Full Scale Dent Rebound Testing of X65 Steel Linepipe

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Abstract. Dents in buried pipelines can be formed due to a number of causes: third party machinery strikes, rock strikes during backfilling, pipe resting on rock, and amongst others. Dents in pipelines would not only affect short and/or long-term integrity, but would also have a potential impact on the pass capacity of in-line inspection and cleaning tools when the size of the dent is large enough. Rebound for an originally constrained dent can decrease the dent depth and improve the pass capacity of in-line inspection and cleaning tools. In order to estimate the rebound capacity of dents especially in spiral weld pipelines, a full-scale dent rebound testing program of X65 steel pipeline was designed and performed. The full scale testing was conducted on the parent material and the spiral welds. Hemispherical and pyramidal indenters were used to generate dents to different depths. Strains around the denting area during formation of the dent and changes in depths due to rebounding after removing indenter were measured. Following each rebound test, the dent profile was portrayed with a 3D laser scanner and the maximum equivalent strain was then calculated. With the information obtained from the above measurements, detailed analyses were performed and a numerical model was developed. In this paper, the approach used for the study is described first. The results and findings are then presented. The effectiveness of the developed numerical model for dent integrity management is demonstrated.

1. Introduction
Dents are created by external force such as rock movement or soil movement. ASME B31.8 defines dent as a permanent deformation of the circular cross-section of the pipe that produces a decrease in the diameter [1].

Mechanical damage has been reported to be the most common reason of failure of transportation pipelines worldwide. United States Department of Transportation (DOT) has reported that 20-40% of serious incidents are due to mechanical damage [2,3].

The impact forces imposed on the pipe causes plastic deformation, i.e. plastic strains, in the form of a dent. The dent might also coincide with the longitudinal, circumferential or spiral welds. The interaction of dent with the weld has always been considered a threat to the pipeline. ASME B31.8 [1] considers dents deeper than 2% and interacting with welds to be injurious and requires an engineering assessment if they are to be left without repair. It mandates removal of dents interacting with welds if they are deeper than 4%.

Dents in pipelines would not only affect short and/or long-term integrity, but would also have a potential impact on the pass capacity of in-line inspection and cleaning tools when the size of the
dent is large enough. Rebound for an originally constrained dent can decrease the dent depth and improve the pass capacity of in-line inspection and cleaning tools.

EPRG established the correlation between unpressurized dent depth and pressurized dent depth\(^4\), \(H_0\) without repair. It mandates removal of dents interacting with welds if they are deeper than 4%.

\[
H_0 = 1.43H_r
\]

Where \(H_0\) is the equivalent dent depth at zero pressure, and \(H_r\) is the remaining dent depth after damage (after spring back) at pressurized condition. 71 experiments related to dents were performed in API1156, the results showed that: Dents (single unconstrained smooth dents) created by an external smooth object that was pressed into an unpressurized pipe rebounded due to elastic spring back upon release of the load. A substantial amount (up to two-thirds) of the initial indentation was recovered in this process. As internal pressure was applied the unconstrained smooth dents continued to re-round and virtually disappeared as the pressure level was taken high enough to significantly exceed the yield strength of the pipe\(^5\).

Because of the potential for re-rounding, it is highly unlikely that unconstrained dents with depths exceeding 5 percent of the pipe’s diameter will exist in areas of a pipeline which have been pressurized to a level of 72 percent of SMYS or more. The results were obtained in tests of pipes with diameter/thickness ratios of 68 or more. It is likely that pipe materials with lower diameter/thickness ratios would behave differently exhibiting less re-rounding \(^5\).

It is prudent to repair dents (replace the pipe) involving a seam weld or a girth weld or score or trim mark if the depth of the dent exceeds 2 percent of the pipe’s diameter\(^5\).

Sanjay Tiku et al. studied the full scale cyclic fatigue testing of dented pipelines and development of a validated dented pipe finite element model. They concluded that the resulting dent depths range approximately between 6.5%-11% OD after removal of the indenter for unrestrained dents of 15% and 20% OD. After the first pressure cycle (either 80% SMYS or 100% SMYS), the resulting dent depths due to pressure rebound range approximately from 1% to 3.5% OD. They also measured the strains during dent formation in the axial and hoop direction at 100 mm away from the dent center on the OD surface. The strain values range from approximately negative 4% strain in the hoop direction to positive 2% strain in the axial direction \(^6\).

Katina Tinacos et al. believed that the dent strain can be more precisely evaluated by taking the benefit of in-field LaserScan technology \(^7\).

In conclusion, all of the reviewed literatures are mainly concentrated on low grade steel. No tests of dents on spiral welds have been described in the literature. In addition, limited strain data is available during the dent rebound process in the previous studies. In order to solve above problems and estimate the rebound capacity of dents especially in spiral weld pipelines, a full-scale dent rebound testing program of X65 steel pipeline was designed and performed. 2 dents were further evaluated using the Laser Scan tool \(^8\). The effectiveness of the developed numerical model for dent rebound is demonstrated.

### 2. Experimental procedure and results

#### 2.1. Testing overview

A full scale dent rebound testing was conducted on the parent material and the spiral welds. Hemispherical and pyramidal indenters were used to generate dents to different depths. Strains around the denting area during formation of the dent and changes in depths due to rebounding after removing indenter were measured.

The spiral weld pipe sample was made of Grade X-65. The pipe sample has 813mm diameter, 9.5mm nominal wall thickness, 12.34m length.

Testing equipment was designed to implement the process of dent generation and rebounding. The hemispherical and pyramidal indenters, as showed in Figure 1, were created to generate the dents with different profile. The hemispherical indenter was used with nominal diameters of 220mm. The pyramidal indenter was used with a size of 152.5mm×152.5mm×76.2mm.
2.2 Type of tests and testing procedure

In order to characterize the dent rebound of X65 steel pipeline, two types of tests were performed to study 1) the effect of indenter geometry (namely, hemispherical vs. pyramidal) on the dent rebound magnitude of different depth and 2) the effects of complicated condition (e.g. the thaw settlement) on the dent rebound.

The testing procedure mainly includes the following: fix the pipeline on the bracket to make the location of preformed dent below the bracket; install the pre-selected indenter, support plate and hydraulic jack, and adjust their positions to make the center of gravity aligned (see Figure 1); apply the loading with hydraulic jack to form the dent according to the pre-determined depth; remove the loading and record the distance of rebound; confirm the depth of dent, the location and the type of indenter and etc.;

![Figure 1. The schematic diagram and the picture of the Test](image)

Table 1 shows the locations of indentation (parent material and spiral welds), type of indenter, maximum depth of the dent formed, depth after rebound, and the rebound rate. It is seen from the table that the rebound rate decreases with the increase of depth for the dents formed by hemispherical indenter. The corresponding rebound rate of dent interacting with spiral weld is more than plain dent on the base.

Figure 2 shows the position of strain gauges. In the tests with hemispherical indenters the distance of the first circle of strain gauges from dent center were bigger than that of pyramidal indenters in order to avoid destroying the gauges.

| Specimen | Location  | Indenter type | Max depth (%OD) | Depth after rebound (%OD) | Rebound rate (%) |
|----------|-----------|---------------|-----------------|---------------------------|-----------------|
| T-1      | parent material | pyramidal     | 12.92           | 7.63                      | 40.95           |
| T-2      | parent material | pyramidal     | 12.92           | 7.13                      | 44.76           |
| T-3      | parent material | hemispherical | 3.44            | 0.8                       | 76.79           |
| T-4      | parent material | hemispherical | 6.27            | 2.46                      | 60.78           |
| T-5      | parent material | hemispherical | 12.92           | 6.64                      | 48.57           |
Figure 2. Gauge positions in the tests

Another experiment was performed to consider the effect on the dent rebound caused by pipeline settlement due to soil displacement. During the rebound testing, the dent of different depth was formed repeatedly with hemispherical indenter and the rebound information was recorded in detail. Table 2 shows the results of dent rebound.

No. T-7-1 to No. T-7-5 tests was performed on the same location. When the depth of dent reached the maximum depth, pipe segment was subjected the loading condition for 18 hours and then removed the loading (T-7-1). The No. T-7-2 to T-7-5 was conducted repeatedly without keeping the loading. The dent of specimen T-8 was firstly formed to the 3.44% OD and then removed the loading to rebound (T-8-1), secondly formed to the 6.15% OD and kept the loading (T-8-2) for 2 hours, finally directly compressed to the maximum depth (T-8-3).

Table 2. Rebound rate considered the pipeline settlement

| Specimen | Location | No. | Max depth (%OD) | Depth after rebounding (%OD) | Rebound rate (%) |
|----------|----------|-----|-----------------|-----------------------------|-----------------|
| T-7      | parent material | T-7-1 | 13              | 6.89                        | 47.2            |
|          |          | T-7-2 | 13              | 7.13                        | 45.3            |
|          |          | T-7-3 | 12.9            | 6.89                        | 46.7            |
|          |          | T-7-4 | 12.9            | 6.89                        | 46.7            |
|          |          | T-7-5 | 12.9            | 7.13                        | 44.7            |
|          | parent material | T-8-1 | 3.44            | 0.8                         | 76.8            |
|          |          | T-8-2 | 6.15            | /                           | /               |
|          |          | T-8-3 | 12.9            | 6.7                         | 48.1            |

3. Rebounding and Strain Data

For 8 hemispherical-shaped indenter 13%OD depth tests, the average rebounding is 48.1% and variance is 0.17%. And for 2 pyramidal-shaped indenter tests, the average rebounding is 42.86% and variance is 0.07%.

There are 25 dents’ excavation data in a 813mm pipe and 23 of them are constrained ones. The initial depths of the dents are derived from ILI data and digs. The depths range between 4% and 10%. The rebounding average is 46.27% and variance is 3.77%.
Figure 3 is a plot of the rebounding data measured in ditch (dig data) and tested in lab (lab test data). In general, the amount of rebounding decreases with the increase of dent depth in the lab tests while the amount of rebounding from dig showed large scatters. However, the average rebounding amount is similar between these two sets of data.

![Figure 3. Rebounding of dig data and test data](image)

Example plots of the data collected during the full scale tests are shown in Figures 4 and 5. The objective of the detailed data collection in the program is to help develop engineering tools or criteria for pipeline dent assessment and screening.

Figure 4 and 5 show the strain of T-2 dent specimen created by pyramidal-shaped indenter. All the strain of the gauge locations are tensile strain.

Figure 4 shows the hoop strain of the location 2, 6 and 10 (designated as channel 2, 6, and 10, respectively, in the figure), which align along the circumferential direction. Maximum strain appears in the Location 6 which is in the middle. For Location 2 which lies nearest to dent center, strain has a peak at 200s then decreases and has a jump after rebounding. Strain of Locations 2 and 6 increases after rebounding, but Location 10 remains almost the same. Points 4, 8 and 12 which are the mirror points have the similar trend.

Figure 5 shows the axial strain of the points 3, 7 and 11, which align along the axial direction. Maximum strain appears in the point 3 which is closest to the dent center. Strain change in the rebounding is not as big as that in circumferential direction. Points 1, 5 and 9 which are the mirror points have the similar trend.

![Figure 4. Hoop strain of T-2 specimen](image)
Figure 5. Axial strain of T-2 specimen

Figure 6 and 7 show the strain of T-5 dent specimen created by hemispherical-shaped indenter. All the strain of the gauge locations are tensile strain.

Figure 6 shows the hoop strain of the Locations 2, 6 and 10, which align along the circumferential direction. What is interesting is that point 2 which is closest to dent center has the smallest strain. The strain of Locations 2 and 6 have big jump after rebounding to about 2 times of the strain before rebounding.

Figure 7 shows the axial strain of the Location 3, 7 and 11, which align along the axial direction. Maximum strain appears in the Location 3 which is closest to the dent center. Strain change is moderate similar to that of T-2 dent specimen. Locations 1, 5 and 9 which are the mirror Locations have the similar trend.

All of other tests either created by pyramidal-shaped indenters or hemispherical-shaped ones have similar trends with T-2 or T-5.

Figure 6. Hoop strain of T-5 specimen
Figure 7. Axial strain of T-5 specimen

The jump of strain in the circumferential direction is an obvious phenomenon in the tests. Figure 8 shows explanation for this. The circumferential strain consists mainly of membrane strain and bending strain. The former is uniform in the shell of the pipe and the latter is negative in the outer of the pipe while positive in the inner. At the early stage of the test, bending strain domains and the strain of the points closest to dent center is negative. Then the membrane strain surpasses and strain of the gauge rises. With the depth increases, dent is steeper and the effect of bending strain becomes more important so the circumferential strain decreases. When the indenter is removed, bending strain is released so the circumferential strain jumps to a higher level which is almost twice the former strain.

Based on the above observation and explanations, there are 2 factors we should take into account for repairs of dents.: 1) because the bending strain is positive in the inner surface of the pipe, the maximum tensile strain of a dent appears in the inner pipe, which may facilitates cracking, therefore, it is necessary to check the crack in the inner surface and 2) because there is big jump in the circumferential strain while rebounding, it is also necessary to control the process to remove rocks.

Figure 8. Components of circumferential strain

4. Laser profilometry
Laser profilometry uses the principle of optical triangulation to obtain dent 3D geometry and dimension measurements. The portable laser system relies on positioning targets placed in a random grid on the surface of the object to be scanned. From the positioning targets the scanners and cameras are able to determine the scanner’s location which is used to map out the surface,
constructing a three dimensional object [9]. This paper conducted the LaserScan for the specimen T-2 and T-5, and calculated maximum equivalent strain of dents using profile data.

![Figure 9. The dent profile by laser profilometry of Specimen T-2 and T-5](image)

The method developed by Blade Energy Partners, Ltd. [10] were used to compute strain components at every point of the dented surface. The maximum equivalent strain of dent showed in the Table 3.

5. Finite Element Analysis
The finite element analysis was performed with the objectives of simulating the whole process of full-scale dent rebound testing of X65 steel pipeline and determining the rebound rate and the strain curves of different measurement locations and the stress/strain distribution around the dent. And the results also will be compared with the strain analysis data in future.

The FEA model with 813mm OD and 9.5mm WT was established using the ABAQUS finite element software. The pipe model was meshed with 8-node linear solid element (C3D8R element. Appropriate boundary conditions were applied on the pipe model to avoid rigid body motion according to the actual situation of field test. The elastic-plastic material property was assigned to the pipe model. The true stress-true plastic strain curve was obtained from the material testing of X65 steel. The hemispherical and pyramidal indenters were also respectively created. And the contact interaction was established between the pipe and the indenter which was defined as a rigid body. Different displacement boundary conditions were applied on the indenter as the loading indenting the pipe.

![Figure 10. Finite Element Model of Hemispherical Indenter Indenting the Pipe](image)

The grid of dent area was refined to increase the accuracy of the simulation results. The loading condition applied on the indenter to form the dent and then applies the opposite loading to simulate the rebound.
The rebound rate for pipe samples T-2, T3, T4, and T-5 by FEA respectively is 79.6%, 67%, 46.2%, 46.2%, which is inconsistent with the rebound testing, see Table 1. The main reason is the inhomogeneity of the pipe material and asymmetry of loading in the re-round test compared to FEA model. Otherwise, the sharpness of pyramidal also has an effect on the re-round rate. Figure 12 and Figure 13 show an example plot of hoop and axial stress distribution for the pipe indented by hemispherical.

There is a wide area around the dent shoulders that experiences a large stress range. The maximum stress is 663.4 MPa, which exceeds the yield strength along the axial direction.

The Figure 14 and 15 show the FEA results of the axial and hoop strain at the location where the strain gauges of specimen T-2 and T-5 were placed.
Figure 14. The strain curve of specimen T-2

Figure 15. The strain curve of specimen T-5

The Table 3 shows the depth and maximum equivalent strain of LaserSan method compared with FEA.

| Specimen | LaserSan Depth after rebounding (%OD) | LaserSan Max equivalent strain (%) | FEA Depth after rebounding (%OD) | FEA Max equivalent strain (%) | Experiment Depth after rebounding (%OD) | Experiment Max equivalent strain (%) |
|----------|---------------------------------------|-----------------------------------|---------------------------------|------------------------------|------------------------------------------|-------------------------------------|
| T-2      | 7.31                                  | 13.7                              | 6.94                            | 11.2                         | 7.13                                     | 6.64                                |
| T-5      | 7.24                                  | 12.2                              | 6.94                            | 10.8                         | 6.64                                     |                                     |

6. Conclusions
The full scale testing was conducted on the parent material and the spiral welds. Hemispherical and pyramidal indenters were used to generate dents to different depths. Strains around the denting area during formation of the dent and changes in depths due to rebounding after removing indenter were measured. Following each rebound test, the dent profile was portrayed with a 3D laser scanner. With the information obtained from the above measurements, detailed analyses were performed and a numerical model was developed. In this paper, the approach used for the study is described first. The results and findings are then presented. The effectiveness of the developed numerical model for dent integrity management is demonstrated. The major results as following:

1) The rebound rate decreases with the increase of depth for the dents formed by hemispherical-shaped indenter. For the same depth dent, rebound rate of the pyramidal-shaped indenter is somewhat lower than the hemispherical-shaped indenter. All rebound rates for the experiments exceed the 40%.

2) Repeatedly loading and loading process have little influence on the rebound value of dent formed by hemispherical-shaped indenter.

3) The rebounding amount of dent correlated with spiral weld is bigger than plain dents.
4) All the strains detected in the tests are tensile. With the influence of bending component, circumferential strains of the points close to dent center have a peak in the process of dent creating and have a jump increase amount to twice the former after rebounding. So it is necessary to control the process to remove rocks.

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