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

Date of Report February 29, 2012

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Project Title Project WP#339: Structural Significance of Mechanical Damage

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For Period Ending: February 29, 2012

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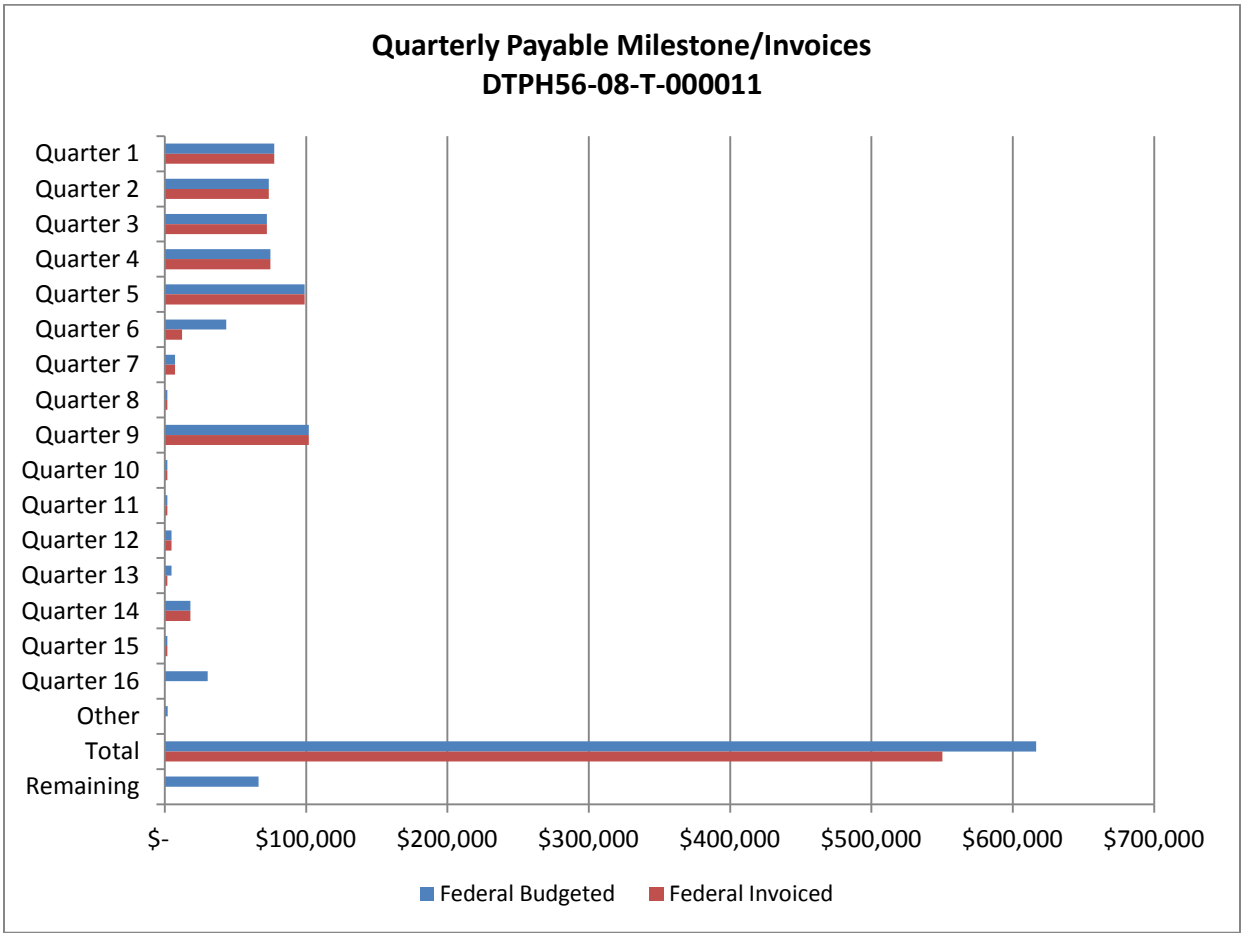
Funds and Work Completed During this Quarterly Period



Technical Status

Technical activities undertaken through the Thirteenth Quarter focused on the following tasks:

- Task 2—Purchase & Characterize Pipe Material
- Task 3—Literature Review
- Task 4—Testing of Dents on Welds and Corrosion Features
- Task 5—Testing of Dents with Gouges
- Task 6--Demonstration of Mechanical Damage Model Performance
- Task 8 – Project Management and Reporting

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

Task 2: Purchase & Characterize Pipe Material

There are currently four different pipe steels in this program:

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

- Pipes 3 are older steel to represent the majority of the pipelines in-service. It was initially intended to provide a manufactured pipe that replicates vintage pipe properties for Pipe 3. 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 the need to use several different pipes retrieved from service: one vintage material for the full-scale testing program for dents, designated Pipe 3, and

- Pipe 3DG for Dent and Gouge study left Houston at the end of January 2012 and should arrive at the GDF SUEZ lab at the end of February 2012. The tables below are the mechanical characteristic of this pipe, exhibiting very low toughness:

Table 1: Chemical analysis of Pipe 3DG (%)

C	S	P	Si	Cr	Mn	Ni	Cu	Other
0.19	0.024	0.017	0.06	0.03	0.91	0.03	0.08	<0.01

Table 2: Tensile and Charpy properties

Yield Strength Lb/in²	Tensile Strength Lb/in²	Elongation%	Charpy at 32°F Specimen size 10mm*6.7mm Ft.lbs
53.5	74.0	33	9

Task 3: Literature Review

The team has completed the literature review regarding cyclic fatigue dent assessment techniques. They will submit a report summarizing the findings and demonstrating the performance of the identified assessment techniques following the completion of the testing.

Task 4: Testing of Dents on Welds and Corrosion Features

BMT has completed the second batch of eight Pipe 3 plain dent specimens. The matrix below shows the current results for the seventeen tests carried out on vintage pipe specimens. It also illustrates the use of four different spherical indenter sizes (2, 4, 8 and 12 in.), five levels of indentation depth, three levels of internal pressure during dent formation and two dent restraint conditions. The tests carried out to date on Pipe 3 are plain dent fatigue tests.

Table 3: Pipe 3 Plain Dent Experimental Specimens

Specimen #	Nominal Indenter Diameter (inch)	Indenter Travel (% OD)	Dent Restraint	Indentation Pressure	Initial Pressure Cycle (%SMYS)	Cyclic Pressure Range (%SMYS)	Dent Depth After Testing Complete (%OD)	Cycles to Failure
41	2	5	R	0%	100%	10%-80%	3.1	69099
42	4	10	R	0%	100%	10%-80%	6	69393
43	4	7.5	R	0%	100%	10%-80%	4.9	30604
44	8	7.5	R	0%	100%	10%-80%	4.1	54036
45	8	7.5	R	40%	100%	10%-80%	4.4	58532
46	12	5	R	0%	100%	10%-80%	3	125525*
47	8	7.5	R	80%	100%	10%-80%	4.3	61865
48	2	15	U	0%	100%	10%-80%	2.9	23482
49	2	10	R	0%	100%	10%-80%	6.3	30604
50	2	15	U	40%	100%	10%-80%	4.3	16600
51	23	15	U	80%	100%	10%-80%	4.8	12131
52	4	15	U	0%	80%	10%-80%	2.5	9226
53	12	20	U	40%	80%	10%-80%	1.3	18636
54	12	15	U	0%	100%	10%-80%	1.0	47702
55	12	20	U	80%	105%	10%-80%	1.4	21018
56	4	20	U	0%	100%	10%-80%	2.5	15473
57	12	20	U	0%	80%	10%-80%	0.8	14091

*Failed outside dent region

Figure 1 shows a typical restrained dent pipe specimen after test completion. The dent center is located at the crosshair marked on the pipe, and the ruler is placed parallel to the pipe's longitudinal axis. In Figure 1 and all restrained dent fatigue tests to date, the cracks were oriented circumferentially and located in either one or both of the axial dent shoulders.

Figure 2 shows a typical un-restrained dent pipe specimen after the completion of the test. The dent center is at the cross hair marked on the pipe and the ruler shown is parallel to the pipe longitudinal axis. There are multiple fatigue cracks in the axial orientation present on the dent shoulders. In most of the un-restrained dent fatigue tests carried out to date, (except for Specimen 54 and 57), the fatigue cracks were oriented axially and located in either one or both the axial dent shoulders (that are along pipe longitudinal axis).

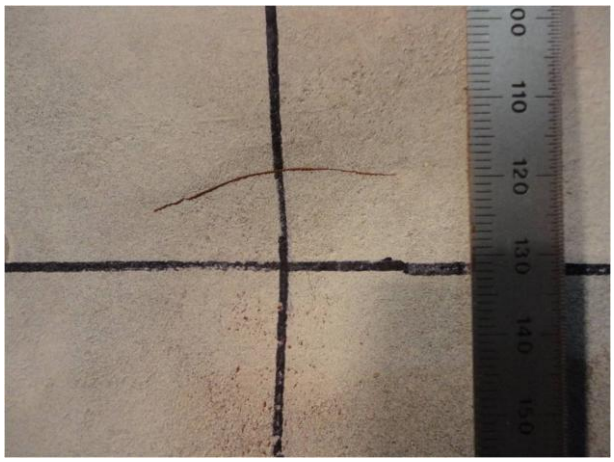


Figure 1: Circumferential Fatigue Crack in the Dent Shoulder in a Restrained Dent (Specimen 41).

Figure 2: Axial Fatigue Cracks in the Dent Shoulder in an Un-Restrained Dent (Specimen 48)

Figure 3 shows a typical strain range path plot along the axial centerline of the finite element model for a restrained dent. As shown in the plot, the researchers observed the maximum strain range on the inner pipe surface (ID) in the axial direction for the restrained dent fatigue tests. Figure 4 shows a typical strain range path plot for an unrestrained dent predicted by the finite element model. In unrestrained dent fatigue tests, the maximum strain range was observed on the outer pipe surface (OD) in the hoop direction.

Based on the observed maximum strain range values, the axially oriented fatigue cracks should initiate on OD surface, away from the dent center in the shoulder region in unrestrained dent fatigue test and the circumferentially oriented fatigue cracks should initiate in the ID surface, away from the dent center in the shoulder region in restrained dent fatigue test

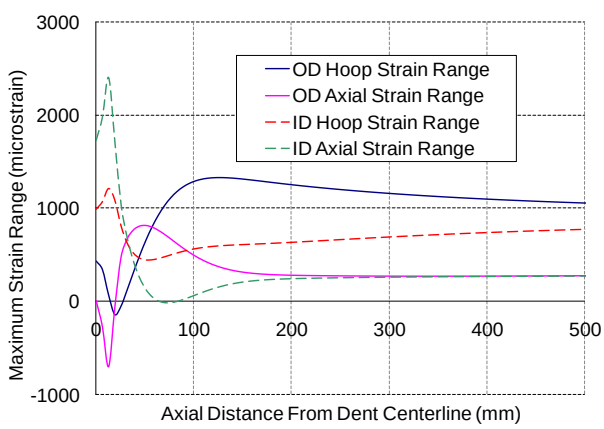


Figure 3: Strain Range Path Plot for a Restrained Dent (Specimen 41).

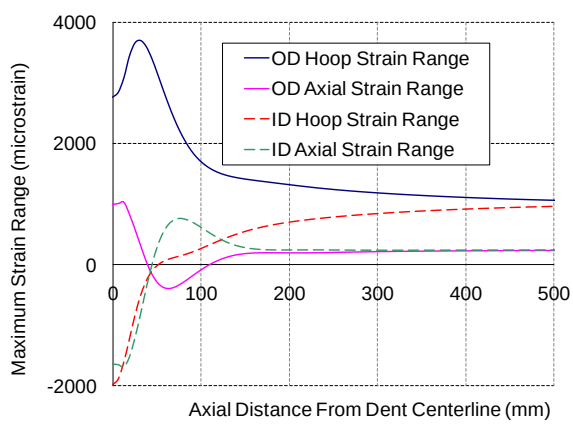


Figure 4: Strain Range Path Plot for an Unrestrained Dent (Specimen 48).

The photograph shown in Figure 5 shows a typical fracture surface of a fatigue crack from a restrained dent fatigue test. The cross section shown is normal to the pipe longitudinal axis with the ID surface at the top of the photograph and the OD surface at the bottom of the photograph. The crack length is longer on the pipe ID surface and multiple crack initiation sites can be seen on the ID surface. Figure 6 is another typical photograph of a fracture surface of a fatigue crack

from an un-restrained dent fatigue test. The cross section shown is parallel to the pipe longitudinal axis with OD surface on top of the photograph and ID surface on the bottom the photograph. There are multiple crack initiation sites on the OD surface and crack length is longer on the pipe OD surface. The large steps seen in the macro are due to the presence of multiple parallel fatigue cracks being broken open.

Figure 5: Fracture Surface of a Fatigue Crack in a Restrained Dent.

Figure 6: Fracture Surface of a Fatigue Crack in an Un-Restrained Dent

The circumferential crack orientation on the ID surface of the dent shoulder in restrained dents and the axial crack orientation on the OD surface of the dent shoulder in unrestrained dents are in agreement with finite element model predictions as shown in Figures 3 and 4 respectively.

Figure 7 and Figure 8 show photographs of two unrestrained dent fatigue test specimens, specimen 57 and 54 respectively where the 12 in. indenter was used to create dents at zero internal pressure. In both cases, fatigue crack locations are close to or at the dent center as compared to earlier observations, as shown in Figure 2, where the fatigue crack location is away from the dent center and at the dent shoulder. In both the test specimens (54 and 57) the final dent depth was around 1% of the OD or lower.

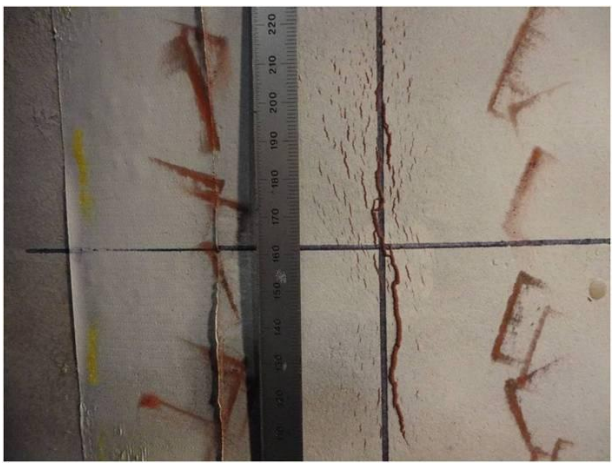


Figure 7: Axial Fatigue Cracks Located in the Dent Center for 1% Un-Restrained Dent (Specimen 57) Created with 12 inch Indenter

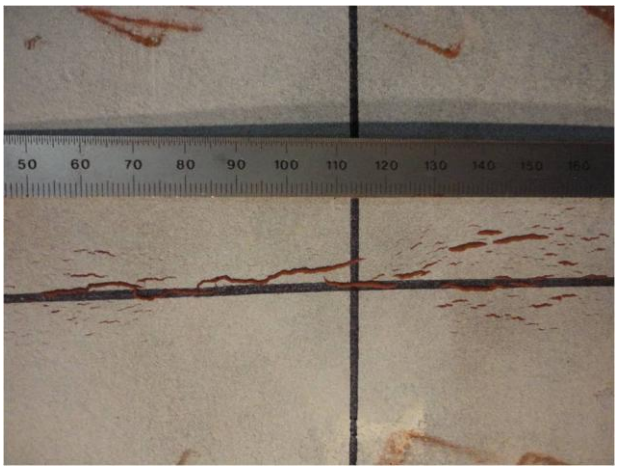


Figure 8: Axial Fatigue Cracks Located in the Dent Center for 1% Un-Restrained Dent (Specimen 54) Created with 12 inch Indenter

Figure 9 shows the strain range plots for the two specimens (54 and 57) as predicted by finite element models. In both cases, the maximum strain range is at the dent center as compared to the earlier example, shown in Figure 4, where the maximum hoop strain range was away from the dent center. It appears that shallow unrestrained dents created by the larger indenter at zero internal pressure, led to a higher hoop strain range at the dent center, and therefore, promoted fatigue cracking in the dent center.

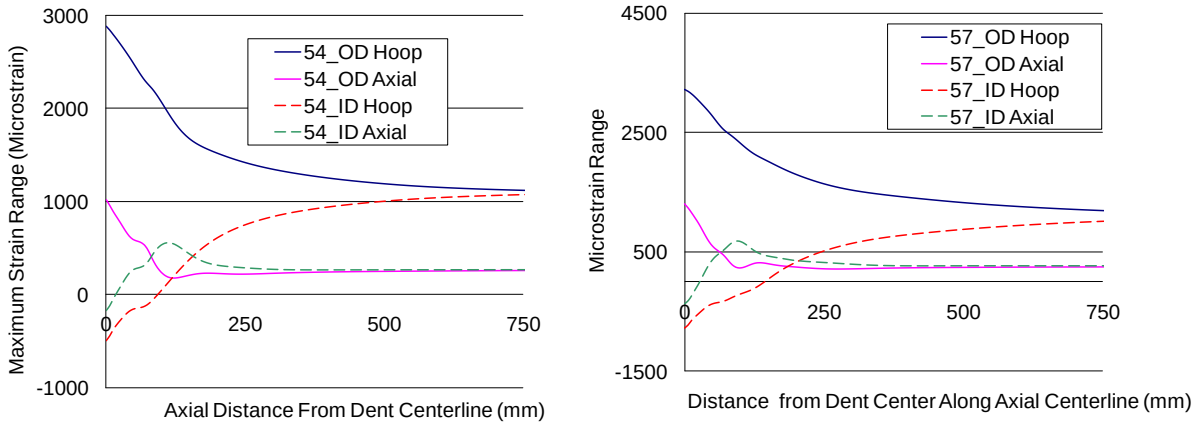


Figure 9 Strain Range Path Plot for Shallow Un-Restrained Dents Created using Large Indenter.

In the present full scale test program, the fatigue crack orientation was circumferential in restrained dent tests and axial in unrestrained dent tests. In restrained dent tests as shown in Figure 1, there was one dominant fatigue crack, as seen from outside in either one or both the axial dent shoulders. In unrestrained dent fatigue tests (except the two shallow dent cases discussed above), there were multiple fatigue cracks as shown in Figure 2 in either one or both the axial dent shoulders. These observations are supported by finite element modeling results. Figure 10 shows the ID axial stress range contour plot for a restrained dent (specimen 41). The maximum stress range is localized and confined to the two dent shoulders and, therefore, appears to promote the formation of a single dominant fatigue crack in the circumferential orientation. Figure 11 shows the OD hoop stress range contour plot for an unrestrained dent (specimen 48).

As shown, there is a wide area around the dent shoulders that experiences a large stress range and therefore results in promoting multiple fatigue cracks in the axial orientation in unrestrained dent fatigue test.

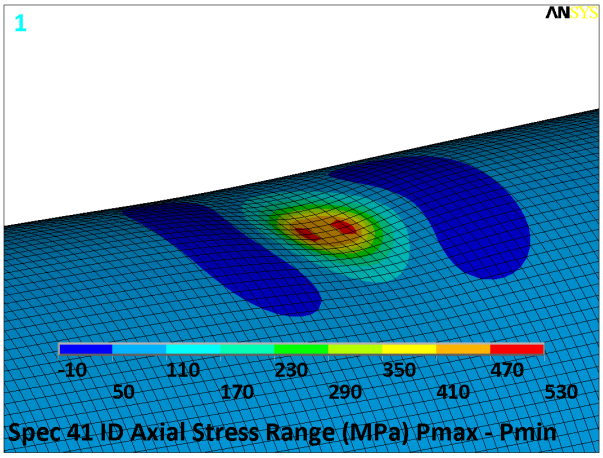


Figure 10: ID Axial Stress Range Contour Plot for Restrained Dent.

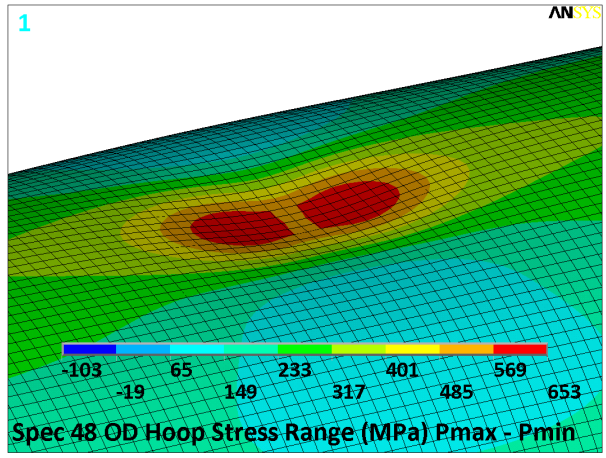


Figure 11: OD Hoop Stress Range Contour Plot for Un-Restrained Dent

The multiple fatigue cracks seen in unrestrained dent cases, as shown in Figures 2, 7 and 8 earlier resemble stress corrosion crack (SCC) colonies in pipelines. However, in the current tests the multiple cracks are similar to what is typically seen in low cycle fatigue tests. The cyclic pressure ranges used in the test program are 10%-80% SMYS which are considered very aggressive and not typically seen in routine pipeline operation. Since, the multiple crack indications in the current tests were present even in the shallow dents, around 1% deep or lower (Figures 7 and 8), so it is conceivable that there can be scenarios present in existing pipelines where deeper unrestrained dents (>1%OD) but experiencing smaller pressure ranges (30-40% SMYS) typical of liquid pipelines may see similar stress ranges as generated in the present test program and therefore promote multiple low cycle fatigue cracks and may potentially be mischaracterized as SCC colonies on the basis of appearance.

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., dent+gouge, 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+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.

The background color in the table represents:

- White: Defects not yet created (vintage pipe)
- Yellow: Defects already created but not yet fully characterized (this includes destructive and neutron diffraction testing for characterizing through wall residual strain
- Green: Defects created and all tests completed.

Table 4: Status of dent+gouge defects in Modern Pipes 1 and 2

Pipe 1 (modern steel X52) 24'' - 0.311''			**Pipe 2 (modern steel X70) - 24'' - 0.354''**	
Type 1 : Dynamic aggression **shallow dent - medium gouge**	Type 2 : Dynamic aggression **shallow dent - severe gouge**	Type 3 : Low dynamic aggression **severe dent - medium gouge**	Type 1 : Dynamic aggression **shallow dent - medium gouge**	Type 2 : Low dynamic aggression **severe dent - medium gouge**
MD-4-1				
Defect 1.1.1b	Defect 1.2.1b	Defect 1.3.1	Defect 2.1.1	Defect 2.2.1
Defect 1.1.2	Defect 1.2.2	Defect 1.3.2	Defect 2.1.2	Defect 2.2.2
Defect 1.1.3	Defect 1.2.3	Defect 1.3.3	Defect 2.1.3	Defect 2.2.3

Table 5: Status of dent+gouge defects in Vintage Pipe 3DG

Pipe 3DG (vintage steel X52) - 26'' - 0.312''	
Type 1 : Dynamic aggression **shallow dent - medium gouge**	Type 2 : Low dynamic aggression **severe dent - medium gouge**
DOT	
Defect 3DG.1.1	Defect 3DG.2.1
Defect 3DG.1.2	Defect 3DG.2.2
Defect 3DG.1.3	Defect 3DG.2.3

GDF SUEZ investigated defect 2.1.1 by destructive metallurgical characterization. As usual, the defect is cut in 10 samples (Figure 12).

Figure 12 : Sample locations of for metallurgical investigation of defect 2.1.1.

On each cut, the researchers performed the following:

- Inspected the steel microstructure
- Identified any present micro-cracks
- Sized, and profiled of micro-hardness along the wall thickness
- Deduced local strains

For the defect in Figure 12, which is similar to defect 1.1.1b, the results confirm those already obtained for other defects created by dynamic aggression. There is a presence of a hardened layer of tooth material which was transferred at the gouge surface to the second layer below. This thermally affected the pipe steel microstructure (Figure 13)

Figure 13: Hard layer and pipe steel microstructure on sample 6.

There are a few micro-cracks at the gouge surface which were created during the tooth impact and/or during the re-rounding caused by removing the tooth. Most of them are very small and only in the hard layer. However, Figure 14 shows one crack beyond the hard layer depth. All of the micro-cracks identified on ten samples are below the 200 µm depth.

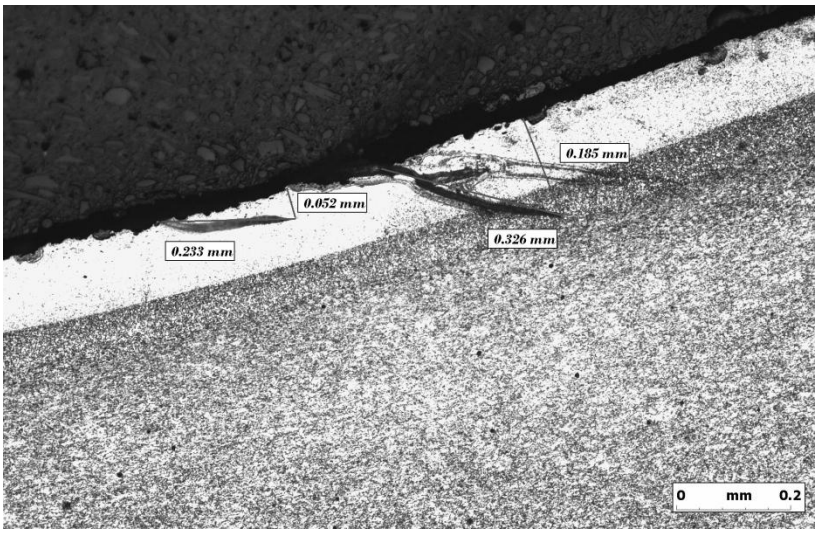


Figure 14: Micro-cracks observed on sample 6.

The micro-hardness profile exhibits high values up to 350 HV in the pipe steel close to the hard layer. This means that the local equivalent strain could reach around 50%-60%. Also under the gouge, but further away from the surface, the local strain stabilizes between 10% and 30%.

Metallurgical investigation of the last defect 2.2.1 created by slower dynamic aggression is underway and the results are expected in March 2012.

Technical Results and Conclusions

Task 2: Purchase & Characterize Pipe Material

Pipes 3DG are underway from Houston to GDF SUEZ labs to start Dent and Gouge experiments on vintage pipes.

Task 4: Testing of Dents on Welds and Corrosion Features

The team at BMT has completed plain dent fatigue tests on Pipe 3.

Task 5: Testing of Dents with Gouges

Metallurgical investigations on defect 2.1.1 created by dynamic aggression confirm previous results on similar defects. There are small micro-cracks in the hard layer which can extend slightly below it (200 µm) The regions has a very high micro-hardness near the gouge surface which reflects large local strains estimated around 50%-60%.

Task 8: Project Management and Reporting

The team completed the required monthly status updates and quarterly reports and also met via teleconference when necessary. BMT and GDF SUEZ presented their experimental results of the dent fatigue test and dent and gouge tests, respectively, at the PRCI research exchange meeting held in Phoenix in February 7-9 2012. Both groups have also submitted papers to IPC 2012.

Technical Issues, Problems or Challenges

The team is planning on submitting a request for a no-cost, extension. Important delays were unavoidable for Dent and Gouge tests on vintage pipes due to time spent to select vintage low toughness pipes and for their delivery.

Also, the scope for the dent fatigue tests needs to be modified in order to account for the modifications, proposed by the project team, and incorporated in tests completed.

Plans for Future Activity

Task 2: Purchase & Characterize Pipe Material

GDF SUEZ will start the material characterization of vintage pipe 3DG upon delivery.

Task 4: Testing of Dents on Welds and Corrosion Features

BMT will prepare a test matrix of four tests of dents interacting with welds for Pipe 3 and circulate it to project team for approval.

Task 5: Testing of Dents with Gouges

GDF SUEZ will complete the destructive characterization of the last defect 2.2.1 and will start defects creation on vintage pipe 3DG upon its delivery and tensile mechanical properties characterization.

Task 8: Project Management and Reporting

The team will complete the required monthly status updates and quarterly reports and also meet via teleconference when necessary.

Business Status

The financial condition of the project is shown in the table below.

		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**	**% Complete**
1	Project Kick Off Meeting and Subcontracting	$9,335	$0	$9,335	$831	$0	$831	100%
2	Purchase & Characterize Pipe Material	$134,674	$0	$134,674	$146,108	$0	$146,108	80%
3	Literature Review	$11,549	$0	$11,549	$8,669	$0	$8,669	100%
4	Testing of Dents on Welds & Corrosion Features	$188,507	$0	$157,363	$599,632	$77,800	$753,725	90%
5	Testing of Dents with Gouges	$150,020	$0	$150,020	$254,404	$0	$237,711	72%
6	Demonstration of Mechanical Damage Model Performance	$22,008	$0	$19,126	$10,930	$0	$5,530	90%
7	Industry Workshop	$12,030	$0	$0	$4,325	$0	$0	80%
8	Project Management and Reporting	$88,366	$1,834	$66,246	$43,959	$0	$21,692	On-going
	GRAND TOTAL	**$616,490**	**$1834**	**$548,313**	**$1,068,858**	**$93,418**	**$1,174,266**	

Schedule

The project schedule is impacted by the time spent to select, to validate and to transfer pipe 3DG from US to France. At this time pipe 3DG is expected to reach at the end of February 2012. The team will be ready to start material characterization and defects creation upon arrival.

Task No.	Task	Scheduled Completion Date	Completed Date	% Complete	Status (if delayed)
1	Project Kick Off Meeting and Subcontracting	8/31/2008	8/31/2008	100%	
2	Purchase & Characterize Pipe Material	8/31/2010	02/01/2011 for Pipes, 1, 2 and 3	80%	Pipe 1, 2 and 3 complete. This task was extended for Pipe 3DG
3	Literature Review	11/30/2009	11/30/2009	100%	
4	Testing of Dents on Welds and Corrosion Features	2/28/2012	Ongoing	85%	
5	Testing of Dents with Gouges	2/28/2012	Ongoing	72%	
6	Demonstration of Mechanical Damage Model Performance	11/30/2011	Ongoing	90%	
7	Industry Workshop	5/31/2012	Ongoing	80%	
8	Project Management and Reporting	5/31/2012	Ongoing	On-going	

Payable Milestones

Payable milestones for this period are shown in the table below.

		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**	**Payable Milestone (Item No)**
1	Project Kick Off Meeting and Subcontracting	$9,335	$0	$9,335	$831	$0	$831	
2	Purchase & Characterize Pipe Material	$134,674	$0	$134,674	$146,108	$0	$146,108	
3	Literature Review	$11,549	$0	$11,549	$8,669	$0	$8,669	
4	Testing of Dents on Welds & Corrosion Features	$188,507	$0	$157,363	$599,632	$16,692	$753,725	
5	Testing of Dents with Gouges	$150,020	$0	$150,020	$254,404	$0	$254,403	54
6	Demonstration of Mechanical Damage Model Performance	$22,008	$0	$19,126	$10,930	$0	$5,530	
7	Industry Workshop	$12,030	$0	$0	$4,325	$0	$0	
8	Project Management and Reporting	$88,366	$1,834	$68,080	$43,959	$0	$21,692	55
	GRAND TOTAL	**$616,490**	**$1,834**	**$550,147**	**$1,068,858**	**$16,692**	**$1,190,958**	