The Role of Process Models, Flow Charts and Material Databases on the Structural Integrity of Transporting Steel Pipeline Systems

János Lukács[1, a], Gyula Nagy[1,b] and Imre Török[1,c]

[1]Department of Mechanical Engineering, University of Miskolc,

H-3515 Miskolc-Egyetemváros, Hungary

[a]janos.lukacs@uni-miskolc.hu , [b]metnagyg@uni-miskolc.hu, [c]metti@uni-miskolc.hu

Keywords: transporting pipeline, structural integrity, Pipeline Integrity Management System, database, burst test, carbon fiber reinforced polymer matrix composite.

Abstract. The lifetime management of different engineering structures and structure elements is one of the important technical-economic problems nowadays. Material databases play important role both on the integrity management (IM) and on the engineering critical assessment (ECA) of the pipeline systems. Material databases collected for general or special purposes and the synergy among the databases can be used to increase the efficiency of the user decisions and the reliability of the lifetime estimation. Different databases were developed for managing different pipeline systems. Data found in standards, in rules, in prescriptions and measured values were integrated in the databases. Additional databases were developed for design calculations and numerical analysis, including physical and plasticity constants of steels, polymers and polymer matrix composites. Theoretical process models were worked out for the decision of managing and assessing typical problems, containing the connections with the different databases. The process models are presented by theoretical flow charts, which can be adapted by potential users for their features. It can be concluded that the applicability of the process models and the flow charts is general; the actual user should add the logical interface between theory and praxis.

Introduction

The treatment of the degradation and failure of different engineering appliances, structures and structural elements, the management of their lifetime is one of the important technical and economic problems nowadays. The cause of it is banal: on one hand a significant number of the structures have already reached or exceeded their originally planned lifetime [1], though their following operation is of general interest; on the other hand the safe and economic operation of the new structures is a basic demand. The experiences of the operation, the frequency data of fractures, and the fracture causing failure statistics [2] of the engineering structures show the high significance of cyclic loadings, fatigue and fatigue crack propagation.

The problem – taking into account the complexity of the question – appears in many dimensions as discussed below. The solution can follow many approaches.

The purpose of this paper is to present an example of the development of an integrity management plan. A practical example illustrates use of the theoretical knowledge in the development of an integrated management system for different pipelines or pipeline systems (PIMS).

The Lifetime Management System (LMS)

The tasks of lifetime management basically appear in technical, economic and political dimensions. Fig. 1 [3] shows these three dimensions, their main elements and the most important connections among the elements and the dimensions. As the figure shows, the connections involve the wording of requirements, the course of data, information and results.

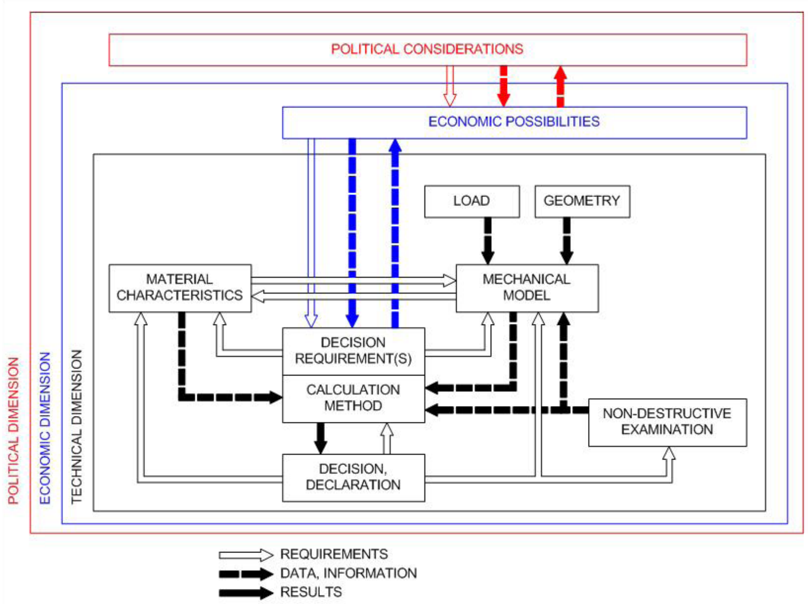

Figure 1. The lifetime management system (LMS) and their dimensions [3].

Dimensions of Lifetime Management

In the technical dimension we can apply many approaches, according as follows:

- microstructural approach;
- design concepts;
- operational approaches (conventional methods, fitness for purpose, structural integrity, integrity management and risk management);
- applied methods (engineering methods and fracture mechanical methods).

Microstructural Approach. Fatigue life can be divided into three phases: initiation of cracks, growth or propagation of cracks, and fracture. According to one approach, the second phase, can also be subdivided into the growth of micro cracks and the growth of macro cracks [4].

According to an other approach the initiation of cracks means the initiation of macro cracks, and involves the initial hardening/softening, the evolution of the dislocation structure, the cyclic strain localisation, the surface relief evolution, the crack nucleation and initiation, the growth of short cracks and finally the initiation of macro cracks [5]. In this case the second phase is the growth of macro cracks or long cracks.

The question, which phase dominating, is very important in addressing the problem. A pipeline operator must also know the detectable size of cracks for given structures or structural elements, because the detection of cracks has physical limits. The operator also needs to know the phase in the total lifetime cycle of the structure, because he must form the inspection and rehabilitation strategies according to that. Crack growth and their propagation can be modelled by different methods.

Design Concepts. The constraint of conscious coexistence with failures has affected our pipeline design approach. The safe-life design has been shifted step by step by the conception of durability, failure tolerance and fail-safe design. [4,6]. Naturally these concepts are also depending on the size of crack, and it is not accidental, that one of the extensions of the classical Wöhler curves (S-N curves) was their complementation with exact crack size. The exact crack size also means the end of the crack initiation phase in these cases [7].

Operational Approaches. Among the operational methods the one for the assessment of corrosion defects of hydrocarbon pipelines is conventional [8]. Although this method already involves the option of the strict fracture mechanical analysis, it is accounted to be conservative [9].

The application of *fitness for purpose* (FFP) conception means a more advanced level [10], according to which the structure is fit for the required application end, if it operates suitably during its planned lifetime. So the structure can damage during the operation, but fracture failure – consistent with reason – cannot occur. The damage or fracture during an unordinary application – different from the designed one – does not affect the basic concept. During the fitness for purpose analysis simple stages and expert levels must be distinguished [11].

Integrity of a structure (SI) means it is fit for purpose at all times during its total lifetime. Three levels can be interpreted as shows Fig. 2 [3]: the global level, the testing level and the computer technology level. These levels, which agree with the technical dimension shown in Fig. 1 can also be divided into further elements, which are closely connected to each other. A good visualization of this is to imagine the levels as the faces of a tetrahedron; in this case the summit of the tetrahedron will be the materials characteristics, the damage processes, the results of the destructive examinations, and the material properties databank.

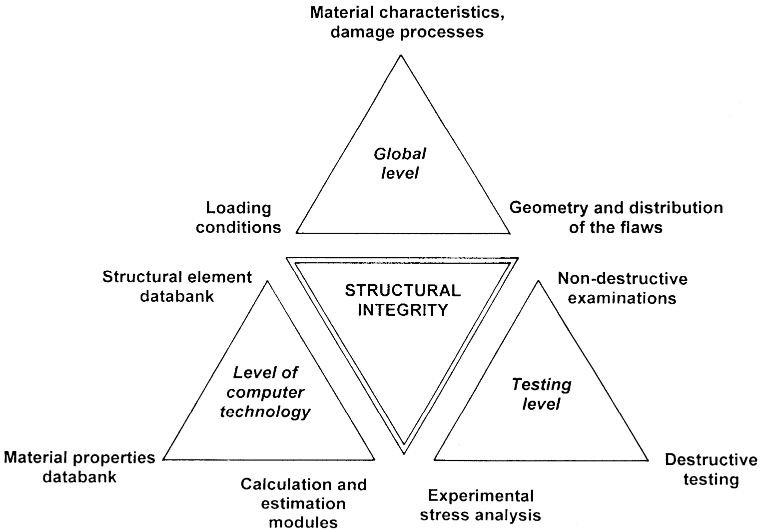

Figure 2. Levels of structural integrity (SI) and their main characteristics [3].

Integrity management systems [12,13] (IMS) generally and necessarily are occupied with the question of risk and interpret it as the collective effect of the supervening probability of the undesired event and the consequences of the event. The pipeline operator can build his own risk analysing and estimation methods and a consequent model [14]. The application of this model can result in the lengthen of structural lifetime.

Applied Methods. The methods, applied in the different approaches are basically two types: engineering and fracture mechanical methods [15].

The *engineering methods* are generally based on experiential or semi-experiential connections, relatively easily manageable and their application does not need expert level knowledge. Their disadvantage is also their relative simplicity; they only can manage the failures using an assumed safety factor.

With the help of the *fracture mechanical method*s the effect of the material discontinuities – and among that the most dangerous ones, the cracks or crack like defects – can be judged and quantified with appropriate safeness. It is an undoubted fact, that these methods are more complicated, their application needs expert level knowledge and the basic condition of their applicableness is the availability of reliable material characteristics.

Databases

As it became obvious earlier, databases play an important role in the estimation of pipeline integrity. Especially it is true in cases where rehabilitation techniques and technologies are also parts of the complex system. The research work concentrates on rehabilitation solution that result in hybrid pipe systems. Their approach is completely general, it includes different pipeline systems:

– steel (hydro-carbon) transporting pipelines;
– steel technological pipelines;
– polymer pipelines for gas transporting;
– cast-iron pipelines for water transporting
– concrete pipelines for refuse water transporting, etc.

It also includes different solutions: optional material quality base pipe, homogeneous or composite reinforcing material, outer or inner reinforcement.

The integrity system being under development includes the following databases:

– pipe material quality, mechanical properties and geometrical dimensions database;
– polymer matrix composite database including base material data and reinforcing phase data;
– pipeline damage and defect database;
– hybrid pipe manufacturing method and technology database;
– burst test results database;
– pipeline operating regulation database;
– hybrid pipe application possibilities database;
– potential users database.

*Material quality database*s include standards and experimental results. They also include the physical, thermo-physical and elasticity characteristics of each material quality and composites.

Table 1. summarizes the structure of the *pipeline failure and defects database*. Both main groups and sub-groups of defects were developed for different pipeline systems, characterising the possible cases.

Table 1. Structure of the pipeline failure and defects database.

Failure and defects of steel transporting pipelines
• ***Geometrical defects***
= Smooth dent
= Kinked dent
= Out-of-roundness (ovality)
= …
• ***Metal loss defects***
= Gouge
= …
• ***Plain defects***
= …
• ***Defects cause of the microstructure changing***
= …
• ***Combined defects***
= …

Table 2. contains the structure of the pipeline failures and defects description. The parameters used correspond with the pipeline systems and the defects main and sub-groups (d = defect depth, D_{max} = maximum outside diameter of the pipe, D_{min} = minimum outside diameter of the pipe, h = defect height, α = angle of the defect, Y = defect length).

Table 2. Description of pipeline failures and defects.

Defect type	Parameter						
	d, mm	D_{min}, mm	D_{max}, mm	h, mm	α, grade	Y, mm	…
Failure and defects of steel transporting pipelines							
Geometrical defects							
Smooth dent	✓						
Kinked dent	✓						
Out-of-roundness (ovality)		✓	✓				
Wrinkle	✓			✓	✓		
Rolling defect					✓	✓	
…							

The *hybrid pipe manufacturing method and technology database* includes the illustrations of each method together with practical examples beside technology descriptions and technology parameters. Fig. 3. shows a steel pipeline section repaired with carbon fibre reinforced (CFR) polymer matrix composite (PMC), before burst test at the Materials Testing Laboratory of the Department of Mechanical Engineering at University of Miskolc.

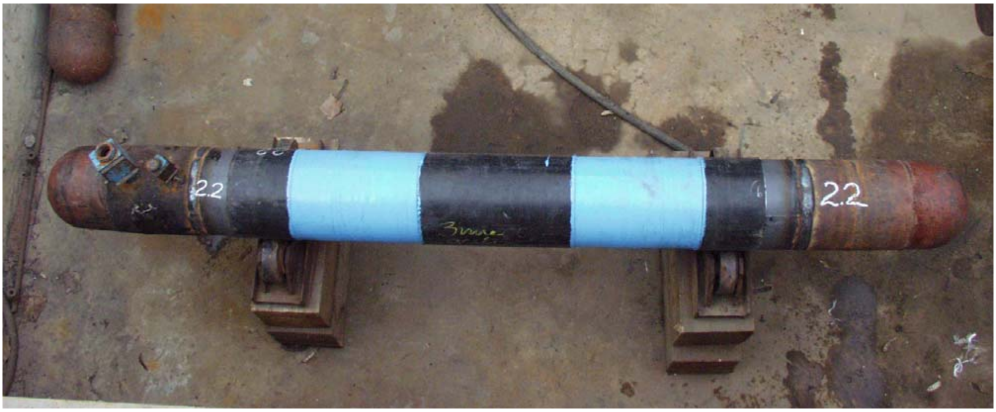

Figure 3. Steel pipeline section repaired with carbon fibre reinforced polymer matrix composite, before burst test (see Table 3., B_b7 pipe section).

The hybrid pipe manufacturing database is based directly on the material quality, the manufacturing method and technology, the damage and defect and the operating regulations database.

A further characteristic of databases is that they try to sum up the common features of different fields and aims at a system approach. From all these together we expect that they put adaptation possibilities in new dimensions both in quantity and quality.

Table 3. demonstrates a part of the *burst tests results database*, including the characteristics of the examined pipe sections and the calculated safety factors (Safety factor = Burst pressure / MAOP and MAOP = maximum allowable operating pressure).

Table 3. Part of the burst test results database.

Pipe section	Characteristics of the pipe section	Examination	Number of cycles	Burst pressure, bar	Safety factor
B_b1	base pipe, without girth weld	fatigue + burst	10^5	276,6	4,32
B_b2	TIG/MMAW girth weld	fatigue + burst	10^5	274,0	4,28
B_b3	TIG/MMAW girth weld(1) and reinforcing(2)	fatigue + burst	10^5	285,6	4,46
B_b4	TIG/MMAW girth weld(1) and reinforcing(2)	fatigue + burst	10^5	287,2	4,49
B_b5	TIG/MMAW girth weld(1) and reinforcing(2)	fatigue + burst	10^5	284,7	4,45
B_b6	artificial failures(3)	fatigue + burst	10^5	268,1	4,19
B_b7	artificial failures(3) and reinforcing(2)	fatigue + burst	10^5	262,9	4,11

(1) Tungsten Inert Gas/Manual Metal Arc Welding, „NOT PASSED" quality.
(2) Carbon fiber reinforced polymer matrix composite.
(3) Circumferential and longitudinal gouges.

Fig. 4 shows a steel pipeline section repaired with carbon fibre reinforced (CFR) polymer matrix composite (PMC), after burst test.

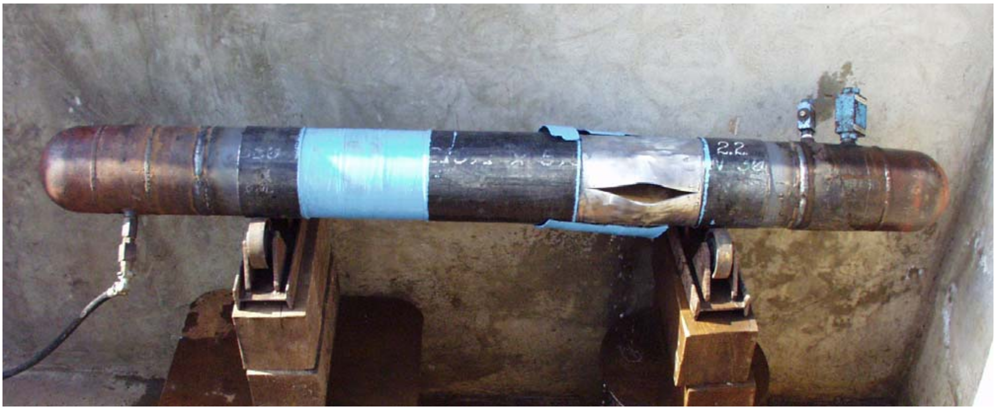

Figure 4. Steel pipeline section repaired with carbon fibre reinforced polymer matrix composite, after burst test (see Table 3., B_b7 pipe section).

Table 4. demonstrates the data structure for different defect assessment methods (t = wall thickness, d_d = dent depth, W = defect width, p/Δp = internal pressure/range, KV_{min} = minimum impact energy, SMYS/SMTS = specified minimum yield/tensile strength). Engineering methods and fracture mechanical methods can be used for the evaluating process; therefore both geometrical and non-geometrical parameters were summarized in the database. The non-geometrical materials data can be found in the materials databases developed for pipe and reinforcing materials.

Table 4. Parameters for different defect assessment methods.

Defect type	Workmanship	ECA	Parameters															
			geometrical								non-geometrical							
			D, mm	t, mm	d_d, mm	d, mm	Y, mm	W, mm	NDT results	…	p, bar	Δp, bar	SMYS, N/mm^2	SMTS, N/mm^2	Kv_{min}, J	MAOP, MPa	design factor	…
Failure and defects of steel transporting pipelines																		
Combined defects																		
Smooth dent on welds	✓		✓	✓	✓				✓		✓							
Smooth dent on welds	✓	✓	✓	✓	✓				✓			✓		✓				
Smooth dent and gouges		✓	✓	✓	✓	✓	✓				✓		✓		✓	✓	✓	
Smooth dent and gouges		✓	✓	✓	✓	✓	✓					✓		✓	✓			
Smooth dent and corrosion	✓		✓	✓	✓		✓	✓			✓							
Smooth dent and EAC[(1)]	✓		✓	✓					✓		✓							
…																		

[(1)] EAC = Environmentally Assisted Cracking..

Process models

Based on the operating regulations database on the one hand and the potential users database on the other hand, there is a normative organism model still under development which helps to elaborate the normative processes necessary for the assurance of integrity.

The essence of the normative model and the normative processes is that they make the adaptation of general principles and methods for definite organisms and tasks possible while taking local opportunities and local limits into consideration. At the same time it is a certain way to increase one's effectiveness, as we do not have to start the whole process from the beginning and develop everything again. The acceptance and dissemination of good practice increases the safety of operation or in other words it may lead to the decrease of operational risks.

Conclusions

Based on the thoughts summarized in this paper, the conclusions are as follows.

– Lifetime management of structures can be interpreted in different but not independent dimensions. The technical dimension aggregates the questions connected to both material failures, and loading and operation of structures.
– The application of fracture mechanical methods and risk assessment techniques has great consequence in the lifetime management of structures.
– In the groups of different structures (e.g. steel structures, transporting pipelines) such optimal dimensions and methods can be found, with the help of which the tasks of lifetime management can be solved in the most efficient way.
– Databases have a determinant role in the integrity assurance of different structures like pipeline systems. The interdependent elements of the developed database system make it possible to accomplish tasks connected to integrity control, especially pipeline rehabilitation in a well-founded way.
– The normative organism model and the adaptation of normative processes describing the operation are still under development. Their use will lead to the effective, reliable (for which

risk is under control) and optimal (according to different aspects) design and operation of pipeline systems.

Acknowledgments

Authors wish to acknowledge the assistance given by the National Scientific Research Foundation (OTKA T049126) and the Agency for Research Fund Management and Research Exploitation (GVOP-3.1.1.-2004-05-0215/3.0) for supporting the research.

References

[1] H. Jakubczak, W. Sobczykiewicz and D. Dudek: Probabilistic Fatigue Life Prediction of Degraded Structures, edited by V. Bicego, A. Nitta and R. Viswanathan, R., in: Proceedings of the International Symposium on Materials Ageing and Component Life Extension, Warley, EMAS, Vol. II, (1995) p. 1231.

[2] S. J. Findlay and N. D. Harrison: Materials Today Vol. 5 (2002), No. 11, p. 18.

[3] J. Lukács: Mater. Sci. Forum Vols. 473-474 (2005), p. 361.

[4] J. C. Newman Jr.: The Merging of Fatigue and Fracture Mechanics Concepts: A Historical Perspective, edited by J. H. Underwood, B. D. Macdonald and M. R. Mitchell, in: Fatigue and Fracture Mechanics: 28th Volume, ASTM STP 1321, ASTM (1997) p. 3.

[5] J. Polák: Fatigue-cyclic Behaviour, in: Advances in Mechanical Behaviour, Plasticity and Damage, edited by D. Miannay, P. Costa, D. Francois and A. Pineau, Proceedings of EUROMAT 2000, Elsevier (2000) Vol. 1, p. 29.

[6] A. C. Picard: Materials Science and Technology, Vol. 3 (1987), p. 743.

[7] C. M. Sonsino and U. Brandt: Influence of the Weld-geometry on the Fatigue Behaviour of 25 mm Thick Aluminium Weldments of AlMg4.5Mn (AA 5083), IIW – Document No. XIII – 1821 – 2000 (2000).

[8] ASME B31G (Revision of ANSI/ASME B31G-1984): Manual for Determining the Remaining Strength of Corroded Pipe. A Supplement to ASME B31 Code for Pressure Piping, ASME (1991).

[9] K. E. W. Coulson and R. G. Worthingham: Oil and Gas Journal (1990) April 9, p. 54.

[10] EN 25817, 1993, "Arc-welded Joints in Steel. Guidance on Quality Levels for Imperfections."

[11] D. Jones: Use for High Resolution Internal Inspection and Fitness for Purpose to Ensure Pipeline Reliability, Proceedings of the IBC Pipeline Risk and Rehabilitation Conference (1996) pp. 1-15.

[12] P. Hopkins and A. Cosham: How Do You Manage Your Pipeline?, Proceedings of the 7th International Conference on Pipeline Risk Management and Reliability (1997) pp. 1-9.

[13] M. Fingerhut and H. Westlake: Pipeline Fitness-purpose Certification, Proceedings of The Pipeline Pigging, Integrity Assessment, and Repair Conference (2000) pp. 1-15.

[14] Hopkins, P., 1998, "Risk and Integrity Management of a Transmission Pipeline," Proceedings of the 2nd International Conference on Advances in Pipeline Technology 98, pp. 1-17.

[15] J. Lukács: *Reliability of Cyclic Loaded Welded Joints Having Cracks*, CSc dissertation, University of Miskolc, Miskolc and Technical University of Budapest, Budapest (1992). (In Hungarian.)