AN INVESTIGATION INTO THE FATIGUE BEHAVIOUR OF A GLASS FABRIC – EPOXY COMPOSITE USED TO REPAIR PIPELINE DEFECTS

ZECHERU GHEORGHE[1*], LAŢA E. ILIE[2], BÂRSAN FLORIN[2]

[1]*Petroleum – Gas University of Ploieşti, Bd. Bucuresti 39, Ploieşti, RO-100680, Romania*

[2] *S.N.T.G.N. „TRANSGAZ" S.A., St. George Enescu 11, Mediaş, RO-551018, Romania*

Abstract: This paper outlines the methodology and the results of the experimental analysis performed by the authors regarding the fatigue behaviour of wraps made of new composite materials, obtained by the reinforcement with glass fibre fabric of an epoxy matrix, applied for repairing metal loss defects on steel pipes of oil, liquid petroleum and natural gas transmission pipelines. The information herein and the aspects explained in this paper must be used for determining the thickness of composite material wraps used to repair pipelines.

Keywords: pipeline defect, repair method, composite material wrap, fatigue behaviour.

1. INTRODUCTION

Repairing metal loss defects of oil, liquid petroleum and natural gas transmission pipelines by means of composite material wraps is one of the currently most used technological procedures, due to its many advantages: the possibility to be applied without taking the pipelines out of service, the relatively low demands regarding the qualification of the team which performs the procedure, avoiding the use of welding procedures, the high mechanical strength and durability of the repair works performed by means of this procedure. The productivity in performing such repair works is much higher than with any other method which requires welding operations; for instance, applying a Clock Spring wrap lasts 15…20 minutes and the finalization of the repair work and obtaining the maximum mechanical strength of the applied wrap doesn't take longer than 2,5 hours.

Among the composite materials designed for repairing pipelines there is also the set of materials conceived and fabricated by a research team from ICECHIM Bucureşti, composed of: a) a composite material (filler), meaning a reactive polymeric composite modified with flexibilizators and mineral fillings, used for covering defects and reestablishing the external configuration of the pipeline being repaired; b) a multilayer composite material – MCM, obtained by embedding many glass fabric layers into a composite matrix, also made by a reactive polymer modified with flexibilizators and mineral filings, used for reinforcement wraps for the defective areas of the pipeline being repaired [1].

The mechanical characteristics of MCM are at the level of composite materials used worldwide for reinforcement wraps for defective areas, as it can be seen by analyzing the data synthesized in Table (1-2). The MCM wrap technology for repairing metal loss defects on pipelines was determined on the base of the results of an experimental setup which showed that the wraps made of this composite material have a good adhesion (with values of the shearing detachment stress τ_{FC} = 13…15 MPa) and assure high reinforcement performances, if the

* Corresponding author, e-mail: gzecheru@upg-ploiesti.ro

outer surface of the steel pipe is appropriately sandblasted (with normal and semifriable spar at the pressure of 0.5…0.9 MPa) before applying them [1,5-7].

The experimental setup whose results are shown in this paper aimed to emphasize the behaviour during variable loads acting upon the MCM wraps and the particularities of their fatigue failure.

2. EXPERIMENTAL SETUP

The experimental setup was performed on a sample of pipe section from one of the pipes of a natural gas transmission pipelines, replaced because of many areas of local metal loss defects, produced by the corrosive action of the soil it had been buried into. The design features of the pipeline the sample was taken from, having the length L_p = 2500 mm, were: outside diameter D_e = 508 mm (20 in); wall thickness s = 7.1 mm, operating temperature t_n = –8...+30 ^{o}C, maximum operating pressure MOP = 3.0 MPa and design pressure p = 6.0 MPa, determined by the formula [8]:

$$p = FTJ\frac{2s}{D_e}R_{t0.5S} \tag{1}$$

considering that the design factor F = 0.60 (corresponding to the including of the pipeline route in location class 2*)*, temperature derating factor T = 1 (because $t_n \leq 120$ ^{o}C), and the helical joint factor J = 1 (because the pipeline was made of SAWH pipes – submerged arc-welded pipes having a helical seam); because the pipes were made of X52 (L360) steel, the values of the mechanical characteristics used while designing the pipeline were: modulus of elasticity (Young's modulus) E_S = 205 GPa; yield strength $R_{t0.5S}$ ≥ 359 MPa; ultimate tensile strength R_{mS} ≥ 455 MPa; percent elongation at failure $A_S \geq 20$ %.

Table 1. Mechanical characteristics of the composite materials used for pipeline repairing.

Composite material	**Composite material reinforcement**	**Mechanical characteristics of the composite material***		
		E_C, GPa	**R_{mC}, MPa**	**A_C, %**
MCM	Fiberglass	17.5 ... 22.7	265 ... 315	1.32 ... 1.60
Perma Wrap	Fiberglass	34.0 … 38.0	580 …620	1.00 … 1.10
Fiba Roll	Fiberglass	7.9 ... 8.7	86 ... 72	2.60 ... 3.10
Clock Spring	Fiberglass	33.8 ... 34.5	630 ... 650	1.06 ... 1.36
TDW RES-Q Wrap	Charbonglass	67.5...69.8	990...1020	-

* measured in the direction corresponding to the pipeline circumference while applying the composite wrap;
E_C – modulus of elasticity, R_{mC} – ultimate tensile strength, A_C – percent elongation at failure.

The pipe section sample had on its outer surface local metal loss defects, as it can be seen in figure 1. The defective area for the sample was examined by means of the Scanner Eddy Current Array equipment, connected to a computer with the software GRIWRAP, which allows the recording, processing and interpreting the data determined. The test results were synthesized, as it can be seen in Figure 1, as the critical profile of the thickness of the sample in the defective area, determined by the river bottom profile method.

Because the metal loss defects are nearby and interact when the sample is loaded at internal pressure, it was determined that the defective area should assimilate with a single defect, having the following geometric features: longitudinal extent or axial length of defect s_p = 570 mm; relative axial length of defect $s_{pr} = s_p / \sqrt{D_e s}$ = 9.5; circumferential extent or transversal length of defect c_p = 152 mm; relative transversal length of defect $c_{pr} = c_p / \sqrt{D_e s}$ = 2.5; minimum remaining thickness of the sample in the defective area s_{mm} = 0.7 mm; maximum depth of the region of local metal loss $d_p = s - s_{mm}$ = 6.4 mm; relative maximum depth of defect $d_{pr} = d_p/s$ = 0.90.

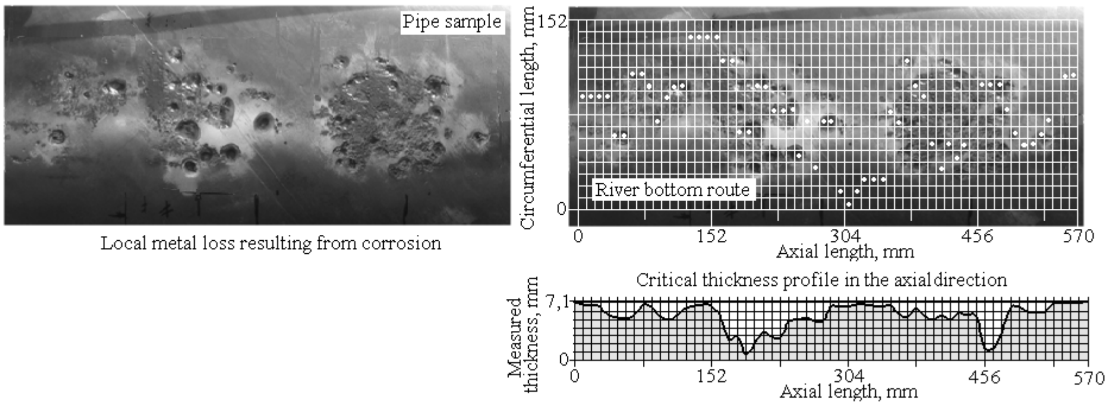


Fig. 1. Metal loss defects on the pipe section sample and the critical profile of the thickness of the sample in the defective area, determined by the river bottom profile method.

The sample was assessed by applying the procedure recommended by [1], in order to check whether the following conditions are fulfilled:

$$p' \geq p \text{ şi } p' \geq MOP \tag{2}$$

p' is the maximum safe operating pressure of a pipeline in which the sample having the previously mentioned defect is embedded, determined by the formula:

$$p' = 1.1p\left[\frac{1-\frac{2}{3}d_{pr}}{1-\frac{2}{3}d_{pr}\frac{1}{\sqrt{A^2+1}}}\right] \tag{3}$$

if $A \leq 4$, or by the formula:

$$p' = 1.1p(1 - d_{pr}) \tag{4}$$

if $A > 4$, the parameter A is defined by the formula: $A = 0.893s_{pr}$. The result of the assessment is synthetically shown in the Defect Assessment Diagram – DAD, in Figure 2, the analytical expressions of the two DAD characteristic curves being obtained by considering the conditions (2) as equal, and the characteristic position of the defect existing on the assessed sample having the coordinates D(s_{pr} = 9.5; d_{pr} = 0.90).

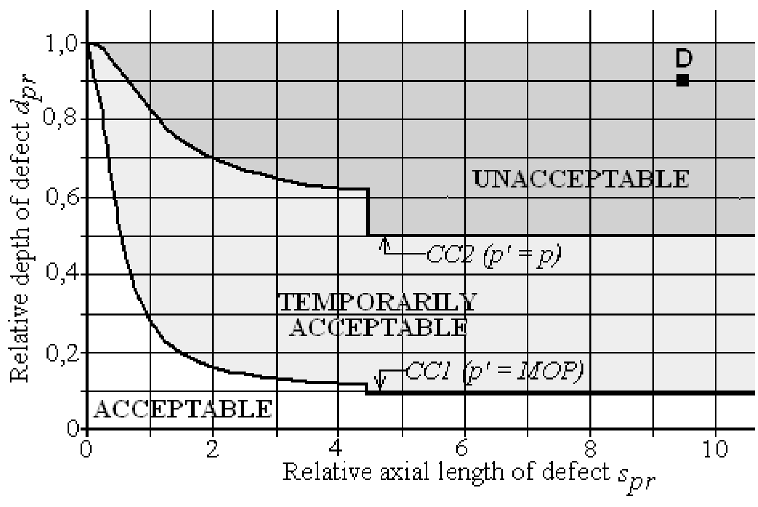


Fig. 2. The result of the assessment of the sample with metal loss defects by means of the procedure in [8].

Because the assessment performed has established as not acceptable the metal loss defect existing on the sample, there was determined further the thickness of the MCM wrap that has to be applied for repairing the sample and reestablishing the mechanical strength performances of this, corresponding to the design conditions of the pipeline it was taken from. With this purpose it was preceded as follows:

- it was taken from the pipe the sample belonged to a traction specimen that was subjected to a test on an INSTRON 8801 machine and there were determined the effective mechanical characteristics of the steel used for it: modulus of elasticity (Young's modulus) E_{Se} = 205 GPa; yield strength $R_{t0,5Se}$ = 376 MPa; ultimate tensile strength R_{mS} = 497 MPa; percent elongation at failure A_S = 20 %;
- there were used the calculation procedures recommended in [1,8] and, considering the effective mechanical characteristics of the sample steel, it resulted that the MCM repair wrap must have the thickness s_C = 10 mm, while its longitudinal extension must be $L_C = s_p$ + 100 mm = 670 mm (the wrap must exceed with 50 mm, on each side, the defective area).

The sample was prepared for testing, the following operations were performed: a) total sandblasting of the outer surface of the sample; b) marking the ends of the area for the MCM wrap to be applied over, using the filler for the metal loss defects and remaking the external configuration of the sample; c) application of the MCM reinforcement wrap. The images in Figure 3 show the way of performing these operations and their result.

Fig. 3. The way of preparing the sample for testing.

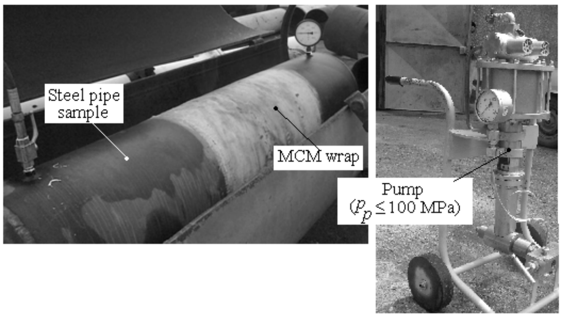


Fig. 4. Components of the stall on which the cyclic pressure test of the sample was performed.

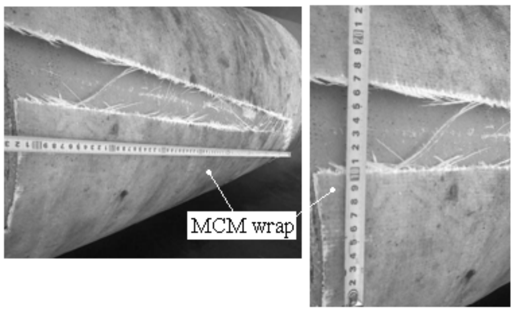


Fig. 5. Aspect of the sample after the failure of the MCM wrap.

Table 2. Characteristics of the pressure cycles the sample was exposed to.

Sequence i =		1	2	3	4	5	6
Pressure p_p, MPa		4	6	8	10	12	14
Time of the cycle sequences, minutes	Pressure rising	6	6	7	8	9	10*
	Pressure maintaining	60	60	60	60	60	-
	Pressure discharging	1	1	1	1	1	-
Number of performed cycles $N_{C,i}$		5	6	6	8	8	1
Max. hoop stress in the MCM wrap $\sigma_{\theta C}$, MPa		26.6	39.9	53.2	66.6	79.9	93.2
Max. specific strain of the MCM wrap $\varepsilon_{\theta C}$, %		0.13	0.20	0.27	0.33	0.40	0.47

* when reaching the pressure p_p = 14 Mpa, the burst of the MCM wrap occurred.

The sample was closed with two ellipsoidal weld-mounted bottoms, was endowed with water filling sleeves, air outlet connections and mounting connections for an gauge for registering the pressure and was subjected to the internal pressure test, on the stall shown in Figure 4, with successive cycles of rising – maintaining – discharging the pressure. The characteristics of the load cycles of the sample up to its failure are shown in Table 2, and the aspect of the sample at the end of the testing is shown in Figure 5; the failure occurred by the rupture of the

MCM wrap, followed by the local burst of the steel sample in the area with the relative depth d_{pr} = 0.8 of the metal loss defect.

3. RESULTS AND DISCUSSION

The results obtained after testing the sample were used for estimating the fatigue behaviour of MCM wraps. With this purpose it was preceded as follows:

- there were calculated using the calculation procedures in [1] the maximum hoop stress intensities $\sigma_{\theta C}$ and the values of the maximum circumferential specific strain $\varepsilon_{\theta C}$ of the MCM wrap, generated during the internal pressure load cycles of the sample; the values obtained are shown in Table 2.
- there was estimated the number of pressure load cycles of the transmission pipelines N_p, that have to be considered as reference fatigue life N_{ref} for the (conventional) defining of a fatigue strength of the MCM wrap; considering that the maximum life is of 40...45 years and the operating pressure has daily cyclic fluctuations (between a minimum and a maximum value), it resulted (conservative) that $N_{ref} = N_p$ = 20000 cycles;
- there were defined the characteristics of the load cycle of each load block $i = 1...n$ (n = 7): maximum cycle stress $\sigma_{C\max,i} = \sigma_{\theta C,i}$; minimum cycle stress $\sigma_{C\min,i} = 0$; asymmetry coefficient of the load cycle $R_{CO} = \sigma_{C\min,i} / \sigma_{C\max,i} = 0$; stress amplitude $\Delta\sigma_{Ci} = \sigma_{C\max,i} - \sigma_{C\min,i} = \sigma_{C\max,i}(1 - R_{CO}) = \sigma_{C\max,i}$;
- it was considered that MCM has a fatigue curve (Wöhler) of the form:

$$(\Delta\sigma_C)^m N_{Cf} = C_f \text{ or } \left(\sigma_{C\max} - \sigma_{C\min}\right)^m N_{Cf} = C_f \text{ or } \sigma_{C\max}^m \left(1 - R_{CO}\right)^m N_{Cf} = C_f \tag{5}$$

N_f being the number of load cycles to failure (fatigue life / endurance) of the MCM; putting $\sigma_{C\max} = f_{Ca} R_{mC}$ ($f_{Ca} \in (0;1)$ is called normalized maximum stress) and $R_{CO} = 0$, the fatigue curve gets the following analytical form:

$$f_{ca}^m N_{Cf} = \frac{C_f}{R_{mC}^m} = C_{fa} \tag{6}$$

Under these circumstances, in order to determine the fatigue strength of MCM there was used the Locati method, which assumes that all the wraps made from the same composite material have the same parameter m of the fatigue curve (Wöhler), but the fatigue strength R_{fC} is dependent on the structure of the material. Therefore, the following steps were taken in order to determine the fatigue strength of the MCM wrap R_{fC} [9,10]:

- ➢ the MCM wrap was subjected to different levels of pressure in sequences $i = 1...n$, for each sequence a number of N_{Ci} cycles being applied, with $R_{CO} = 0$ and different levels of maximum stress $\sigma_{C\max,i}$ and the stress amplitude $\Delta\sigma_{Ci} = \sigma_{C\max,i}$ respectively; obviously, because $\Delta\sigma_{Ci}$ increased from each level to the next, the MCM wrap failed when reaching the load sequence n;
- ➢ considering a random value of normalized fatigue strength f_{Cax} and assuming that the slope of the fatigue curve is m, the number of cycles for each load sequence which resulted in failure $N_{Cf,i}$ was calculated as follows:

$$N_{Cf,i} = \left[\frac{f_{Cax}}{f_{ca,i}}\right]^m N_{ref}, \; i = 1...n \tag{7}$$

where N_{ref} = 20000 is the reference fatigue life for determining the fatigue strength $R_{Cx} = f_{Cax} R_{mC}$ (R_{Cx} is the highest value of the maximum stress of the variable load sequence which does not result in fatigue failure after N_{ref} cycles);

- ➢ knowing the values of $N_{C,i}$ and $N_{Cf,i}$, $i = 1 ... n$, the fatigue damage at each variable load sequence $D_{Cf,i}$ was calculated using the following formula:

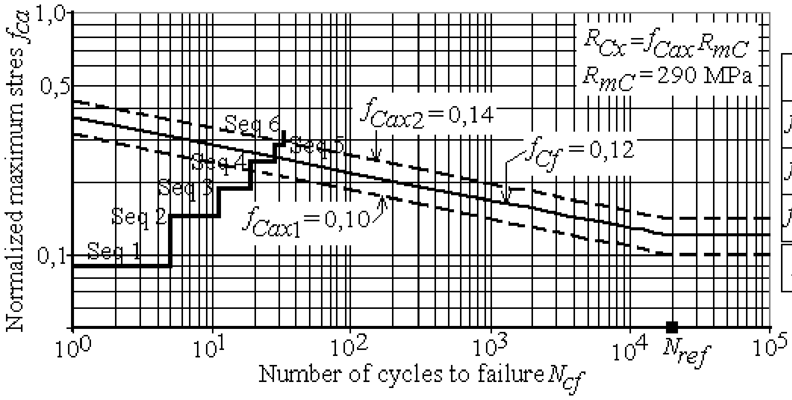
$$D_{Cf,i} = \frac{N_{Ci}}{N_{Cf,i}} < 1, i = 1...n \tag{8}$$

and the cumulative fatigue damage DC, as follows:

$$DC = \sum_{i=1}^{n} D_{f,i} = \sum_{i=1}^{n} \frac{N_i}{N_{f,i}} \tag{9}$$

➢ repeating the previous steps for different values of f_{Cax} and $R_{Cx} = f_{Cax}R_{mC}$, the normalized fatigue strength f_{Cf} and fatigue strength R_{fC} of the MCM wrap were calculated, defined as the values of f_{Cax} and R_{Cx} where the cumulative fatigue damage reached $DC \cong 1$.

Figure 6 shows the results of applying the Locati method for determining the fatigue strength R_{fC} and the normalized fatigue strength f_{fC} of the MCM wrap assuming the value of m = 8.7 (determined in [11] as being experimentally determined for a composite material, having an epoxy matrix and the reinforcement component of glass fibres, similar to MCM) in the analytical expression (6) of the fatigue curve (Wöhler). The values of the characteristics which define the fatigue behaviour of MCM wraps, obtained by using the Locati method, were: normalized fatigue strength f_{Cf} = 0.12; fatigue strength R_{fC} = 35 MPa ≅ 0.12R_{mC}; these values must be taken into account when determining the thickness of MCM wraps which are applied over the steel pipelines with metal loss defects.



f_{Cax}	R_{Cx}, MPa	DC
f_{Cax1}=0,10	29,0	4,6059
f_{Cax2}=0,14	40,6	0,2466
f_{Cax3}=0,12	34,8	0,9993
f_{Cf} = 0,12	R_{fC} ≅ 35	1

Fig. 6. Determining the fatigue strength of the MCM wrap by means of the Locati method.

4. CONCLUSIONS

For repairing pipelines designed for the transport of combustible fluids (oil, liquid petroleum and natural gas) without taking them out of service there are chosen technologies that don't involve welding procedures, a simple and safe solution being the application of composite material wraps, such as MCM wraps, obtained by embedding many layers of glass fibre fabric into a composite matrix made of a reactive polymer modified with flexibilizators and mineral fillings.

Due to the fluctuations of the operating pressure of pipelines, the composite material reinforcement wraps applied for repairing defects can be subjected to variable loads and, thus, when determining their thickness one must know their fatigue behaviour characteristics. For determining the fatigue strength of composite material reinforcement wraps there can be used the method suggested within this paper, based on the use of the results of the variable pressure cycle test, up to the burst, of some samples taken from the pipe section this kind of wraps had been applied over.

The reinforcement MCM wraps can be successfully used for repairing pipelines, because they have high mechanical strength characteristics (modulus of elasticity E_C = 17.5...22.7 GPa; ultimate tensile strength R_{mC} = 265...315 MPa; percent elongation at failure A_C = 1.32...1.60 %), at the level of the best wraps used worldwide and they have an acceptable fatigue strength ($R_{fC} \cong 0.12R_{mC}$).

REFERENCES

[1] Zecheru, Gh., Draghici, Gh., Dumitru, Gh., Diniţă, A., Raport final la contractul cercetare no. 39/2007, Universitate Petrol – Gaze din Ploieşti, 2008.
[2] * * * Rehabilitation of corroded pipelines and pipes with FibaRoll, Catalog FibaRoll / FTi Ltd, 2006.
[3] * * * Clock Spring – The fast economical solution for permanent pipeline repair, Catalog 2006.

[4] * * * Black-Diamond Composite Wrap For Pipelines, T. D. Williamson Inc., Bulletin No. 5300.002.01, July, 2004.
[5] Zecheru, Gh., Laţa, E.I., Draghici, Gh., Diniţă, A., Mechanical Properties of a New Composite Sleeve for Pipeline Repair, Revista de materiale plastice, no. 1, 2011.
[6] Zecheru, Gh., Draghici, Gh., Laţa, E.I., Diniţă, A., In-service Repair of the Transmission Pipelines, Buletinul Universităţii Petrol – Gaze din Ploieşti, vol.LXII, Seria Tehnică, no. 2, 2010.
[7] Zecheru, Gh., Draghici, Gh., Laţa, E.I., Diniţă, A., With and Without Welding Maintenance Technologies for the gas transsmission pipelines, Proceedings of the 2nd South east European IIW International Congress, Sofia, 2010.
[8] * * * ISO/TS 24817, Petroleum, petrochemical and natural gas industries – Composite repairs for pipework – Qualification and design, installation, testing and inspection, 2006.
[9] Zecheru Gh., Drăghici Gh., Meşca D., Effect of Ultrasonic Impact Treatment on the Fatigue Behaviour of the Fillet Welded Lap Joints between Steel Plates, Buletinul Universităţii Petrol – Gaze din Ploieşti, no. 4, 2009.
[10] Zecheru Gh., Meşca D., Drăghici Gh., Fatigue behaviour of beams made by welding of thin plates or profiles, Sudura, no. 4, 2010.