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In-time monitoring of fatigue damage

Chmelko,V.[a]*, Kliman, V.[b], Garan, M.[a]

[a]Slovak University of Technology in Bratislava, Faculty of Mechanical Engineering, Institute of applied mechanics and mechatronics, Námestie slobody 17, 812 31 Bratislava, Slovak republic
[b]Institute of Materials and Machine Mechanics, Slovak Academy of Sciences, Račianska 75, 831 02 Bratislava 3, Slovak republic

Abstract

In-time monitoring of the fatigue damage for a structure in a real operation is the complex problem, including :
- measurement of the operational loading and evaluation stress-strain state
- transformation of the loading into a critical section (notch)
- using the material properties for a corresponding material
- in-time calculation of the fatigue damage increase, etc.

This contribution includes the brief analysis of these steps and explains the processing of the measured deformation state without re-calculation the strain into stress in detail and presents the results from the installed in-time monitoring system of the fatigue damage in a real operation of gas pipelines.

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Keywords: monitoring, fatigue, damage

1. Introduction

In-time monitoring of fatigue damage lies in continuous sensing of stress i.e. strain with respect of time in critical place of the structure and its continuous processing into the form allowing calculation of the current fatigue damage increment using the known material properties [1]. The current value of the fatigue damage in the specific time t_i is given as an addition of the previous damage increments until the time t_{i-1} and current calculated increment D_i according

* Corresponding author. Tel.: +421 2 57296225; fax: +421 2 52925743, +421 52497890.
E-mail address: vladimir.chmelko@stuba.sk

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the following expression

$$D_{akt} = \sum_{t_i=1}^{i-1} D_i + D_i \quad (1)$$

where interval between t_i and t_{i-1} introduces the time length in which the loading process is processing and the fatigue damage is calculating.

Such increment monitoring system of the current fatigue damage in critical place of the structure safeguards as follows the continual sensing of the loading in critical place, continuous evaluation of stress-strain state, peaks detection of the extreme values, separation of the loading amplitudes and calculation of the fatigue damage increment using the known material parameters. The overall process must be justified in a way so that during the sensing of a loading in a time ti+1 must conduct all operations with the previous loading process. The performance of the monitoring system must have some reserve for visualization the behavior of the fatigue damage and archiving the loading process including archived the data of the previous time sections. Next, the data organization must be ensured and their history in order to avoid the stream interruption of the measuring data as well as losing the information i.e. overloading the recorded hard drives.

In the contribution, there is presented this attitude that is applied on the critical places installed on the gas pipeline system of the compressor station. The service of these pipelines is characteristic except the loading with and internal pressure also with addition vibrating which is induced by the dynamic during the operation of the compressors. The main objective of this monitoring system except the recording of the development of the fatigue damage is the registration and recording of the so called non-standard loading situations e.g. owing to the instability of the pipeline subsoil. Early registration and consideration of the effects these situations will allow to prevent the collapse of the pipeline. The emphasis is placed on the procedures which allow the solution and processing of all tasks in a real time.

2. Processing of strain signals

Continuous sensing of the loading in real operation is realized by strain gages possibly with other sensors for strain. Assignment of the corresponding stress to measuring strain is the step which can significantly affect the magnitude of the stress amplitudes what is documented by Fig.1 with measuring curves for material steel C55. From the strain value of 0,1% is possible to identify the significant difference in the recalculated value of the stress for individual material models represented by curves display on Fig. 1. Difference of corresponding stress value of 20 MPa and more is then projected into multiple difference of the fatigue lifetime value. For purpose of the continual monitoring is than suitable remain the measuring loading process in the form of the strain. That means processing the measuring strains into comprehensive process of maximum strain in the measuring cross-section. As an example we introduce the annular cross-section loaded with internal pressure including additional loading of bending and torsion. There is necessary to use minimum of 6 strain gages for distinct determination of the critical point in the cross-section area assuming the proportional loading for known direction of the transversal force [2]. Condition of loading proportionality in view of the loading source to which is the internal pressure and its pulsations well satisfied. For annular cross-section of the pipeline was used system of circumferentially deployment of the strain gages in order to allow separation of the individual components of the loading (Fig.2). Using of this system is possible to determine the most stressed point of the cross-section including the component of main strains. Deployment of the strain gages circumferentially along the annular cross-section in the spacing of 120^o (rosette in this point of action of the transversal force in the vertical direction) allowing separation of the individual components of loading (ε_N – strain from normal force, ε_{Mo} – strain from bending moment, γ_{Mk} – shear strain from torque moment, γ_{Mk} – shear strain from transversal force, ε_r – strain from internal pressure in radial direction, ε_t – strain from internal pressure in tangential direction).

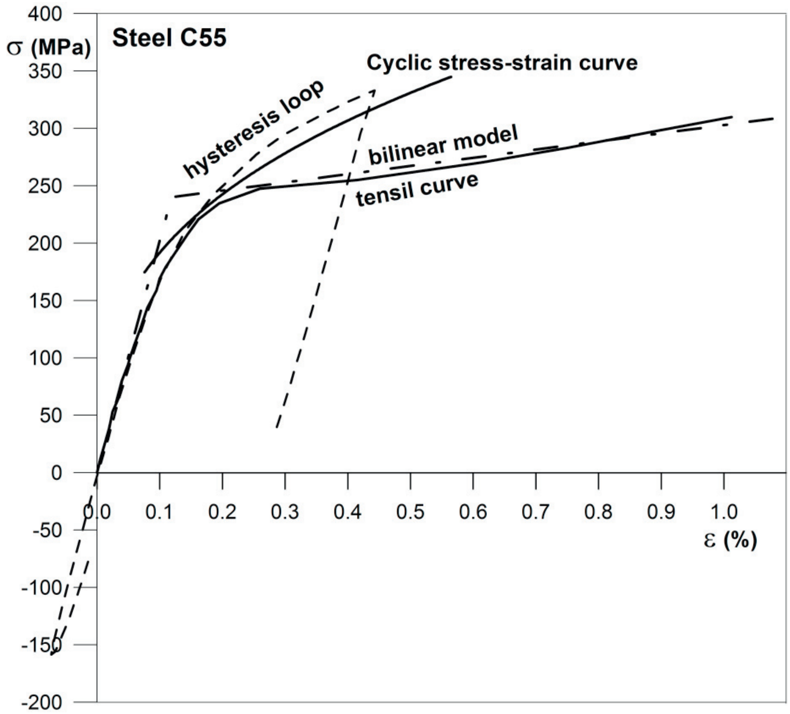

Fig.1 Some stress-strain models. Measured at low carbon steel C55.

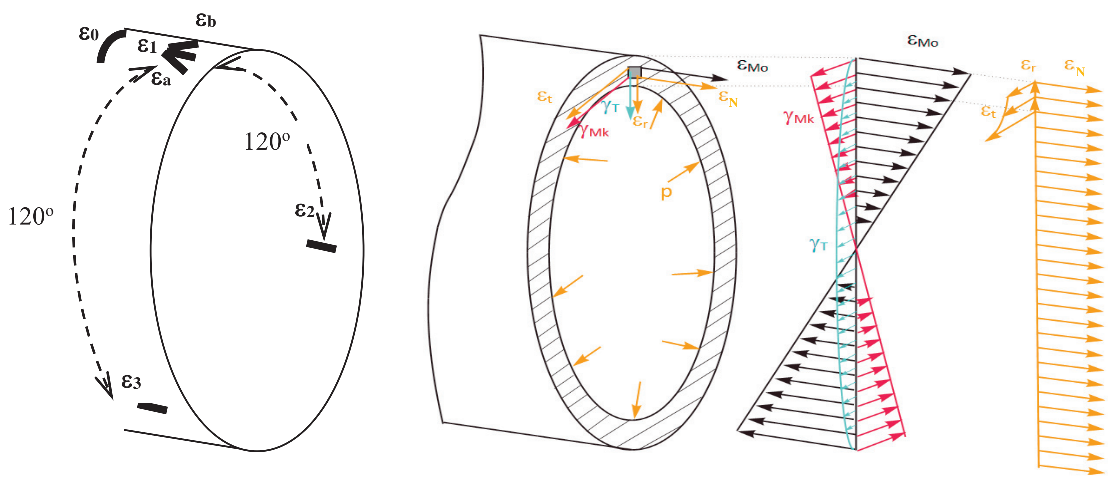

Fig.2 Deployment of the strain gages circumferentially along the annular cross-section in the spacing of 120° (rosette in this point of action of the transversal force in the vertical direction) allowing separation of the individual components of loading (ε_N – strain from normal force, ε_{Mo} – strain from bending moment, γ_{Mk} – shear strain from torque moment, γ_T – shear strain from transversal force, ε_r – strain from internal pressure in radial direction, ε_t – strain from internal pressure in tangential direction).

On the basis of the expressions [3] arising from the Mohr's circle is possible to determine the components planar strain in the most stressed point on the surface of the cross-section according to the following expressions

$$\varepsilon_x = \varepsilon_N + \varepsilon_{Mo} = \left(\frac{\varepsilon_{1k} + \varepsilon_{2k} + \varepsilon_{3k}}{3}\right) + \frac{2}{3}\sqrt{\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2 - \varepsilon_1\varepsilon_2 - \varepsilon_1\varepsilon_3 - \varepsilon_2\varepsilon_3}$$
$$\varepsilon_y = \varepsilon_a + \varepsilon_b - \varepsilon_x$$
$$\frac{\gamma}{2} = \frac{\varepsilon_a - \varepsilon_b}{2} \quad (2)$$

where ε_{1k}, ε_{2k}, ε_{3k} are the values of strain in axial direction requiring the thermal compensation
ε_N, ε_{Mo} are the values of strain from the normal force resp. from the bending moment

The values of the main strains are then

$$\varepsilon_1 = \frac{\varepsilon_x + \varepsilon_y}{2} + \sqrt{\left(\frac{\varepsilon_x - \varepsilon_y}{2}\right)^2 + \left(\frac{\gamma}{2}\right)^2}$$
$$\varepsilon_2 = \frac{\varepsilon_x + \varepsilon_y}{2} - \sqrt{\left(\frac{\varepsilon_x - \varepsilon_y}{2}\right)^2 + \left(\frac{\gamma}{2}\right)^2} \quad (3)$$

In radial direction the component of the strain induced by internal pressure equals

$$\varepsilon_3 = -\frac{\varepsilon_{0k}.2.h}{D_S} \quad (4)$$

where ε_{0k} is strain in tangential direction of pipeline circuit requiring thermal compensation (Fig.2)
h is the thickness of pipeline wall
D_s is mean diameter of the pipeline

Using the Tresca's hypothesis registered in the ASME (stress intensity) for this type of structure [4] is then

$$\varepsilon_{red} = max(\varepsilon_1, \varepsilon_2) - \varepsilon_3 \quad (5)$$

3. Calculation of the fatigue damage

Using the overall strain process with respect of time into the calculation of the fatigue damage require using of corresponding material properties [5,6] which can be acquired from the life time curve in the following form

$$\varepsilon_{ac} = f(2N_f) \quad (6)$$

By measuring on specimens created by material of the pipeline on the electrohydraulic pulsator (in the mode of the controlled amplitude of the total strain) is possible to acquire relationship displayed in the Fig. 3.

For the purpose of accelerating the calculation of the fatigue damage increments in a real time was in this case approximated the life time curve by the following expression

$$\varepsilon_{ac} = \varepsilon_d'(2N_f)^d \quad (7)$$

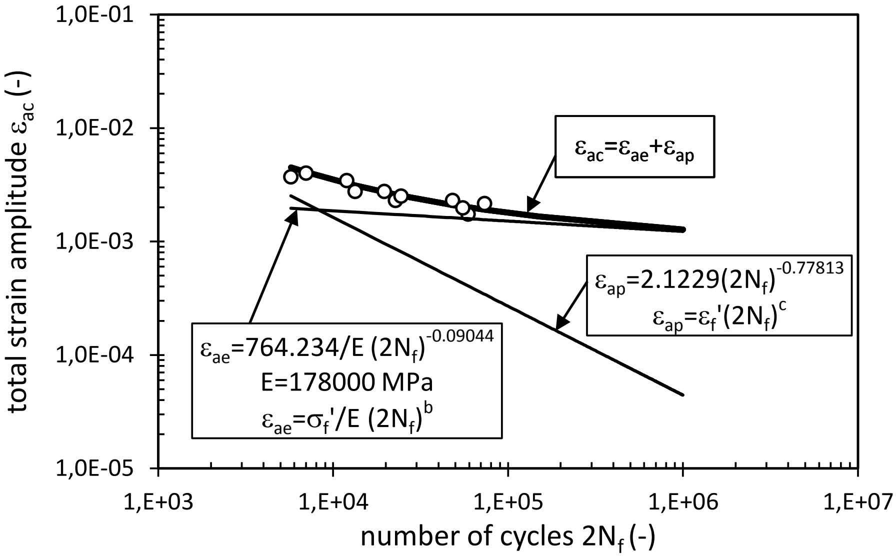

Fig.3 Manson-Coffin fatigue-life curve for the pipeline material (steel St 52)

Table 1. Fatigue-life test results (steel St 52).

$2N_f$ (-)	ε_{ac} (-)	σ_a (MPa)	comment
48110	0.0022945	282.765	
19576	0.0027543	303.522	
59038	0.0017432	264.58	loading mode:
22702	0.0023035	281.4	ε_{ac} = const
11954	0.0034277	323.094	
7000	0.00401	325.061	
55100	0.0019739	250.353	E = 178000 MPa
5734	0.003699	358	
13358	0.002762	322	
24444	0.002509	307	
73344	0.002158	277	
7460		350	
60854		300	
104994		283.367	σ_a = const
236768		270	
477522		260.59	
1037494		231.097	

This entitles us to a high coefficient of correlation in the regression based on the relationship (7) Fig. 4.

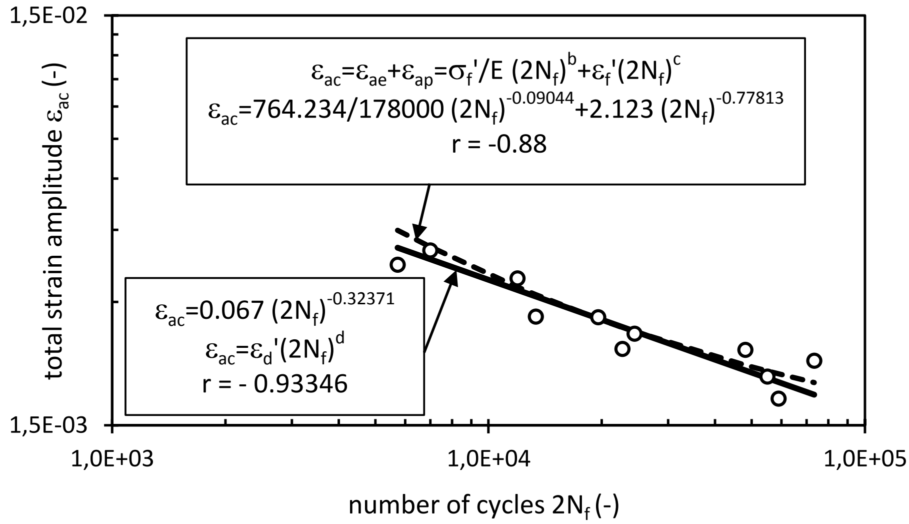

Fig.4 Compare the fatigue life curve with exoerimental results. o - experimental points (Table 1)

The known material properties acquired from this dependency allow to use the Palmgren-Miner's accumulation formula [7,8]

$$D = \sum \frac{n_i}{N_{fi}} \quad ,$$

$$\text{where} \quad N_f = \frac{1}{2}\left(\frac{\varepsilon_{ac}}{\varepsilon_d^{'}}\right)^{\frac{1}{d}} \quad . \tag{8}$$

The loading process in the form of overall maximum strain with respect of time $\varepsilon_{red(t)}$ has in a real operation in general non-harmonic character. Using the standardized Rain-Flow algorithm [9] is possible to determine macroblock of harmonic cycles in the form suitable for on-line monitoring. Proposal of Rain-flow method suitable for on-line monitoring lies in that ordinates of the process acquired at the time t_i are elaborated with the remainder of the rain-flow method of the previous process. These ordinates are joined before the current process and then used as an input of calculation of the rain-flow. The procedure of calculation describe in the work [10].

4. Realization of the on-line monitoring system - results

In-time monitoring system pursuing the fatigue damage was installed on the gas pipeline of the transit courtyard in year 2010. This monitoring system continuously evaluates increments of the fatigue damage in 9 critical cross-section. The cyclic properties were acquired by direct cyclic tests on the specimens of materials. Development of the overall loading process in two critical places of the pipeline in the form of the stress is displayed in Fig.5. Behaviors are calculated using the expressions (5) and multiplied by Young's modulus for visualization in the diagram (calculation of the fatigue damage is realized only for the extreme values of strain). The loading process is characterized by high mean value. Significant amplitudes of loading bring shutdowns and slopes of the pressure (see month 08). Increment of the fatigue lifetime per year represents 0.1 % what means that the operation of the pipeline was safety in view of the occurrence of the fatigue crack. In the following monitoring period the system recorded high descent of the mean value of the overall loading (Fig. 6). From the measuring data was possible to identify the cause of this increment – it was addition bending stress that appeared in result of decrease of the subsoil because of the effect of more raining.

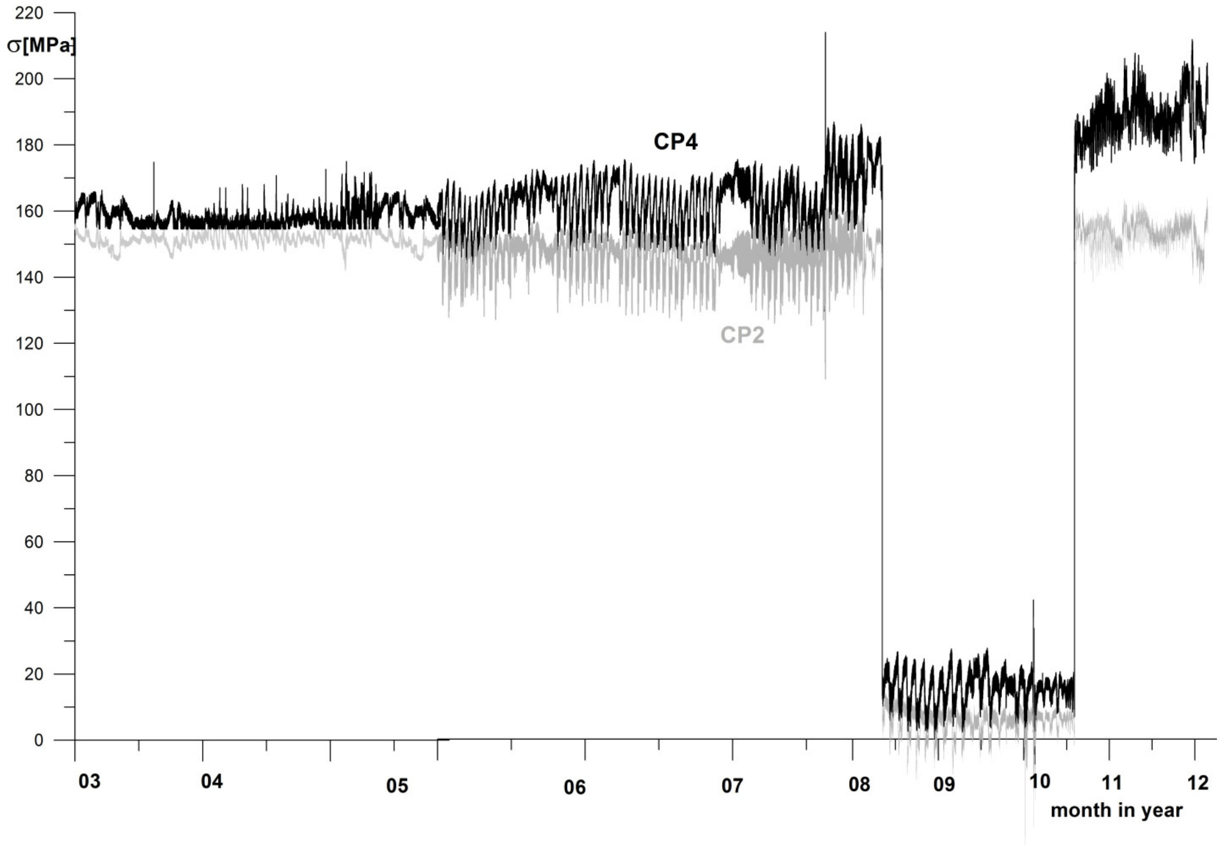

Fig.5 The year-round development of the overall maximum stress in two critical places KM2 and KM4 of the pipeline.

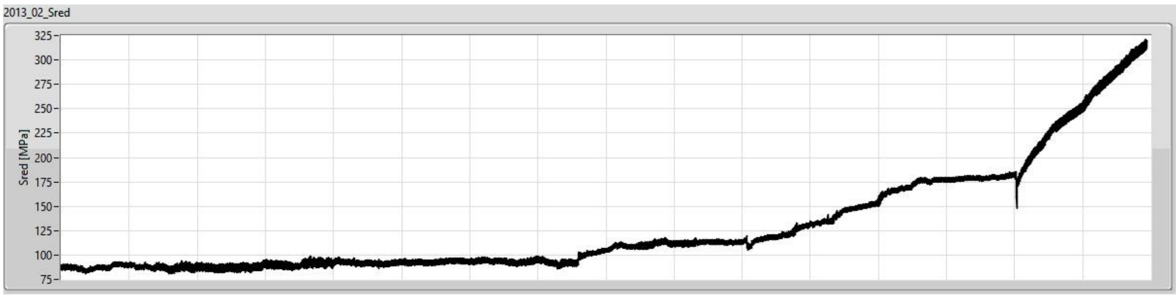

Fig.6 Descent of the mean value of the loading stress in one critical place during one month.

Conclusion

In-time monitoring of the fatigue damage based on the processing of the measuring loading in the form strain with respect of time as well as calculation of the increments of fatigue damage in presented form brings in operation results that during the projection of the pipelines was impossible to consider. Range of this contribution does not allow to describe all useful information that is represented monitoring system able to provide. During 4 years of operation is this monitoring system significant tool (together with others non-destructive methods [11]) of monitoring the safety of operation for the given structure.

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References

[1] Chmelko,V., Kepka, M.: In-time Monitoring of the Fatigue Safety in Operation of the Pipelines Parts. AIJCR, 4, 2014, p.50-55

[2] Chmelko, V.: PUV 5069/2012, G01L 5/10.

[3] Poděbradský, J.: Determination of service load components by strain gauge measurement. Strojnícky časopis (Journal of Mechanical Engineering) - in Slovak, 43, 1992, 472-478

[4] ASME Boiler and Pressure Vessel Code, Section VIII, Division 2: Pressure Vessels – Alternative Rules, 1983 SI Edition

[5] Margetin, M., Chmelko V.: Experimental quantification of the fatigue stress concentrator on MIG butt welded S355 steel specimen. Transactions of the VŠB – Technical University of Ostrava Mechanical Series, 59, 2013, p. 45-50

[6] Ďurka, R., Margetin, M., Šulko, M.: In: 14th International Conference "Applied Mechanics 2012",. Pilsen, The University of West Bohemia, 2012. p. 29-32, ISBN 978-80-261-0097-3,

[7] Palmgren,A.: Verfahrenstechnik, 68, Berlin, 1924, s.339

[8] Miner, M.: Journal of Applied Mechanics, 67, 1945, A159

[9] Amzallag,C.-Gerey,.P.-Robert,J.L.-Bahuaudt,J.: Standardization of the Rainflow Counting Method for Fatigue Analysis. International Journal of Fatigue, 16, 1994, s.287

[10] Jároši, M.: The influence of individual factors on fatigue life prediction under random loading of structures. Bratislava, Slovak Academy of Sciences 2007 (PhD. Thesis, in Slovak).

[11] Šulko, M., Chmelko, V.: In: 10th International Conference "Applied Mechanics 2008", Gliwice, Silesian University of Technology, 2008. ISBN 978-83-60102-49-7. - CD Rom.