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THE FAULT TREE ANALYSIS OF CAUSES OF THE WELDED PIPES FAILURES IN EXPLOITATION

Premature failure or damage of parts and components of the oil and gas well piping, as well as pipelines for transport of oil and gas, are generally caused by the simultaneous influence of a large number of technological, metallurgical, structural and exploitation factors. Therefore, the convenient structural solutions, which provide the mechanical safety of parts and integrity of structures, can be realized only through total comprehension of their behavior in various operation regimes.

Importance of technical diagnostics for monitoring and state analysis of welded pipes/pipelines in oil industry is considered in this paper. An analysis of causes of the welded pipes failures in exploitation has been performed through use of the fault tree analysis. Based on the suggested structure of a database, regarding the causes of failure, possibilities are presented to set measures for prevention of damage and failure of welded pipes/pipelines and for extension of their service life. A suggestion for improvement of the organizational scheme for monitoring the state and maintenance of welded pipes/pipelines during the exploitation has been made, as well.

Keywords: *welded pipes, damage, failure, the fault tree, database, preventive measures*

1 Introduction

Due to the fact that oil and gas well piping and pipelines for transport of oil and gas are considered as highly responsible structures, quite susceptible to corrosion and occurrence of cracks, Figures 1 and 2, it is very important to know the pipe's residual strength, in the case that any of the mentioned types of damages would appear on them [1].

The API 5CT standard prescribes regulations for production of protective seam welded pipes, which are used in wells, [2-4]. Automatic or semi-automatic production of welded pipes enables the continuous production of longitudinal-seam welded pipes where the basic intention is to reach the welding speed equal to speed of the pipe-forming. Machines aimed for the continuous production of longitudinal-seam welded pipes are mainly designed for the automatic high-frequency contact welding [5].

Based on the precise examination, regarding the defect type and size, as well as on calculation of operating ability of the welded joint, the decision, referring to possibility of reintegrating the pipe into the system, can be made [6-9].

Steel pipes in oil industry are continuously exposed to corrosive effects, which are enhanced by high pressures and temperatures existing within the well. Corrosion can cause a decrease of steel's mechanical properties, which in turn, in combination with unfavorable operating conditions, may lead to appearance of an initial crack and a subsequent fracture. Failure of protective pipes can be caused and accelerated by various corrosion mechanisms [10-15], or some other factors [16-18].

2 Technical diagnostics

During the exploitation of oil well piping and transport pipelines, useful properties of assemblies and their constitutive parts get gradually degraded. Degradation of the material properties and/or deformation of elements, can get accelerated due to exploitation and assembling errors, therefore, the periodic or permanent diagnostic measurements and periodic inspections are necessary in order to keep under control the processes that may create conditions leading to a system failure.

If the technical diagnostics was carried out correctly, it would prevent sudden failures of well piping and transport pipelines, ensure safe working conditions for the employees, rational techno-economic exploitation and protection of the environment.

Procedures for the pipe column inspection mostly consist of the following actions [1]:

- coupon testing through use of the steel plates, located within the pipeline, to monitor the corrosion layers,
- determination of hydrogen content through application of an analyzer,
- determination of the CO_2 and H_2S contents, as well as the iron content (if the Fe content is less than 0.02%,

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***Figure 1** General corrosion of well pipes*

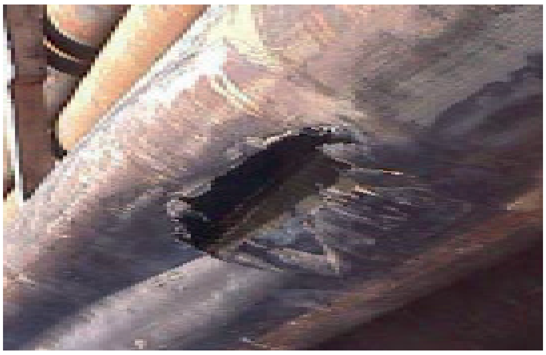


***Figure 2** Pipeline failure*

FeS_2, which actually causes the corrosion, cannot be created),

- determination of the Benfield solution content (content of Fe less than 0.02%, V < 0.7% and H_2S),
- determination of inhibitor content in the condensate (for protection of the pipe surfaces),
- ultrasonic wall thickness measurement,
- corrosion inspection of the pipes' inner surfaces through use of a calibrator,
- inspection performed through use of the corrosion measuring probes,
- ultrasonic inspection of the gas pipeline inner surface during the operation.

Procedures for inspection of the oil and gas transport pipelines include:

- inspection of the gas pipelines' inner surfaces during the operation through use of the magnetic flux leakage (MFL) inspection method using the MFL inspection tools (magnetic flux expands longitudinally with respect to the pipeline axis),
- inspection of the gas pipelines' inner surfaces during the operation through use of the combined MFL inspection tool,
- ultrasonic wall thickness measurement,
- ultrasonic inspection of the gas pipelines' inner surfaces during the operation.

3 Failure analysis of welded pipes in oil industry

The production systems, such as oil wells, are very hard to analyze due to their complex structure, operating conditions and inaccessibility of pipes. In such cases, the fault tree analysis can be very successfully applied, with several minor simplifications. The fault tree is suitable for analyses of the complex systems, consisting of functionally related or dependable subsystems with different performances. The fault tree analysis is regularly used for the nuclear power plants, aircrafts and communication systems, chemical and other industrial processes. However, that does not apply to processes in the oil industry. Through analysis of singular influences, the fault tree provides the conclusion, which refers to causes of and singular contributions to failure [19-21].

Main advantages of the fault tree method are:

- the simple graphic depiction of the logic of failure,
- the logic of failure can be followed gradually,
- the possibility of making the quality and quantity analysis, through use of the Boolean algebra,
- the quantity analysis can be carried out when the quantity input data is available. When there is no reliable input data available, only the quality analysis is carried out,
- the fault tree analysis can envelop various influences, unlike other methods,
- no special training and knowledge are necessary for application of the fault tree method.

Results of the fault tree analysis are used for failure prevention, failure analysis, or in other words for influence of various factors on reliability, as well as for clearer definition and quantifying of individual influences that affect the reliability, ensuring conditions that would provide for the good reliability.

During the process of oil/gas exploitation, the well piping and transport pipelines are subjected to varying loads (pressure, temperature) and to occurrence of corrosion in all the parts of the system, starting from the well, until the master pipeline entry and through the pipeline to the consumer. Failures of welded pipes during exploitation or transport of oil/gas, which occur due to damaging, influence the operation reliability and safety. Failures generally occur due to corrosion fatigue, Figure 3. Procedures concerning the material degradation of pipes/pipelines during the exploitation are presented in Figure 4. However, it is not uncommon that defects pass undetected during the NDI (non-destructive inspection) methods, Figure 5. Conditions for the crack propagation until it reaches the critical size (case A – Figure 3) are presented in Figure 6. Legends of symbols and notation presented in Figures 3 to 6 are shown in Tables 1 and 2, respectively.

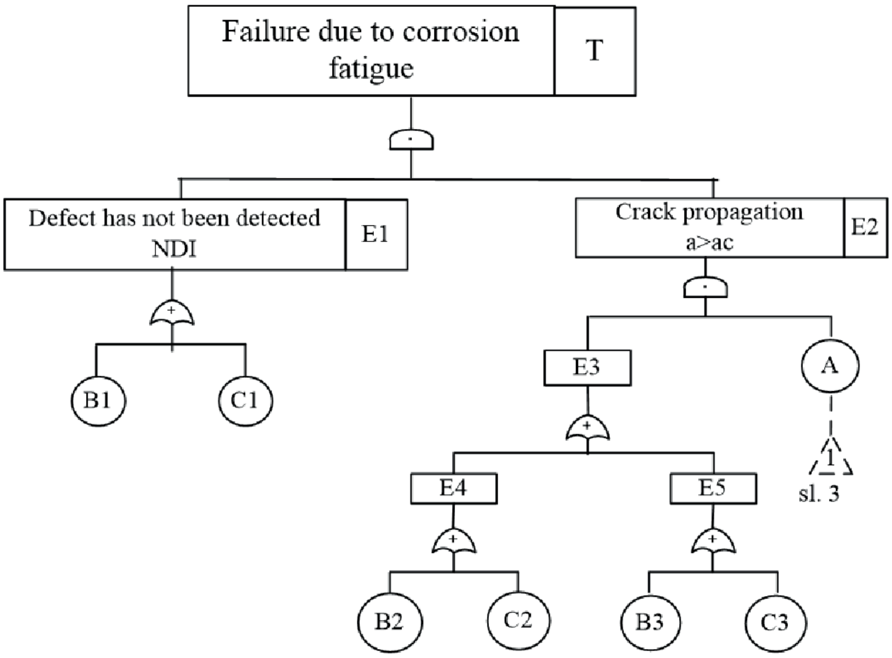


Figure 3 *Schematic presentation of failure due to corrosion fatigue*

Table 1 *Legend of symbols used in Figures 3 to 6*

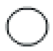
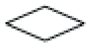
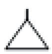
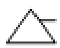
Symbol	Meaning
	Elementary event, initial defect
	Intermediate event or on top (I)
	Undeveloped event due to a lack of information
	AND gate: a defect on the output side occurs if all defects on the input side occur
	OR gate: a defect on the output side occurs if one defect on the input side exists
	Further development of the fault tree on the other figure
	Entrance of the part of the fault tree from the other figure

Table 2 *Notation presented in Figures 3 to 6*

Notation	Meaning
T	Failure due to corrosion fatigue
E1	Fatigue defect has not been detected
E2	Crack propagation, $a > a_c$
E3	Defect has not been detected by the NDI methods
E4	Defect has not been detected by the NDI methods immediately after the occurrence
E5	Defect has not been detected by the NDI methods in the later stages of inspection
A	Conditions for the crack propagation
B	Device does not detect the defect
C	Operator does not detect the defect despite the fact that the device is capable of detecting it

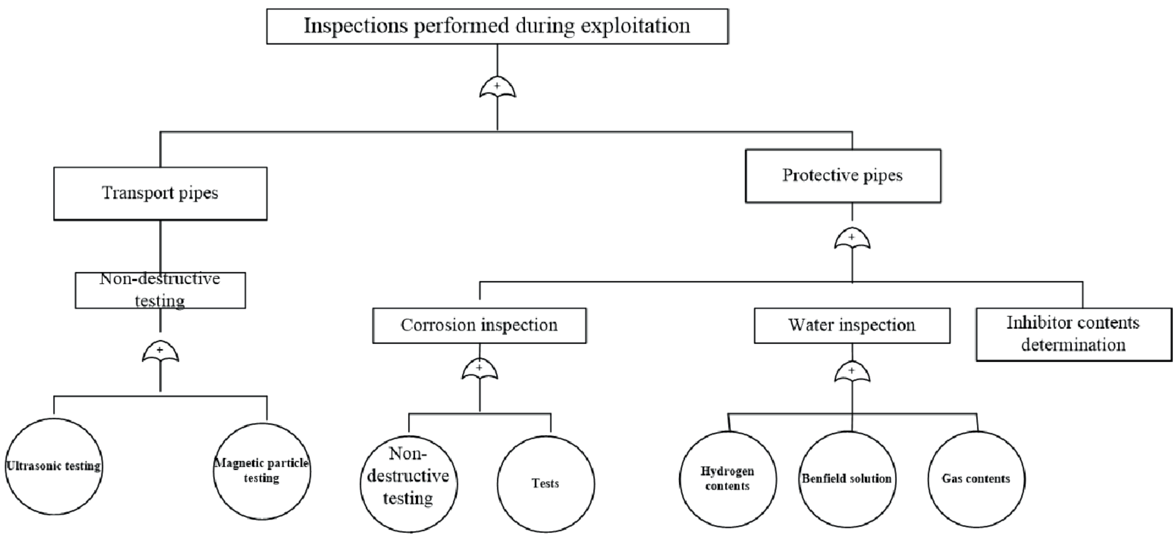


Figure 4 *Scheme of the pipeline material degradation inspection during exploitation*

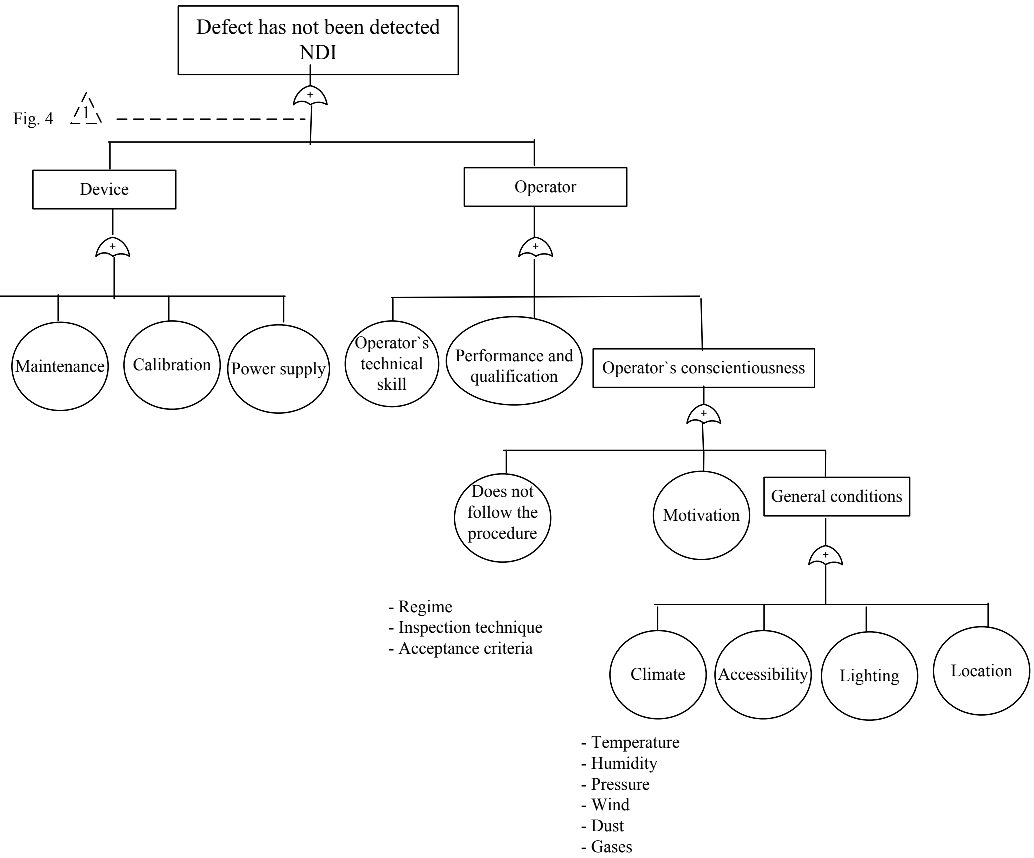


Figure 5 *Scheme of the event elaboration - defect has not been detected*

Derivative of the reduced fault tree is:

$$T = E1*E2$$
$$= E2(B1 + C1) - A*E3(B1 + C1)$$
$$= A(E4 + E5)(B1 + C1) - A(B2 + C2 + B3 + C3)(B1 + C1)$$

By applying the law of absorption one gets $T \approx A(B1 + C1)$.

4 Database

An adequate database is required if one wants to obtain the reliable evaluation of integrity and suitability for operation of the structure elements of welded pipes/ pipelines in the oil industry. Additional software packages enable the more efficient use of databases, analysis of certain influential factors, possibilities of failure prevention

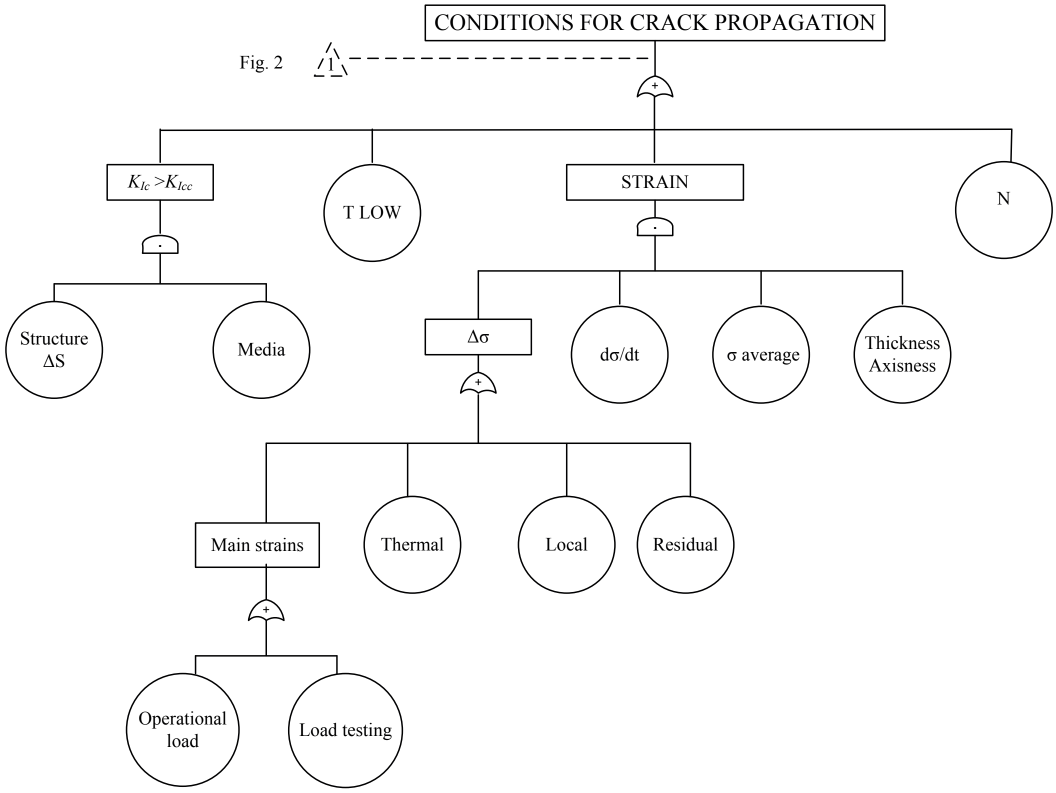


Figure 6 *Scheme of elaboration of possibility for the crack propagation until it reaches $a > a_c$ (event A in Figure 3)*

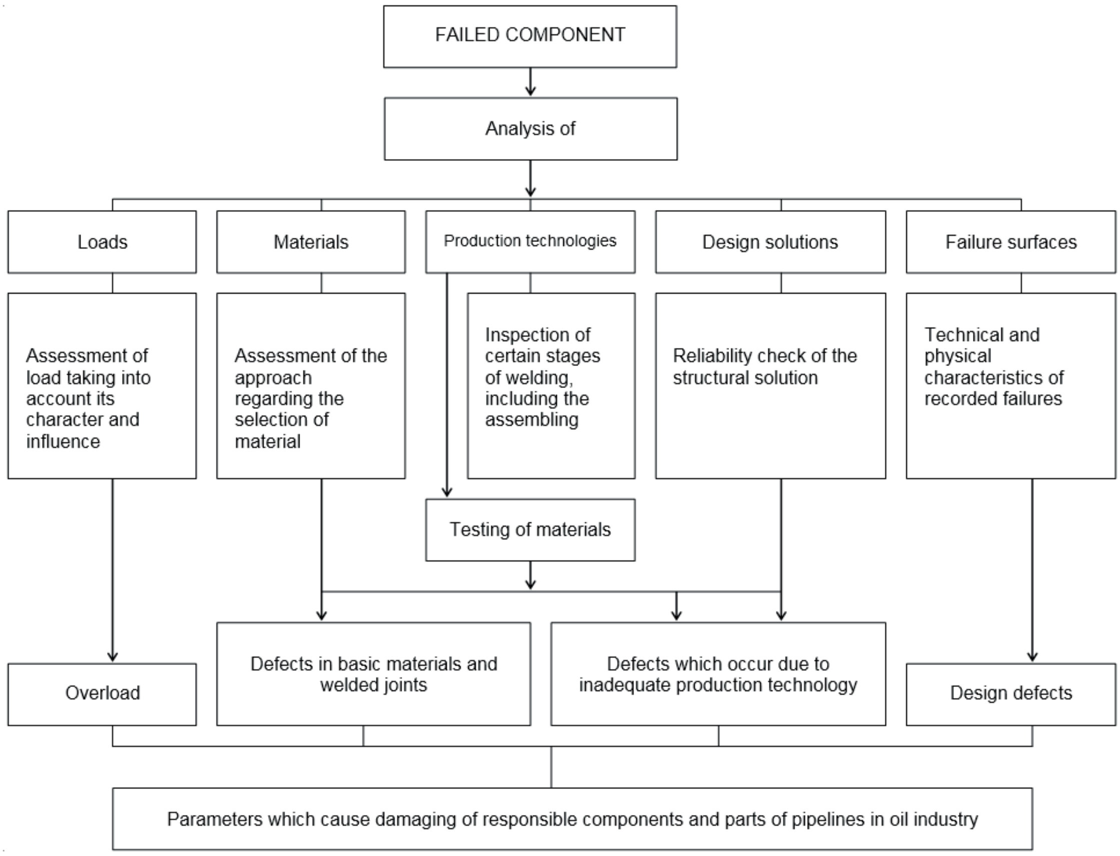


Figure 7 *Process analysis of damage and failure of welded pipes and pipelines in oil industry*

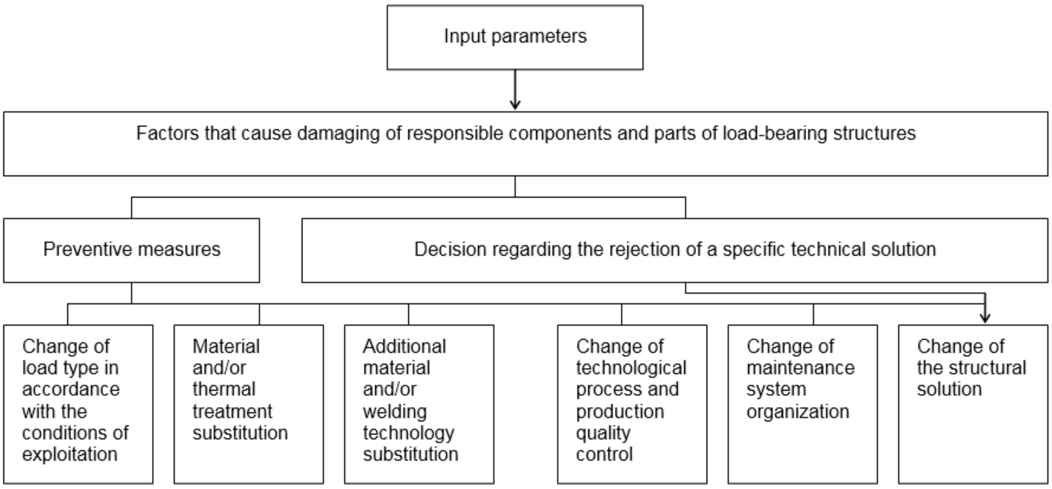


Figure 8 *Preventive measures*

and creation of alternative solutions in all the phases of design and structure development.

Creation of the damage and failure analyses of parts and elements of bearing structures is enabled by information on improvement of the design methods for bearing parts and elements of bearing structures, as well as on improvement of properties of the existing materials and technologies for their processing and development of new materials. The damage and failure analyses can enable development of new technical solutions and testing methods already in the prototype phase. A systematic approach is required if one wants to determine and prevent causes of damage and failure, Figure 7.

Databases, which refer to realized inspections and failure analyses, regarding adequate oil and gas well piping, as well as transport pipelines, offer big possibilities when it comes to determining changes of the mechanical properties of materials and welded joints. This is due to the fact that a large number of influential factors are varying and some undesirable effects should be reduced to bearable values, or, in other words, the satisfying structural solution should be created.

5 Measures for damage and failure prevention

Causes that can lead to failure could be determined through analysis of damage and failure of responsible parts and pipeline elements in oil industry, thus enabling the decision making, referring to rejection of the specific technical solution or preventive measures, Figure 8.

The preventive measures, shown in Figure 8, are primarily related to execution of processes that can, in a certain way, influence the integrity and service life of a pipeline, which can be determined according to experience or based on conducted analyses.

Variation of the load type can significantly affect the integrity of a structure, since the pipeline can in some phase of exploitation be exposed to tensile stresses, which belong into a group of the most unfavorable ones. Therefore, changing the load, e.g. from tensile to compression, can have multiple effects on extending the service life.

Material replacement, as one of the preventive measures, implies the substitution of material at critical places for the sake of extending the pipeline service life. For instance, there are frequent examples that the used material is inadequate from the aspect of corrosion [21-22], thus it *per se* represents the critical point of a structure, what preventively can be solved by replacing the critical material.

The same applies for the places of joints in construction, where the referral is to the welded joints and vicinity of the weld and not to the material as a whole [8, 16, 23].

Sometimes, the preventive measures can be related to the process of manufacturing the construction. During the design, it is recommended to select the technological process of the construction execution in such a way that it corresponds to the type of construction, as well as to its exploitation conditions. If, during the construction operation, was found out that the cause of failure could be in the way the construction was made, it could be possible, in some of the following phases, to change the construction production process in order to eliminate the cause of possible failures.

In this phase, it is very important that the maintenance personnel defines the critical spots in a proper manner and determines the real cause of failures, based on which they can propose certain measures for the purpose of extending the construction's service life [10, 24].

Finally, if some of the mentioned measures did not produce the desired effect, the solution should be sought in the design phase. Namely, different examples from practice have shown that poorly designed construction can cause serious problems, which cannot be eliminated by any other measure, but by correcting the error made in the design or manufacturing phases.

A decision to reject a specific technical solution can initialize making of a new, optimal structural solution, in

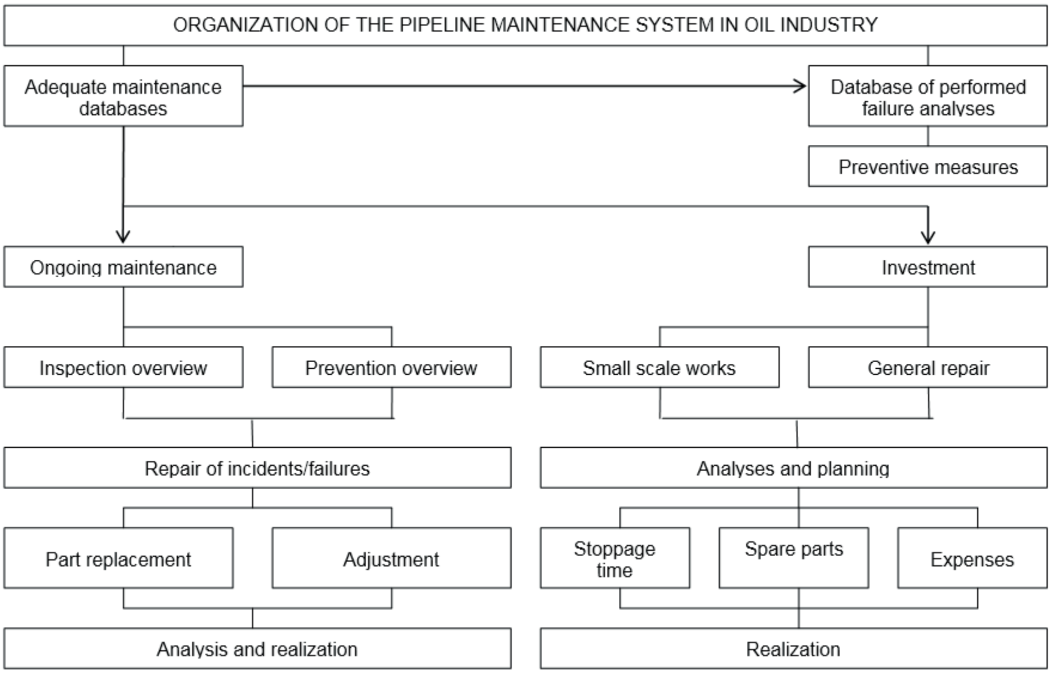


***Figure 9** Organizational model of the pipeline maintenance system in oil industry*

varying load conditions, for various operation regimes, dimensions of parts and bearing structure elements, shapes of welded joints, materials, processes and quality of production.

When the responsible parts and pipeline elements are concerned, a change of the load type, according to the exploitation conditions can lead to experimental determination of operational loads, as well as to change of the structural solution and determination of operating conditions and load regimes, which would secure the reliable operation for the specific technical solution.

Change of technology of the production process refers to alteration of shapes and dimensions of parts and elements of bearing structures, welding procedures, basic material and regimes of the heat treatment.

Alteration of inspection of the production quality refers to the more strict inspection and testing before and during the production, as well as after assembling.

Since all those measures for prevention of damage and failure represent the group of complex and expensive solutions, which are assumed to be able to enhance the security of responsible parts and pipeline elements, many eminent institutions all over the world have undertaken the comprehensive experimental research in order to develop techniques for simpler and cheaper improvement of the static and fatigue properties of parts and pipeline elements in the oil industry.

Improved techniques that were thus achieved are not equally successful with various structural solutions, because their effects depends on the load type and regime, material properties and type of a structure that consists of welded elements. Therefore, recommendations referring to application of certain methods primarily depend on possibility of a structure building and designer`s experience.

Organization of a maintenance system, regarding piping and transport pipelines, depends mostly on the shape and structure of tubing, exploitation conditions, number of employees, experience of experts and adequate databases regarding maintenance and inspection of pipelines in oil industry.

Based on realized researches and experience based data regarding the pipeline maintenance system in oil industry, an organizational model of the pipeline maintenance system in oil industry is proposed, shown in Figure 9.

6 Conclusions

Presented results and realized research offer big possibilities regarding behavior analyses of welded pipes and pipelines in oil industry. That was done to determine changes in mechanical properties of materials and welded joints of oil and gas well piping and transport pipelines, in conditions when many of the influential parameters are varying. This presents an attempt to design safer structures and/or to reduce certain undesirable effects to bearable values, i.e. in other words to design a satisfying solution regarding the well structures and transport pipelines as a whole.

Quick and reliable solution of problems, regarding responsible parts and structure elements, is achievable only with help of adequate databases. Additional software packages can enable the more efficient use of those databases, as well as analyses of certain influential factors, improvement techniques, possibilities for failure prevention and alternative solutions in all the phases of designing and development of the well structures and transport pipelines in the oil industry.

***Note:** The shorter version of this research was presented at 24th International Seminar "SEMDOK 2019", reference [25].*

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