Implementing of 3D Scanning Techniques in the Analytical and Numerical Assessment of Pipelines with Volumetric Surface Defects

IONUȚ LAMBRESCU, MIHAIL MINESCU*, ALIN DINIȚĂ
Petroleum – Gas University of Ploiesti, 39 București Blvd., 100680, Ploiesti, Romania

The paper presents a proposal for a new approach in the assessment of the pipelines with volumetric surface defects (VSD), in order to appreciate the VSD strength and to decide if it is accepted as it is or is necessary to apply a repairing techniques.The assessment begins, in the authors' view, with a 3D scan of the defect area (the defect should be situated on the exterior of the pipe, in a visible region), followed by a reverse engineering step, when the result of the 3D scan is processed and finally transformed in a 3D solid, susceptible to support a Finite Elements Analysis (FEM) of tensions distribution in the pipeline wall. This analysis will provide the first set of data regarding the severity of the defect. The process is after that completed, if necessary, with the repairing step and a final FEM evaluation of the pipeline's condition.

Keywords: Surface pipeline defect, 3D scanning, Finite elements analysis, Pipe repairing

Pipelines are seen as one of the most practical and economically efficient ways of transporting dangerous and flammable substances for which road or rail transport is often impossible. It is well known that in design of a pipe are essential the choice of the material and the establishing of its diameter, so that it meets all the requirements of operation. For pipelines of great importance, there are procedures whereby their optimal diameter [1] is established, economically or technologically. With all the attention paid to the design and operation of pipelines, the accidents in their operation are still met. According to international historical data [2], gas pipeline accidents happen even if the frequency of these situations is generally low compared to road or rail accidents. Moreover, pipeline accidents often lead to impacts of major importance. The rapid assessment of the volumetric surface defects (VSD) and the need to obtain criteria and analytical methods for assessing the mechanical resistance of piping with such VSDs becomes a necessity for pipe system operators [3]. In this paper, the authors conducted a case study by combining the 3D scanning technique of defects, reverse engineering, numerical analysis Finite Elements Method (FEM) [4,5] and analytical evaluation [6]. The rapidity, accuracy and operability with which the 3D scanning technique is applied to determine the characteristic dimensions of VSD on pipelines can be a viable solution for rapidly assessing the load-bearing capacity of pipelines with such VSD.

Experimental part

3D scanning of a pipe section with VSD

In order to asses numerically (Finite Element Method – FEM) a pipe segment with a real VSD was selected. To this deffect a 3D scanning has to be performed. The result of this phase has to be processed such as a 3D solid is obtained. This solid will be used for the FEA stage of our work. The scanning process has been performed using an HP 3D Structured Light Scanner Pro 3. The area with the VSD has been isolated on the selected pipe and scanned as can be seen in figure 1.

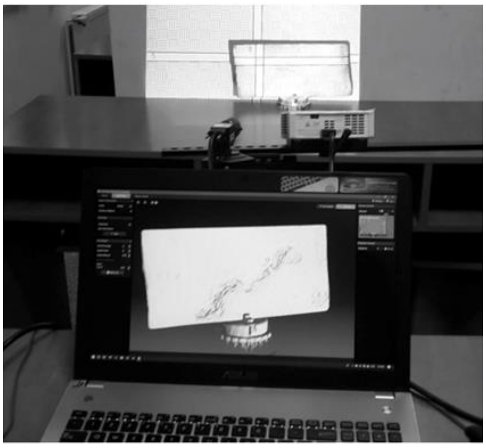

Fig. 1. Setup of the scanning process

**email.: mihail.minescu@yahoo.com*

About the pipe we shows that this a pipe, with the exterior diameter of 508 mm and a wall thickness of 10 mm, and it is part of a gas transport route . From this pipe a section with VSD has been cut to be used in further analysis. The result of the scanning process is depicted in figure 2.

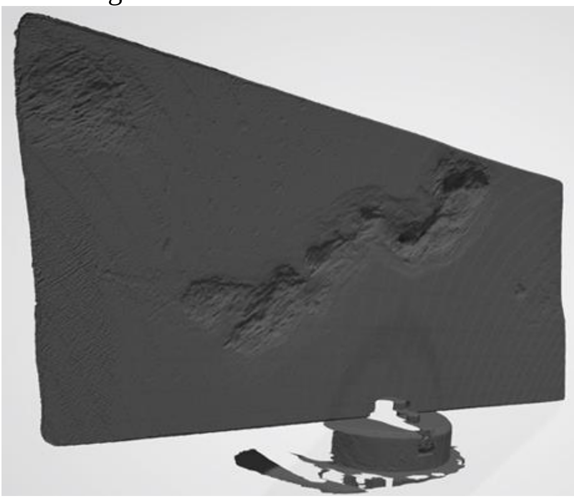

Fig. 2. Scanned pipe area with VSD

The scanned pipe segment has been saved in the stereolithography (STL) format. The STL file has been further processed, using reverse engineering techniques, until a solid has been obtained. The resulting solid has been reintegrated (using CAD software packages) into a pipe segment as can be seen in figure 3.

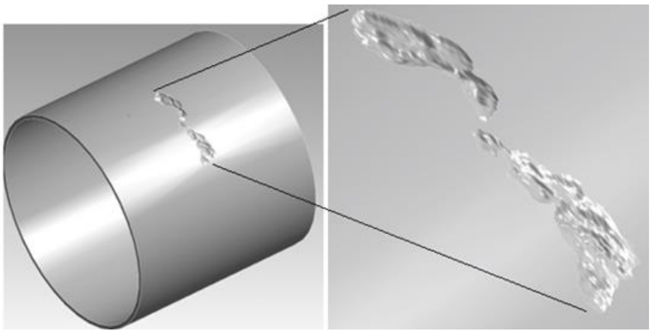

Fig. 3. Pipe area with VSD reintegrated into the pipe segment

The process of STL to 3D solid conversion introduced geometric errors of less than 0.1 mm. The maximum depth of the defect has been measured to be 7.5 mm (75% out of the 10 mm pipe wall thickness). That is in good accordance with mechanical measured depths of the VSD.

Finite element method analysis of the pipe segment with a real VSD

The resulting 3D model of the pipe segment with VSD has been analyzed using ANSYS software for tension stress distribution. Since pipes must work in the linear-elastic domain, the analysis was a structural linear one (Static Structural). It known that the pipe material was a L290MB steel, with a Minimum Yield Strength *SMYS* = 290 N/mm^2. It is also known that the pipe is subject to a 2 MPa interior pressure, and has been fixed at both ends.

In order to get good results, the FEM integration structure (the mesh) has been refined in the VSD area, to an average size of 0.5 mm (tetrahedron elements).

The results of numerical analysis for the pipe with VSD are presented in figures 4 and 5. The maximum stress value (Von Misses) is 274.12 MPa. The maximum circumferential stress is 238.12 MPa, while the maximum radial stress is 50.41 MPa. It is important to show that all maximal values recorded in the same place.

Considering a Design Factor of 0.72 (Pipes in Class 1, Division 2), the SMYS of 290 MPa is reduced to a value of 208.8MPa, that is less than the maximum recorded Von Mises stress (274.12 MPa). So the pipeline defect must by repaired.

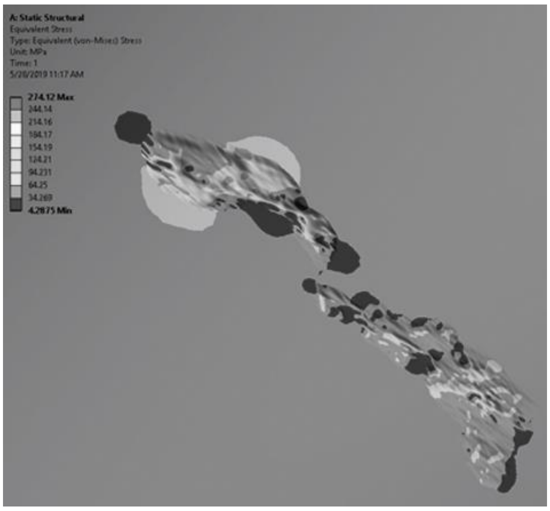

Fig. 4. Von Misses stresses in the VSD area

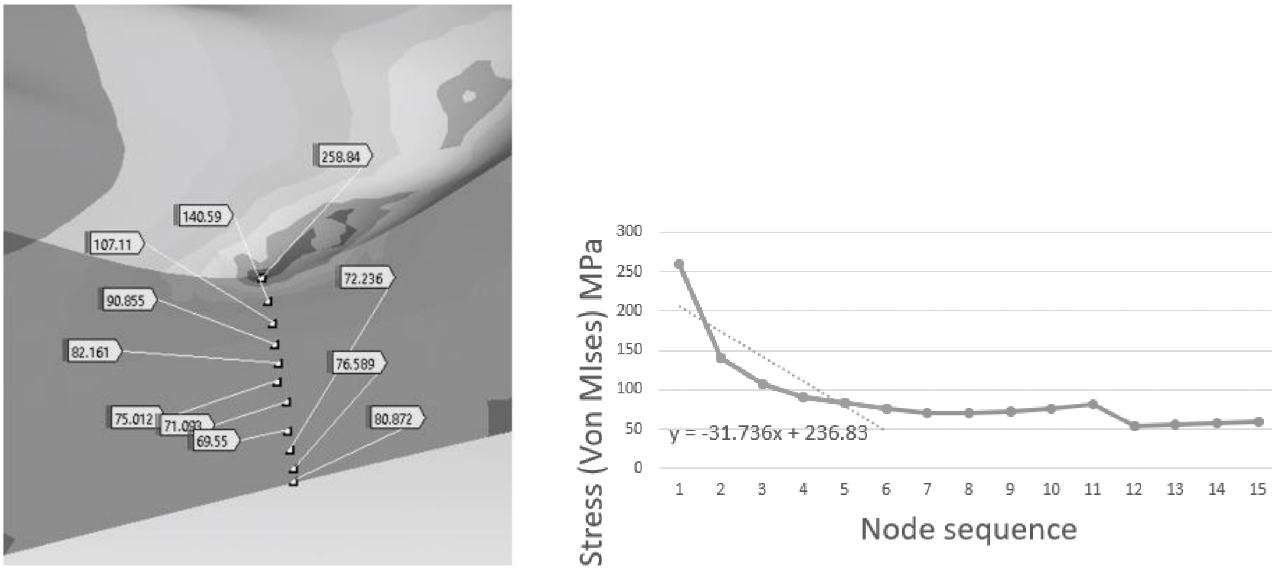

Fig. 5. Von Mises stress variation on wall thickness

Figure 5 presents the Von Mises stress variation on wall thickness in the area with the maximum stress values.

Finite element analysis of the pipe segment with a machined VSD

In practice, in the VSD area of a pipe, a machining process is performed, in order to eliminate the stress concentrators, possible micro cracks that could evolve and generate failure.

The purpose of this machining process is also to prepare the pipe with VSD for a repairing technique with a filler and composite wrap.

This section presents the results of a FEA analysis for the same pipe with a machined area instead of the real VSD.

The VSD was positioned in such a way that allowed us to use symmetry, reducing thereby the number of elements and the computing effort.

Figure 6 presents the same pipe, after the real VSD has been machined. The dimensions of the machined area are 215 x 55 x 7.5 mm. The fillet radius is 14 mm.

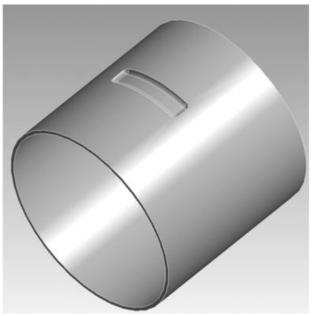

Fig. 6. Pipe with machined VSD

For the same pipe, with the same interior pressure (2MPa) and with identical ends fixtures, the Von Mises equivalent stress distribution is presented in figure 7. The maximal value reached is 159.98 MPa (one can also see the un deformed model).

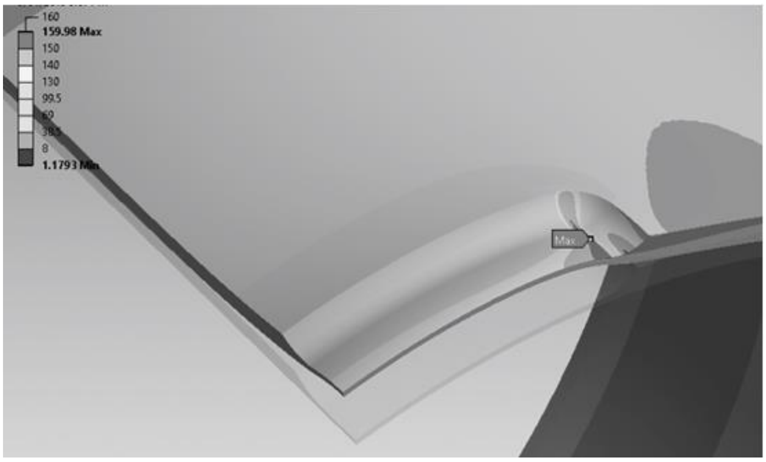

Fig. 7. Von Mises stress distribution for pipe with machined VSD

Finite element analysis of the pipe segment with a machined VSD after repair

After the machining process, a filler is used to fill the VSD, then a repair composite wrap is applied all around the pipe in the VSD area.

The principal mechanical properties of the materials used are presented in table 1.

Table 1
MECHNICAL PROPERTIES OF THE MATERIALS USED

Property	**Pipe**	**Filler**	**Composite wrap**
Young's Modulus [MPa]	203000	3000	20000
Poisson's Ratio	0.3	0.33	0.4
Tensile Yield Strength [MPa]	290	-	-

In figure 8 one presents the Von Mises stress distribution only for the pipe with VSD. These values have to be compared with the ones presented in figure 4. The maximal Von Mises value is 114.83MPa.

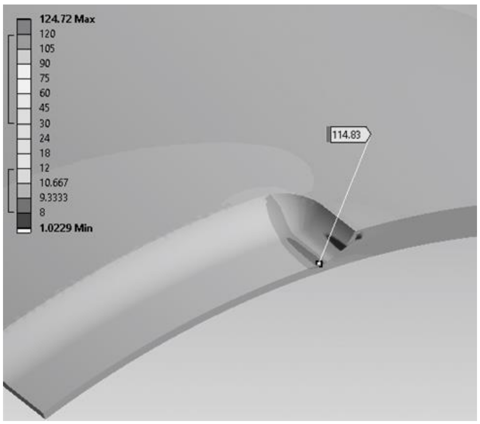

Fig. 8. Von Mises stress distribution for repaired pipe

Analytical methodology for assessing a pipeline with volumetric surface defect (VSD)

In order to assess the volumetric surface defects, usually produced by corrosion, several methods are developed by research institutes established in this field and currently included in normative documents or standards such as ASME B31G; ASME B31.8; API Standard 579, BS 7910. The application of this methodology is limited to the assessment of wall loss in pipelines within the following limitations [7]: metal loss due to external or internal corrosion; metal loss of any depth with respect to the pipe wall, except that due consideration shall be given to the accuracy of measurements and effective corrosion rates when the depth of metal loss exceeds 80% of the actual pipe wall dimension; metal loss in pipe where internal pressure is the primary loading. The analytical methodology used for evaluation of a ***VSD***, locate on the pipes wall, involves the following steps [7,8]:

Step 1. Specify the initial anomaly evaluation data, grouped into the following:

-the constructive characterization of the pipeline (the outside diameter D_e, the effective wall thickness t);

-technical conditions of pipelines operation (maximum allowable pressure *MOP*);

-data for the values for different factors used in pipeline design stage (Design Factor-*F*, Temperature Derating Factor-*T*, Longitudinal Joint Factor-*J*);

-mechanical characteristics of the steel from which the pipe element is made of (specify minimum yield strength-*SMYS*);

-data for characterization of the anomaly geometry (length of *VSD* - extension in longitudinal direction - s_p, maximum depth of *VSD* - d_p).

Step 2. Primary anomaly evaluation; considering the maximum depth d_p and the maximum relative depth of the anomaly d_{pr}, calculated with the following relations:

$$d_{pr} = \frac{d_p}{t} \tag{1}$$

the following criteria shall apply:

-if $d_{pr} < 0.1$ qualifies the *VSD* as an imperfection, it is decided to continue the operation of the pipelines without the application of maintenance and the assessment is considered completed;

-if $0.1 \leq d_{pr} \leq 0{,}8$ moves to step 3;

-if $d_{pr} > 0.8$ qualifies the *VSD* as a defect, it is decided to repair it by applying corrective maintenance and the evaluation is considered completed.

Step 3. As it is shown in relation (2), where B is defined by relation (3), compute the maximum admissible s_{pa} length of *VSD* to characterize it as an imperfection

$$s_{pa} = 1{,}12B\sqrt{D_e t} \tag{2}$$

$$B = \sqrt{\left(\frac{d_{pr}}{1.1d_{pr} - 0.15}\right)^2 - 1} \tag{3}$$

We notify that B may not exceed the value 4 (if the corrosion depth is between 10% and 17.5% use $B = 4$ in Eq. 2). After s_{pa} length the following criteria applied: if $s_p < s_{pa}$ qualifies the *VSD* as an imperfection; if $s_p > s_{pa}$ the *VSD* qualifies as a defect.

Stage 4. Establishing of the maximum operating pressure of the pipeline and construction of the ***Defect Acceptance Chart - DAC***; the design pressure *p* and the maximum operating pressure *p'* considering the *VSD*, are calculated using the relations (4) and (5) where the parameter *A*, depending on the relative length of *VSD*, is defined as: $A = 0{,}893s_{pr}$.

$$p = FTJ\frac{2t}{D_e}SMYS \tag{4}$$

$$p' = \begin{cases} 1.1p\left(\dfrac{1-\frac{2}{3}d_{pr}}{1-\frac{2}{3}d_{pr}\frac{1}{\sqrt{A^2+1}}}\right), & if\ A \leq 4 \\ 1.1p\left(1-d_{pr}\right), & if\ A > 4 \end{cases} \tag{5}$$

The pipeline with *VSD* can be used, at the parameters for which it was designed, if the conditions (6) are simultaneously respected.

$$p' \geq p \text{ şi } p' \geq MOP. \tag{6}$$

In order to check quickly whether the conditions (6) are fulfilled, the ***Defect Acceptance Chart - DAC*** is constructed. This graph contains two characteristic curves, analytically defined when the conditions (6) become as equalities. So:

-from condition $p' = p$, results the analytical expression (7) of the first characteristic curve of ***DAC***

$$d_{pr} = \begin{cases} \dfrac{0.1}{1.1-\dfrac{1}{\sqrt{0.797449s_{pr}^2+1}}}, & if\ s_{pr} \leq 4.479 \\ 0.09091, & if\ s_{pr} > 4.479 \end{cases} \tag{7}$$

-from condition $p' = MOP$, results the analytical expression (8) of the second characteristic curve of ***DAC***

$$d_{pr} = \begin{cases} \dfrac{1.1 - \dfrac{MOP}{p}}{1.1 - \dfrac{MOP}{p} \dfrac{1}{\sqrt{0.797449 s_{pr}^2 + 1}}}, \ if\ s_{pr} \le 4.479 \\ 1.1 - \dfrac{MOP}{p}, \ if\ s_{pr} > 4.479 \end{cases} \quad (8)$$

For the case studied in this paper it is considered that the ***DAC*** is built taking in consideration only the condition (7) and representing in abscissa the length of *VSD* s_p and in the ordinate the depth of *VSD* d_p.

Case Study – data

D.1. Outside Diameter D_e = 508 mm;.

D.2. Wall Thickness t = 10 mm.

D.3. Maximum Allowable Pressure MOP = 20 *bar*.

D.4. Specify Minimum Yield Strength $SMYS$ = 290 N/mm^2.

D.5. Design Factor $F = 0.72$ (Pipes in Class 1, Division 2).

D.6. Temperature Derating Factor T = 1 (pipeline with operating temperature <120^{0}C).

D.7. Longitudinal Joint Factor J = 0.8 (Helical Welded Pipes).

D.8. Maximum Depth of *VSD* d_p = 7.5 mm.

D.9. Maximum Length of *VSD* s_p = 55 mm.

Applying the described evaluation methodology, the ***DAC*** was constructed for *VSD* analyzed in the case study, the diagram being presented in figure 9.

The characteristic point of the VSD evaluated has the coordinates (s_p; d_p). After the ***DAC***'s representation of the characteristic point of the *VSD*, because the characteristic point is in the TEMPORARY TOLERATED region, the predictive maintenance activities must be applied.

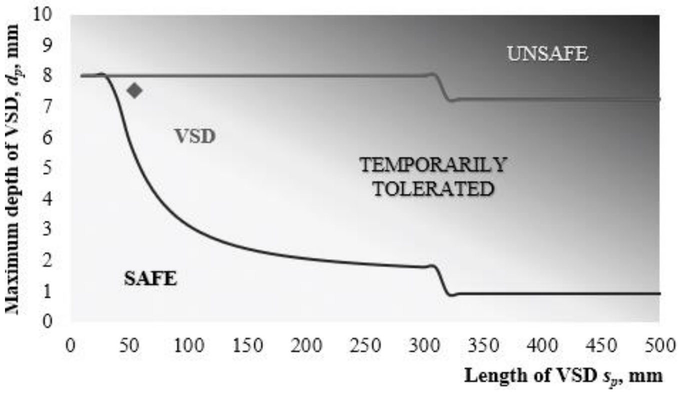

Fig. 9. Defect Acceptance Chart for VSD analyzed

Conclusions

The geometric complexity of VSD type defects can be easily evaluated by 3D scanning. Successful implementation of a maintenance pipeline system is correlated with the speed and accuracy of VSD defect assessment. A 3D scanning using structured light has proven to be a precise technique for determining the geometrical characteristics of VSD defects, characteristics that are necessary to assess the mechanical strength of the pipes.

The efficiency of the numerical and analytical evaluation of the VSD defect analysed, both in initial and repaired condition, was achieved by rapidly taking over the geometric model from 3D scan.

The analysis of the FEM results allows us to make the following statements:

In order to assess the VSD influence on the pipe safety, as already mentioned, we considered a Design Factor of 0.72 (Pipes in Class 1, Division 2). As a consequence, the SMYS of 290 MPa, is reduced to a value of 208.8MPa.

In table 2, we present a comparison between the three cases, real VSD, machined VSD and machined and repaired VSD. The data considered are the maximal Von Mises and circumferential stress, the ration between the Von Mises stress on the outer and inner face of the pipe and the slope for the linear trend line for the data describing the variation of the Von Mises stress on the wall thickness in the area with maximal values for the stress.

Table 2
COMPARISON BETWEEN THE THREE ANALYZED CASES

	Real VSD	**Machined VSD without repair**	**Machined VSD with repair**
	[MPa]		
Max Von Mises (VM)	274.12	159.98	114.83
Max Circumferential	238.12	177.54	125.94
Ration max VM/min VM	4.32	1.613	2.17
Slope linear trend line for the data like those in figure 5	-31.74	-10.8	-6.29

The analysis of table 2, allows us to appreciate that, in the case of the real VSD the values of stress on the wall thickness are rapidly decreasing, indicating that the situation is not as dangerous as it initially appeared. For the other cases (VSD machined and VSD machined and repaired), the decreasing of Von Mises stress is slower. This tendency is in good relation with the values of the slopes for the linear trend line. We mention that for the real VSD, the slope for the linear trend line from table 2 has been calculated only for the first six values, since there is a clear tendency of flattening for the rest of the curve (figure 5).

As a final conclusion, we appreciate that the 3D scanning can help and improve the quality of the process of assessment of pipes with VSDs, providing a tool to a more precise evaluation of the VSD 3D geometry, but also, through a reverse engineering approach allows a first and exact evaluation of the stress distribution in the VSD area.

References

1. E. SHASHI MENON, Gas Pipeline Hydraulics, CRC Press, 2005
2. G D GOODFELLOW G.D., LYONS C.J., HASWELL J.V., UKOPA Pipeline Product Loss Incidents and Faults Report (1962 – 2017).
3. GHEORGHE ZECHERU, PETRO YUKHYMETS, GHEORGHE DRAGHICI, ANDREI DUMITRESCU, Rev. Chim. (Bucharest), **66**, no. 5, 2015.
4. DUHOVNIK J., DEMŠAR I., DREŠAR P, Springer 2015, ISBN 978-3-319-03861-2
5. OSSAI C., I., Infrastructures 2017, 2, 15
6. PAUL M. KUROWSKI, SAE International, 2017
7. * * * B31G - Manual for Determining the Remaining Strength of Corroded Pipelines.
8. ZECHERU GHEORGHE, LAȚA E. ILIE, BÂRSAN FLORIN, Journal of Engineering Studies and Research, Volume 17, No. 2, 2011

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