Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 25 ISSUE 2 December 2007

Numerical strength and fatigue analysis in application to hydraulic cylinders

W. Torbacki*
Szczecin University of Technology, Al. Piastow 41, 71-065 Szczecin, Poland
* Corresponding author: E-mail address: torbacki@ps.pl

Received 13.03.2007; published in revised form 01.12.2007

Analysis and modelling

ABSTRACT

Purpose: The main issue of this paper is to present results of strength and fatigue limit analysis applied to piston type hydraulic cylinders. It will also shows advantages of application of the up-to-date digital chain of engineering analysis within which CAD tools are being used as well as strength and fatigue limit analysis.
Design/methodology/approach: Computer analysis of the strength analysis by using Finite Element Method (FEM) and fatigue life analysis by using Fatigue Life Prediction Method (FLP) were carried out.
Findings: The most strenuous and at the same time opened to a damage risk cylinder zones were localized. Two construction solution possibilities of fixing the tongue stub with a hydraulic cylinder jacket were analysed. Finally Wöhler fatigue graphs for a different values of operating average pressure and stress concentration factor were presented.
Research limitations/implications: Further researches should concentrate on modifications and analysis which will help to recognize the best possible zones of fixing a tongue stub with a hydraulic cylinder jacket in order to find the best configuration of construction kinematic pair.
Practical implications: Modern engineering construction analyze require not only standard strength analysis but also calculation of fatigue life.
Originality/value: The paper can be useful for person who performs strength analysis with a use of finite element method but has never used digital fatigue life analysis method. It might be also useful for a person interested in recognizing of both methods.
Keywords: Computational mechanics; Finite Element Method; Fatigue Life Analysis; Strength analysis

1. Introduction

It is estimated that about 60% of permanent damages are caused by fatigue changes of materials and elements. That is why it is so important to apply only reliable engineering tools while performing the strength and fatigue limit analysis of the construction elements. Nowadays, there are available quite a lot of systems which are using the finite element method (FEM) [1-8] for a strength analyze. To the most known and at the same time offering a similar functionality level belongs: ABAQUS, ANSYS, CATIA, I-DEAS, MSC.NASTRAN. There are also available many systems for fatigue life calculations [9-11]: FEMFAT, FE-SAFE, LMS VIRTUAL.LAB DURABILITY, MSC.FATIGUE. This group of programs, thanks to built-in data import modules, use the results of strength analysis to estimate the degree of fatigue life.

Fatigue life analyse of construction elements performed with finite element method can reduce or even totally eliminate the costs resulting from repeated redesigning or withdrawing defective products. It is also possible to significantly reduce cost of tests which are performed before prototype production. For analysis of fatigue life in a high-cycle range a well know to designers method of combining the stress values with a corresponding to it number of cycles to damage were used. Some sources [12-13] states that the boundary between low and high-cycle fatigue life amounts around 10^4 or 10^5 number of cycles. But more important than to precisely determine the border value is to state that calculation held in a high-cyclic fatigue range are performed for cycles in an elastic work zone and in a low-cyclic fatigue range in a elasto-plastic work zone.

2. Numerical model

A double-sided hydraulic cylinder with one-sided piston rod fastened by lug with a solid bush was analyzed (Fig. 1a).

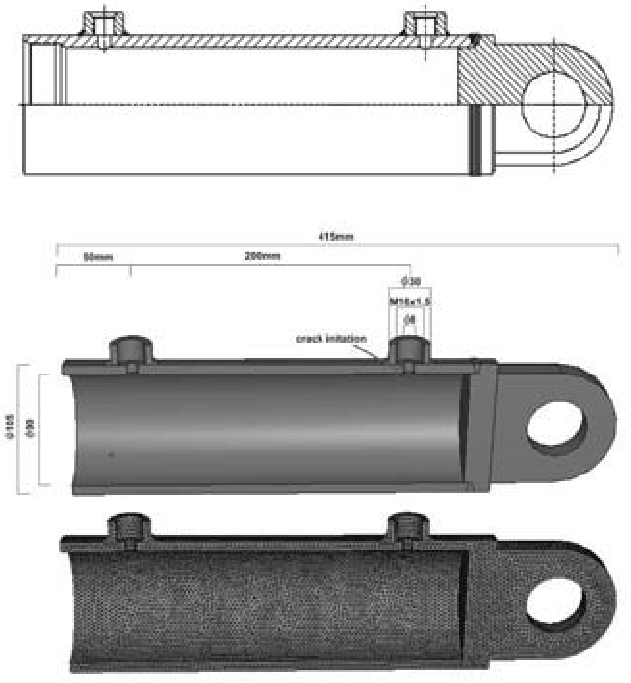

Fig. 1. Hydraulic cylinder (a), CAD model (b), FEM discretization (c)

Such kind of fixing: (i) prevents a transfer of transverse forces through the piston rod, (ii) allows to a pass over a mass of cylinder elements, (iii) allows to pass over friction force in a fixing articulated joints. Figure 1b presents CAD spatial model of this cylinder. The cylinder diameter is 105 mm, the piston diameter is 90 mm, the cylinder stroke is 250 mm. The total length of the cylinder together with lug is 415 mm. Cylinders are made of steel St52 (ultimate strength R_m = 520 MPa, yield strength R_e = 330 MPa, Young module E = 210 GPa). Actuator strength and fatigue life analysis was executed for deterministic, sinusoidal variable loads.

In a digital analyse process two calculation models were used. The first one assumes a perfect shape of fillet weld which connects bringing working factor stubs with cylinder jacket. The second model omits this connection. It is assumed that the stub and cylinder are recognized as one element. Both models were analysed twice with a use of a various kinds of spatial finite elements.

In the first case model discretization was based on tetrahedral finite elements. In the second one on a hexahedral. Figure 1c presents a discrete FEM model divided into tetrahedral finite elements.

3. Numerical strength analysis

The exact place of inserting a working factor into hydraulic cylinder is very important in relation to construction issues. As a result of analysis it was stated that these are the places of highest stress value in a whole construction.

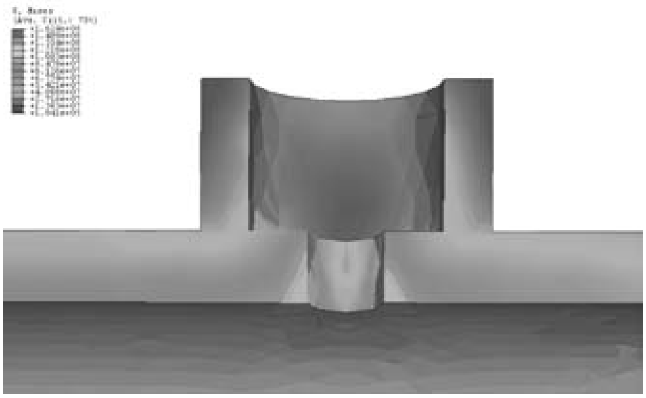

Fig. 2. Contour lines of Huber-Mises reduced stress: tetrahedral model with no filled weld

The maximum reduced stress values recognized with Huber-Mises hypothesis are localized in surroundings of such places. In the tetrahedral model with no fillet welds the value amounts 162 MPa (Fig. 2) and 138 MPa in a model with fillet welds. For the hexahedral model they adequately amount 159 MPa and 135 MPa.

4. Numerical fatigue limit analysis

Numerical fatigue life analysis (number of cycles to damage) carried out with the use of FLP systems enable to determine also other fatigue factors. Example of such factor is FOS (Factor of Strength) which describes the fatigue life of materials within a function of working stress. A Goodman (Fig. 3) or Soderberg formulas are the usually used to determine this factor.

The factor of safety (*FOS)* is introduced as:

$$FOS = OB/OA. \tag{1}$$

From geometrical similarity we get:

$$\sigma_a/(\sigma_f / K_f) = (R_m/FOS - \sigma_m)/R_m. \tag{2}$$

From which follows

$$1/FOS = \sigma_m/R_m + K_f\,(\sigma_a/\sigma_f). \tag{3}$$

Let us substitute in Eq. (3) R_m with R_e (based on Soderberg line [14]) we obtain a new formula for a safety of factor:

$$1/FOS = \sigma_m/R_e + K_f\,(\sigma_a/\sigma_f) \tag{4}$$

which is known as the Soderberg equation.

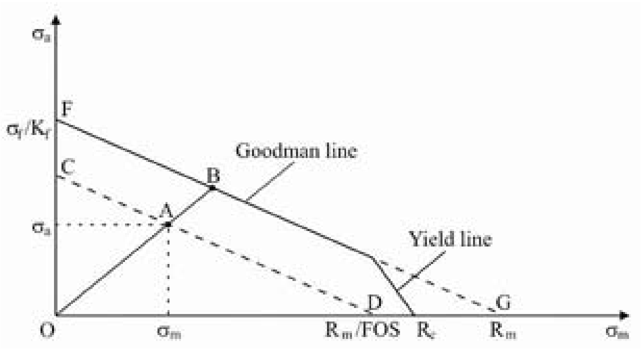

Fig. 3. Goodman line: σ_a – stress amplitude, σ_m – mean stress, R_e – yield strength, R_m – ultimate strength, σ_f – stress adequate to a number of fatigue life N cycles, K_f – fatigue notch factor [14]

Strength analysis results obtained with finite element method (FEM) allows to recognize input data for FLP rank system which is helpful for determine the fatigue life. It is well known that the results received within strength analysis carried with the use of tetrahedral finite elements might be less accurate than the analysis with the use of hexahedral finite elements.

In an analyzed models the difference in a stress value for both cases was lower than 2%. Due to higher maximum values in tetrahedral models (they influence the fatigue life) they were chosen for a further fatigue limit analysis. A complete results of this analysis will be introduced in another publication.

In case of considering a welded joints within the analyzed model most FLP systems for determine fatigue life use BS 7608 [15] recommendations.

This standard concentrates on welded joints and calculations of its fatigue life. BS 7608 divides welded joints into classes ased on a area of expected fatigue crack initiation. Each class is assigned with a letter symbol and is also described with a acceptable range of transferred stress. The highest B class is described with value of 150 MPa for number of 10^6 cycles and the lowest G class has a value of 50 MPa.

Analysis of cylinder fatigue life were performed for maximum inner pressure value p_{max} with assumption of asymmetrical double-sided cycle with a mean pressure value p_m of 10, 20 and 28 MPa.

Figure 4 presents a graphic representation of FOS factor prepared for both models with an assumption of selected stress concentration factor $K_t = 2$ [14], maximum pressure $p_{max} = 20$ MPa and mean pressure $p_m = 10$ MPa.

FOS factor which in some specific construction areas can obtain values higher than one points to safe places (the reduced stress is lower than assumed yield strength) and for values lower than one it point to danger areas (the reduced stress is higher than assumed yield strength).

For a models prepared without a weld the lowest value of FOS factor is 0.63 and for a models with a weld the minimum value of factor is 0.89. The model with a weld enables to receive more authoritative results since it is more similar to a physical object.

Figures 5 and 6 present (for both models) an influence of pressure changes p_m and stress concentration factor K_t on a transferred by the construction number of fatigue cycles N.

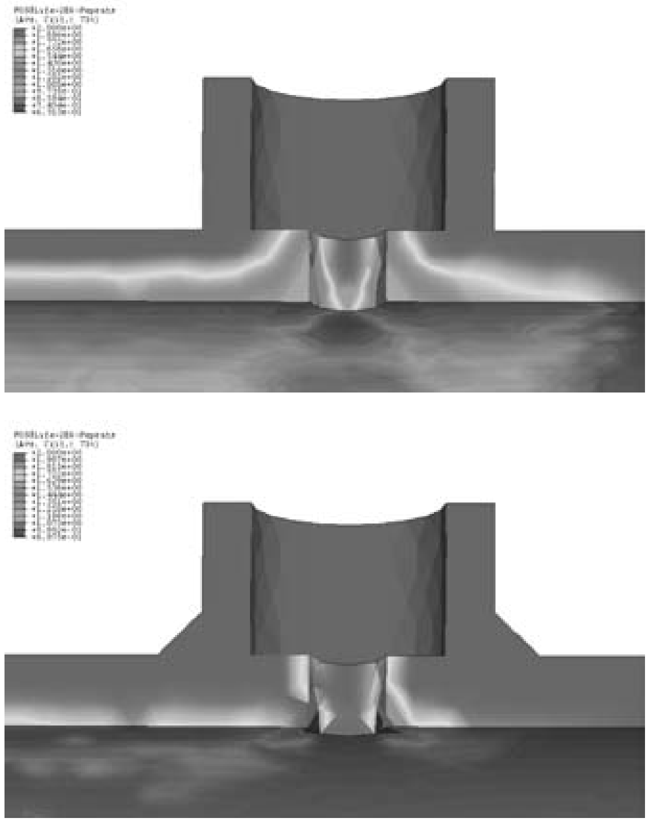

Fig. 4. Distribution of FOS: (a) model without a weld, (b) model with weld

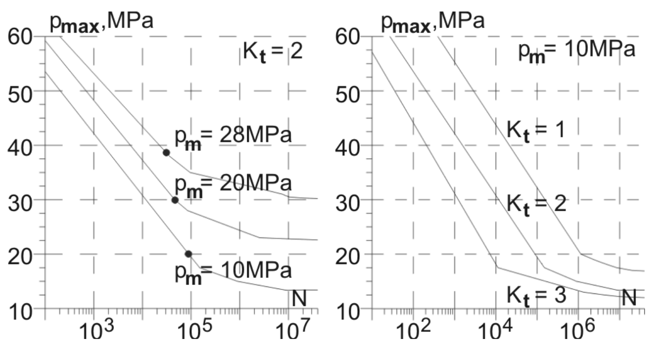

Fig. 5. Wöhler fatigue graphs (in scheme $p_{max} – N$) for a three different values of: (a) mean pressure p_m, (b) stress concentration factor K_t, model without a weld

Comparing figures 5a and 6a it can be stated that the model with a weld for the same values of mean pressure p_m achieves a fatigue life for higher values of maximum inner pressure p_{max}. It can be easily noticed that for a parallel values of mean pressure p_m and maximum pressure p_{max} and amplitude of pressure p_a (compare black points on figures 5a and 6a) model with the weld acquires higher N values. A set of selected, precise numerical data transferred by construction number of fatigue cycles N presented on figures 5 and 6 were gathered for both models in Tables 1 and 2.

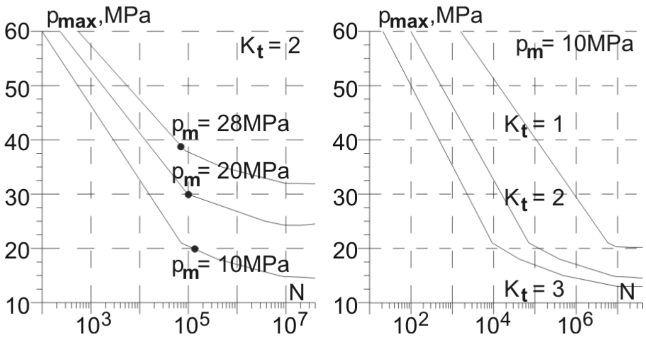

Fig. 6. Wöhler fatigue graphs (in scheme $p_{max} - N$) for a three different values of: (a) mean pressure p_m, (b) stress concentration factor K_t, model with a weld

Table 1.
Number of cycles N and corresponding values: maximum pressure p_{max}, mean pressure p_m, amplitude of pressure p_a, model without weld, stress concentration factor $K_t = 2$

p_m, MPa	p_{max}, MPa	p_a, MPa	N
10	20	10	89129
	13,3	3,3	2E+7
20	30	10	48263
	22,8	2,8	2E+7
28	38	10	32175
	30,2	2,2	2E+7

Table 2.
Number of cycles N and corresponding values: maximum pressure p_{max}, mean pressure p_m, amplitude of pressure p_a, model with weld, stress concentration factor $K_t = 2$

p_m, MPa	p_{max}, MPa	p_a, MPa	N
10	20	10	144544
	14,6	4,6	2E+7
20	30	10	99043
	24,5	4,5	2E+7
28	38	10	71394
	31,7	3,7	2E+7

5. Conclusions

Executed numerical strength and fatigue life analysis applied to hydraulic cylinder are an example application of modern computing engineering tools. The digital analyze process should contain such elements as: preparation of model within a CAD systems, strength analysis performed with finite element method and analysis of fatigue life. The most strenuous and at the same time opened to a damage possibilities cylinder zones were localized. Two construction solutions of fixing the tongue stub with a hydraulic cylinder jacket were analysed. Also Wöhler fatigue graphs for a different values of operating mean pressure and stress concentration factor were presented.

References

[1] E. Armentani, R. Esposito, R. Sepe, The effect of thermal properties and weld efficiency on residual stresses in welding, Journal of Achievements in Material and Manufacturing Engineering 20 (2007) 319-322.

[2] M. Czechowski, Fatigue life of friction stir welded Al-Mg alloys, Proceedings of the 13th Scientific International Conference „Achievements in Mechanical and Materials Engineering" AMME'2005, Gliwice – Zakopane, 2005, 83-86.

[3] S.K. Ghosh, A. Niku-Lari, CAD/CAM and FEM in Metal Working, Pergamon Press, New York, 1988.

[4] S. Kobayashi, Metal Forming and the Finite Element Method, Oxford University Press, New York, 2006.

[5] M. Mirzababaee, M. Tahani, S.M. Zebarjad, A new approach for the analysis of functionally graded beams, Journal of Achievements in Material and Manufacturing Engineering 17 (2006) 265-268.

[6] J. Robinson, FEM in the Design Process, Robinson and Association, Devon, 1990.

[7] P. Šimeček, D. Hajduk, Prediction of mechanical properties of hot rolled steel products, Journal of Achievements in Material and Manufacturing Engineering 20 (2007) 395-398.

[8] Y. Zhang, D. Redekop, Shell element simulation of the push method of tube bending, Journal of Achievements in Material and Manufacturing Engineering 17 (2006) 301-304.

[9] W.D. Pilkey, Peterson's Stress Concentration Factors, J. Wiley and Sons, New York, 1997.

[10] T.H. Childs, K. Maekawa, T. Obikawa, Y. Yamane, Metal Machining: Theory and Applications, Butterworth-Heinemann, Guildford, 2006.

[11] E. Zahavi, D. Barlam, Nonlinear Problems in Machine Design, CRC Press, Boca Raton, 2000.

[12] M. Łubiński, A. Filipowicz, W. Żółtowski, Metal Structures. Part I., Arkady, Warsaw, 2000 (in Polish).

[13] S. Kocańda, J. Szala, Foundation of Fatigue Calculation, PWN, Warsaw, 1997 (in Polish).

[14] E. Zahavi, V. Torbilo V, Fatigue Design. Life Expectancy of Machine Parts, CRC Press, Boca Raton, 1996.

[15] BS 7608, British Standards Institution, 1993.