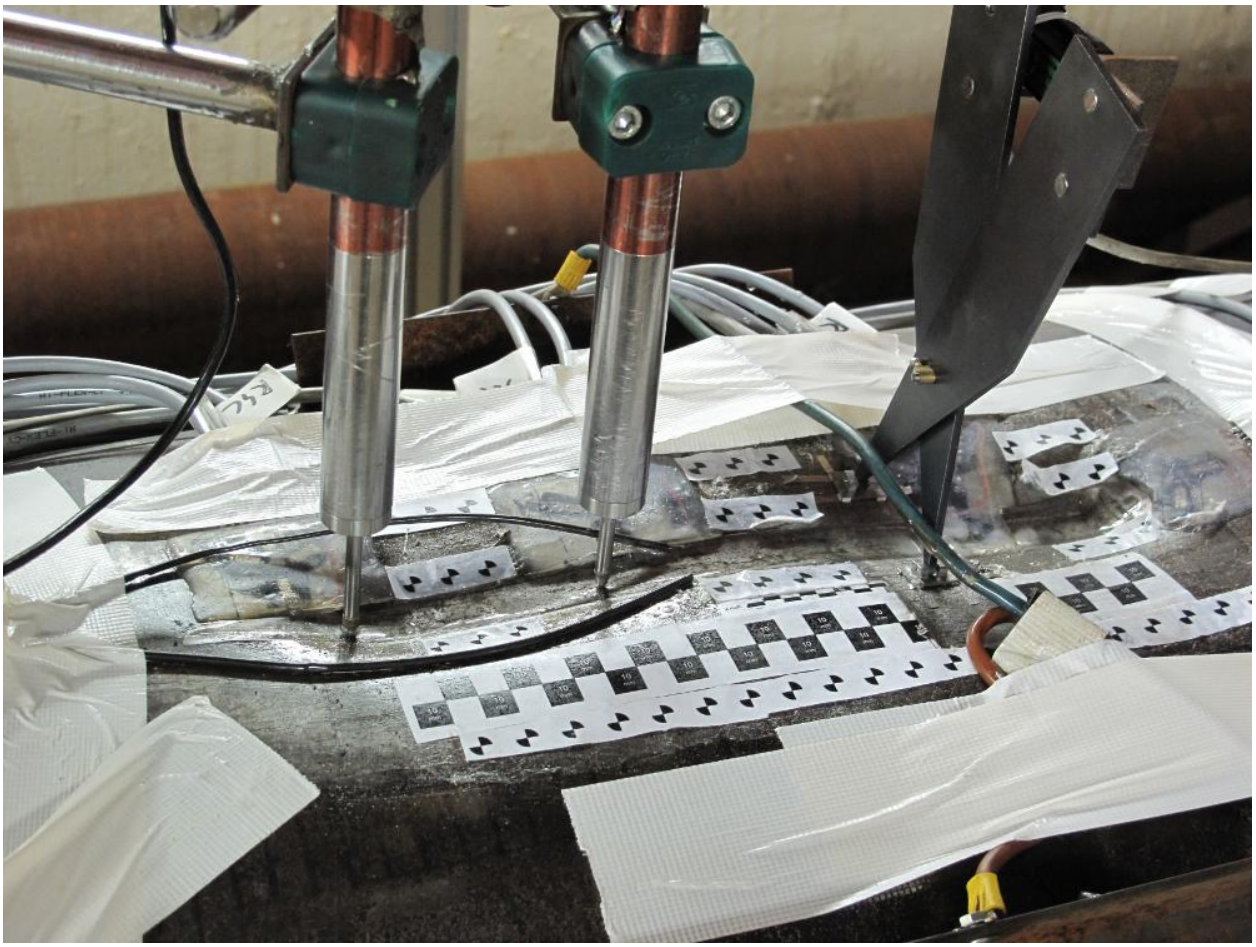


Figure 3: **Instrumentation of defect 2.2.3 (view after fatigue failure)**

The pressure cycling range was between 20-60 bar which was the same 40 bar pressure range as used for all other fatigue tests. This level of pressure was low to compare with the burst pressure around 190 bar (193 bar was measured at the burst of similar defect 2.2.2). The choice of this pressure range was motivated by observations and data that showed dent bulging occurring just above the pressure of dent creation at 20 bar. This was documented using the new instrumentation which recorded the conditions of the sample during the burst test failure. In comparison, the team used a cycling range of 88 – 128 bar on defect 2.1.3. The sampled failed soon after starting the cycling. The camera showed a water drop on the crack initiated in the gouge near targets 3-4 as captured with the camera at 2007 cycles (**Figure 4**).

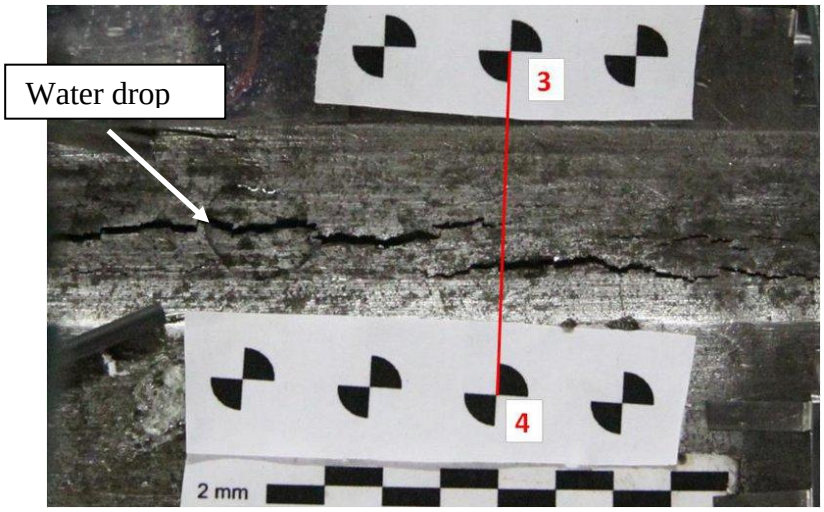


Figure 4: Water drop from crack in the gouge at 2007 cycles (defect 2.2.3)

The team observed the initiation of a crack in the gouge near the targets 3-4 around 1300 cycles as shown in **Figure 5**.

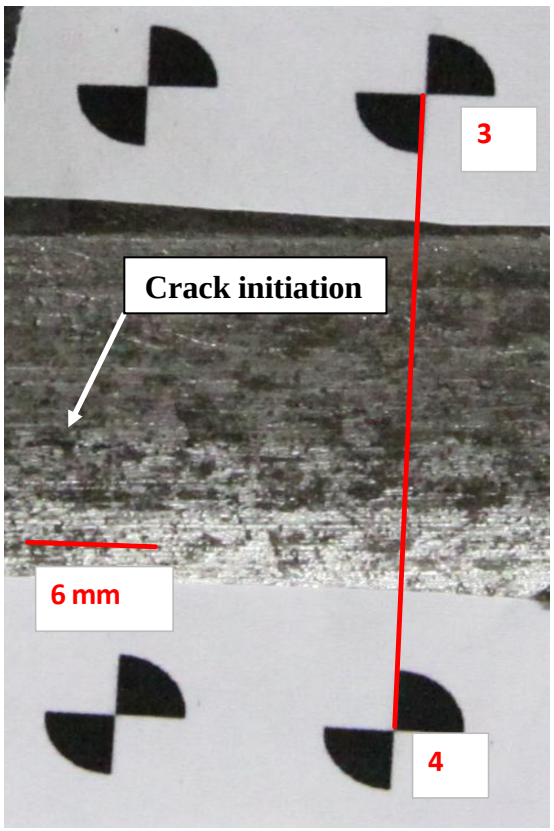


Figure 5: Crack initiation at the gouge bottom around 1300 cycles (defect 2.2.3)

Figure 6 shows the opening displacement from two different measurements: the clip gauge and the distance between opposite targets (1-2 and 3-4) as the sampled is cycled. The opening displacement is recorded each cycle at the minimum pressure and at the maximum pressure. The

two opening displacement measurements agree closely. The opening displacement slope accelerates around 1300 cycles which corresponds to the crack initiation at the gouge bottom. The slope is steeper for targets 3-4 and the clip gauge than targets 1-2 (see targets position on photo of figure 6). This may be due to the fact that the crack initiation is observed closer to targets 3-4 and to the clip gauge than to targets 1-2.

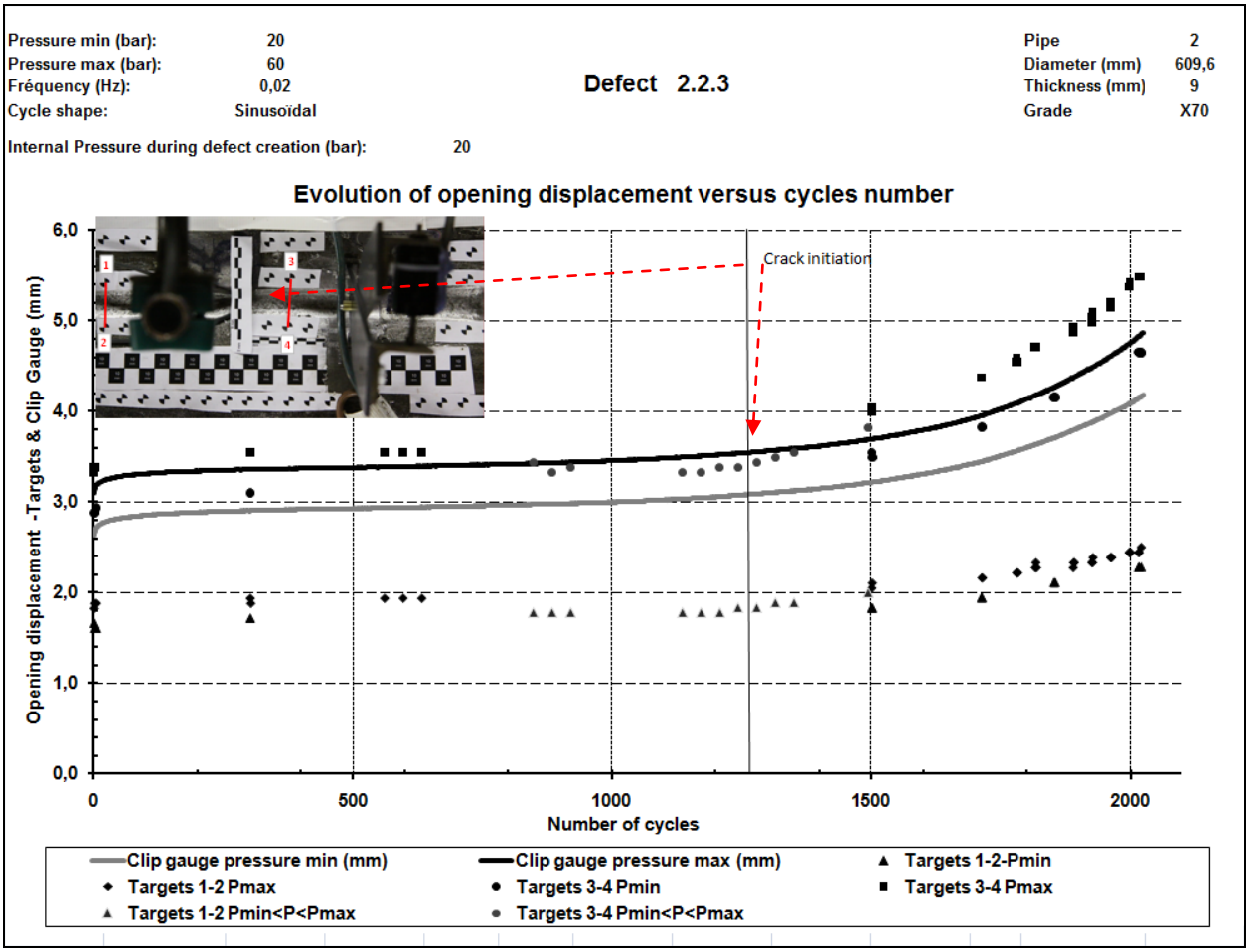


Figure 6: Evolution of clip gauge opening and targets distances (defect 2.2.3)

The test equipment recorded significant acoustic emission signals between 1730 and 1930 cycles and from 2007cycles until failure where they observed a water drop escaping from the crack with the camera. However, the researchers did not find any acoustic signals between 1930 and 2007 cycles. Finally, the acoustic equipment also recorded six other smaller intermittent acoustic emission signals in the range of 350 cycles to 800 cycles before seeing the crack initiation at the gouge bottom around 1300 cycles.

SEM (Scanning Electron Microscope) was used to investigate the surface of a small crack in the hardened layer of previous defect 1.1.3. A pure cleavage is observed as shown in **Figure 7**. This result confirms the very high brittleness of this area.

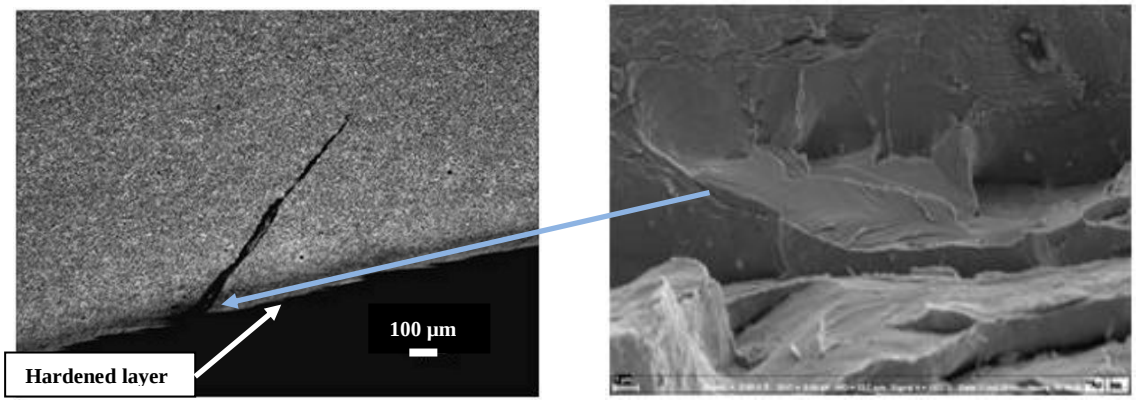


Figure 7: Small crack at the gouge surface of defect 1.1.3 and pure cleavage observed by SEM in the area of hardened layer of the crack surface.

Task 8: Project Management and Reporting

The team continues to submit monthly and quarterly reports, and meets as necessary to discuss the test results.

Issues, Problems or Challenges

As discussed above, the team plans to complete preliminary material characterization of the vintage pipe in early September for Pipe 3 and later for other vintage pipes (i.e., Pipe 4 and other pipe materials used for dent+gouge test samples). However, the full characterization will continue through at least March 2011. The team believes that this delay will not affect the overall project schedule, since the other testing will continue in parallel during this time. The team is in the process of evaluation options to expedite the characterization process.

Plans for Future Activity

Planned activities for the project are presented below.

Task 2: Purchase & Characterize Pipe Material

The full-scale testing on vintage pipe material will begin once the materials are delivered to the test facilities (SES in Houston, TX, and GDF SUEZ in Saint Denis, France). Prior to delivering the materials to the testing facilities, BMT and SES will perform preliminary material characterization to verify that the selected materials are representatives of vintage pipe properties. If the material is considered representative of vintage pipe properties, the team will carry out a detailed characterization.

Task 4: Testing of Dents on Welds and Corrosion Features

Full scale dent testing of the vintage pipe specimens (Pipe 3) will commence within the next quarter, following the completion of the detailed material characterization testing program.

Task 5: Testing of Dents with Gouges

GDF SUEZ will perform fatigue test on defect 1.3.3.