Selection of network structures of pipeline systems resilient to mixed damage

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Abstract. *Pipeline transportation systems are used for the purpose of delivering to consumers various substances, materials, including those required for continuous flow processes. The operation of such complex industrial facilities is associated with some risks and possible failures of individual units and assemblies due to various causes. The paper examines the specificity of pipeline transportation systems behaviour in emergency situations. The development of such processes may cause the disconnection from the source of some or all end product consumers. The process of damage may occur in accordance with the following mechanisms: progressive damage, when individual pipeline systems fail in a random order; progressive blocking, when individual transportation nodes fail in a random order. An accident scenario, in which progressive damage to linear elements and blocking of transportation nodes simultaneously occur within a system, represents mixed damage. The* **Aim** *of this paper is to develop the criteria for estimating a pipeline transportation systems' resilience to mixed damage, as well as the methods for solving routine problems of synthesis of network structures resilient to such process.* **Methods of research.** *The ability of a specific system to resist mixed damage depends on its network structure and is identified by means of simulation. The structural changes caused by mixed damage are described with a cyclogram, whose parameters indicate the number of damaged linear and blocked point elements within one cycle of system exposure. A comparison of the network structures' ability to resist mixed damage is only possible in case they are comparable. For that purpose, the analyzed systems must have identical numbers of nodes, linear elements, as well as end product consumers. Additionally, such systems must be exposed to mixed damage with identical cyclograms.* **Results.** *The simulation of the mixed damage process identified such characteristic as the average percentage of system components, whose failure causes disruption of the connection of all consumers to the source, as well as the average percentage of nodes, whose blocking causes a complete disconnection of the source from all consumers. The developed method of estimation of resilience to mixed damage allows solving the following structural synthesis problems: selection of the position of the source of the end product within the given network; selection of the position of new consumers within an existing system; definition of the locations of additional fragments' connection to the system; selection of coupling linear elements when additional fragments are connected to a transportation system.* **Conclusions.** *Mixed damage is a hazardous development scenario of an emergency situation and is associated with rapid degradation of the transportation capacity of pipeline systems. Various network structures vary in terms of their ability to resist mixed damage, while their resilience characteristics should be identified using computer simulation. A comparison of the mixed damage resilience characteristics is only possible for comparable network structures with equal numbers of nodes, linear elements and end product consumers. Additionally, the same cyclogram of mixed damage must be used.*

Keywords: *pipeline, system, structure, damage, network, accident, resilience.*

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Pipeline transportation systems are used for the purpose of delivering various substances, materials, including those required for continuous flow processes [1-7].

The operation of such complex industrial facilities is associated with some risks and possible failures of individual units and assemblies due to various causes [8-11]. In some cases, the failure of linear elements (pipelines) does not cause a noticeable limitation of the system's performance due to the presence of redundant connections and alternative ways of delivering the end product.

If, as the result of internal or external effects, a sequence of structural element failures occurs within a system, such development of the accident may cause the disconnection from the source of initially some, then all end product consumers. A failure in a random order of a set of a system' linear elements is called progressive damage [12, 13].

The failure of an individual transportation node makes it unable to handle transportation flows, and such point element of the system becomes blocked. Sequential blocking of point elements of a system in a random order is herein called progressive blocking [14, 15].

If, during accident development, both progressive damage to linear elements and blocking of transportation nodes occur simultaneously, such system exposure is considered as mixed damage.

The development of mixed damage is associated with a rapid degradation of the system's transportation capabilities, however technical literature does not provide any information regarding the patterns of this process, as well as methods of estimating the systems' ability to resist its development.

The aim of this paper is to develop the criteria for estimating pipeline transportation systems' resilience to mixed damage, as well as the methods for solving routine problems of synthesis of network structures resilient to such process.

Mixed damage is characterized by cyclogram T(α.β). Parameters α and β indicate the number of sequentially damaged linear elements and blocked transportation nodes within one system exposure cycle. Under the defined mixed damage cyclogram, for each moment of system time the exact number of operable structural elements of the analyzed network entity can be specified.

Using computer simulation [16, 17], the following resilience characteristics of the analyzed network entity were identified.

Average share of linear system elements φ_{EL}, whose damage causes the disruption of the connections between the source and all end product consumers.

Average share of transportation nodes φ_{UZ}, whose damage under conditions of mixed damage causes the disruption of the connections between the source and all end product consumers.

All calculations were performed using MathCAD [18, 19]. The above characteristics should be considered as the projections of vector $\vec{\Phi}^*$ on the coordinate axes that allows estimating the system's ability to resist mixed damage.

The module of this vector $\left|\vec{\Phi}^*\right| = \sqrt{\varphi_{EL}^2 + \varphi_{UZ}^2}$ generally characterizes the resilience of the analyzed network structure [20]. The higher is value $\left|\vec{\Phi}^*\right|$, the better is the examined item's resilience to mixed damage. Practically speaking, the value of the of the above characteristics consists in the fact that they enable comparative analysis of the resilience of various network entities.

However, a correct comparison of values φ_{EL}, φ_{UZ} and $\left|\vec{\Phi}^*\right|$ is possible only in the structures are comparable. For that purpose, they must have identical numbers of:

- linear elements;
- transportation nodes;
- end product consumers.

Additionally, the conditions of damage of the analyzed network structures must be similar, i.e. be described by the same damage cyclogram T(α.β).

A series of computing experiments has established that the correlation of the resilience indicators of the sets of comparable network structures does not depend on the adopted damage cyclogram, but is rather defined by the existing set of intrasystem communications. That means that for a random set of comparable network entities the correlation between their resilience does not depend on the specific conditions of mixed damage.

Then, the estimation of the correlation of the resilience of a number of comparable network structures only requires defining the corresponding values of $\left|\vec{\Phi}^*\right|$ in the conditions of test input with characteristics $\alpha = \beta = 1$. The above structures are regulated in terms of their resilience to mixed damage in such a way as to ensure correspondence between more resilient systems and higher values of $\left|\vec{\Phi}^*\right|$.

Let us note that in case of test input with cyclogram T(1.1) there is a consecutive alteration of random damage of one linear element and blocking of one transportation node of the system. This exposure pattern is further used for the purpose of comparative estimation of the ability of comparable network structures to resist mixed damage.

Routine problems of structural synthesis of pipeline systems resilient to mixed damage

The study of the specificity of network structures behaviour when affected by mixed damage is of practical interest. This specificity should be taken into consideration with regard to problems of structural analysis and synthesis of pipeline systems of various complexity and purpose. The properties of alternative network structures and design decision-making must be evaluated subject to the specified comparability requirements. Let us examine some typical design problems, as well as methods of solution.

Selection of the position of the source of the end product within the given network

Problem definition. Within the given network structure with known positions of consumers, it is required to identify the location of the source of the end product, whereas the system's resilience to mixed damage is the highest. The structural synthesis problem in this case is solved by comparing the values of $\left|\vec{\Phi}^*\right|$ of network entities with different locations of the source.

Let us examine alternative network structures designated SKA, … SKD shown in Fig. 1. They are characterized by varied location of source A and each have 13 nodes, 23 linear elements and 9 product consumers. In the course of the computation, each of the above structures was exposed to mixed damage with cyclogram T(1.1).

Under such conditions, all the above systems are comparable, while the comparison of corresponding values of $\left|\vec{\Phi}^*\right|$ proves to be correct. The calculation data obtained for samples of the size of 10^4 elements are shown in Fig. 1.

It can be seen that the worst location of the source corresponds to structure diagram SKA, while the highest value $\left|\vec{\Phi}^*\right|$ can be observed in case diagrams SKC and SKD are used.

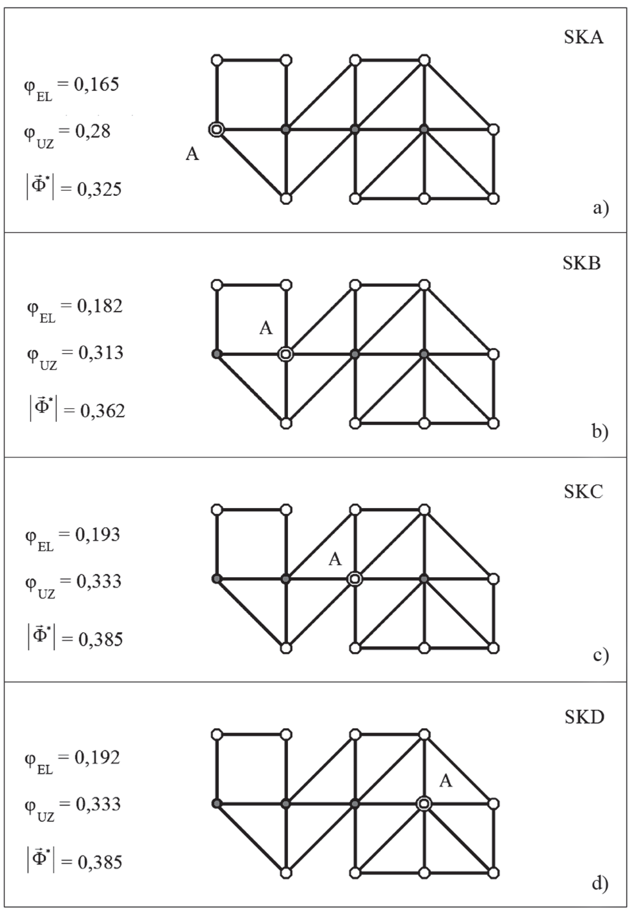


Fig. 1. Structure diagrams of the SKA (a), … SKD (d) pipeline systems with different locations of the source of the end product A

At the same time, the resilience of the pipeline systems with structure diagrams SKC and SKD proves to be identical. Thus, while solving the problem at hand, one of those structure diagrams should be selected. The ultimate solution in this case depends on the additional conditions or limitations that take into consideration, for instance, the possible cost of practical implementation of those two variants.

Selection of the position of new end product consumers within an existing system

Problem definition. In a system with a known location of the source and several end product consumers, it is required to identify the location of additional consumers, whereas the resilience to mixed damage is the highest.

Fig. 2 shows the layouts of network structures with source A and additional end product consumer B, C and D to be included in the system.

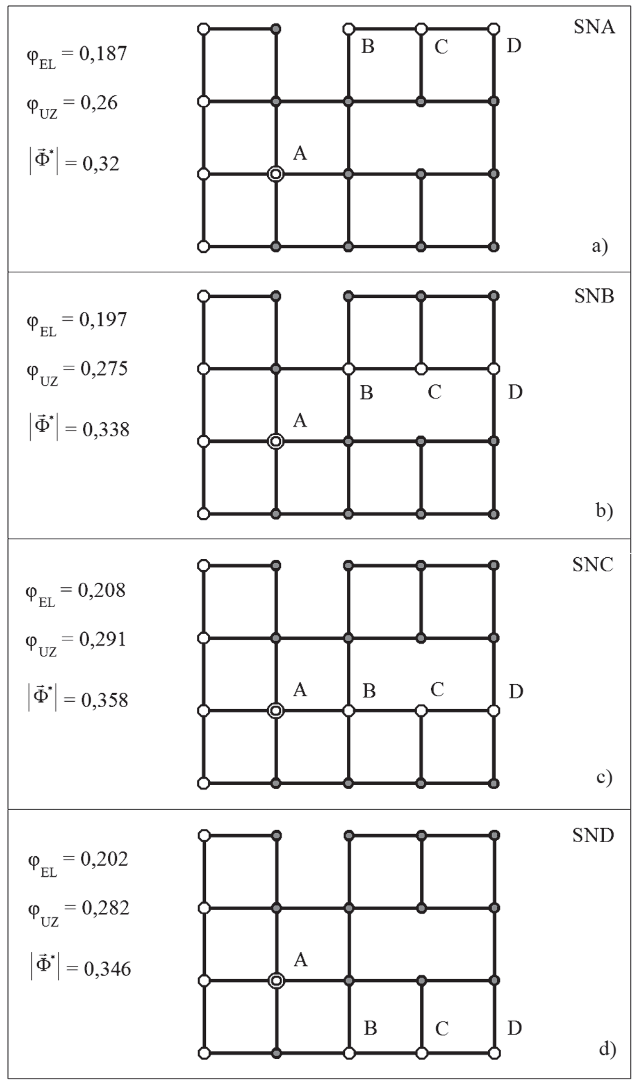


Fig. 2. Structure diagrams of the SNA (a), … SND (d) pipeline systems with different locations of the end product consumers B, C, D

The difference between the above options consists in the location of such consumers in the network. It is required to analyze and select the network structure with the highest resilience to mixed damage.

Let us assess the comparability of the structure diagrams shown in Fig. 2. They all include the same number of nodes, linear elements and product consumers. In case such structures are exposed to mixed damage with cyclogram T(1.1) the values of resilience indicators can be correctly compared to each other.

The values of resilience characteristics identified as the result of simulation for samples of the size 10^4 elements are shown in Fig. 2. It can be seen that the structure designated SNC is characterized by the highest resilience to mixed damage. The value of $\left|\vec{\Phi}^*\right|$ of such network entity is about 1.12 times higher than the corresponding value of structure SNA with the worst properties.

Thus, the network entity designated SNC should be considered as the solution of the structural synthesis problem.

Selection of the locations of an additional fragment connection to the system

Problem definition. The planned reconstruction of a pipeline system aims to extend its capacity and introduce an additional fragment with a number of consumers. There are several ways this extension can be implemented. The option must be selected that would enable the highest achievable resilience to mixed damage for the specific pipeline system.

An example structure diagram of a pipeline system and extension fragment are shown in Fig. 3. The extension includes consumers B, … G that are connected to each other and can be included into the original system with the creation of network structures SFA and SFB (Fig. 4).

In terms of the capabilities of the newly created system all the above extension options are equivalent. It is required to evaluate the resilience of SFA and SFB to mixed damage, as well as select the best extension option.

At the first stage of analysis it is required to identify if the above network entities are comparable. In this case the answer will be positive, as they have matching numbers of nodes, linear elements and end product consumers. Additionally, the analyzed entities are subsequently exposed to mixed damage with the same cyclogram T(1.1). The identified values of $\left|\vec{\Phi}^*\right|$ are shown in Figure 4.

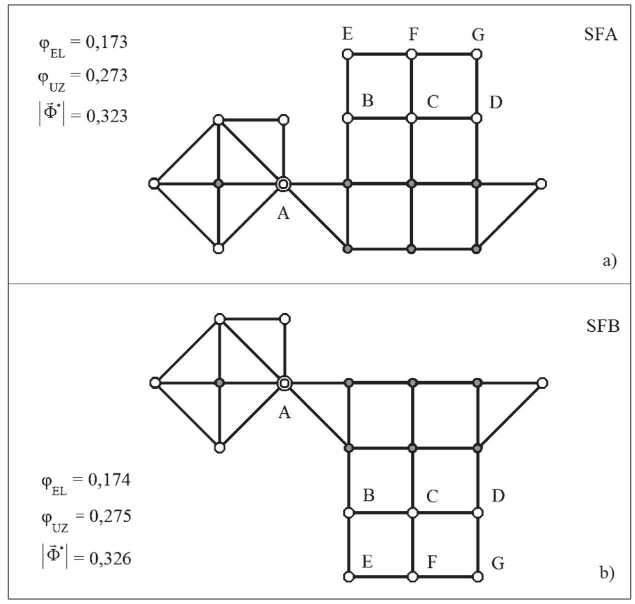


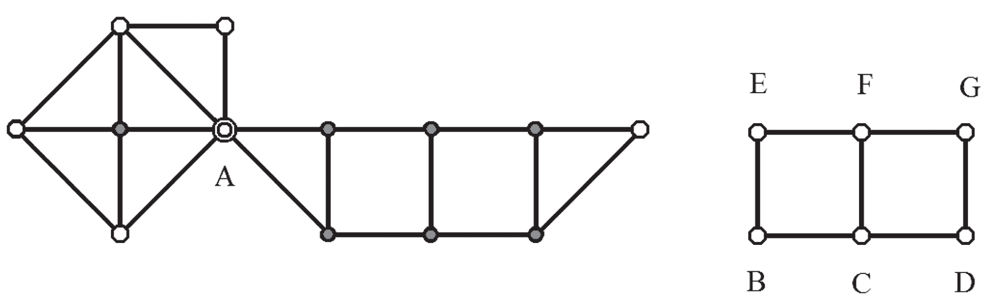
Fig. 4. Structure diagram of pipeline systems SFA (a) and SFB (b) corresponding to the different extension options

As simulation used samples of the size of 10^4 elements, the obtained expected values have 2 decimal significant figures. That means that the resilience to mixed damage of network structures SFA and SFB turns out to be identical. In this context, the ultimate choice is to be made subject to additional criteria, e.g., subject to the results of installation activities cost estimation.

Selection of coupling pipelines when an additional fragment is connected to a transportation system

Problem definition. The reconstruction of the pipeline transportation system is associated with the inclusion of a fragment that may contain several end product consumers. For the given number of additional pipelines, it is required to select the locations of their connection to the system and the fragment. The resulting network structure must have a high resilience to mixed damage.

Let us then examine the problem related to the connection of an extension fragment that includes 10 end product consumers (Fig. 5).



a) b)

Fig. 3. Structure diagram of the pipeline system (a) and extension fragment with 6 end product consumers (b)

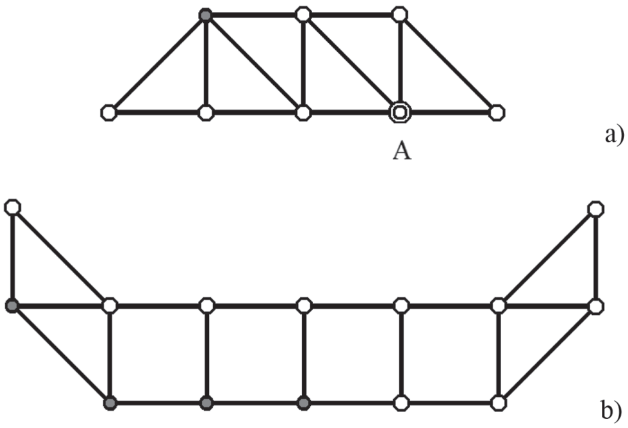


Fig. 5. Structure diagram of a pipeline transportation system with source A and 6 product consumers (a), as well as the diagram of the connected extension fragment with 10 consumers (b)

The connection is to use 4 additional pipelines. Fig. 6 shows the available connection options that allow achieving the goals of the reconstruction. At the same time, it is required to identify which of the examined options ensures the highest system resilience to mixed damage. Let us assess the comparability of network structures SOA, …. SOD shown in Fig. 6.

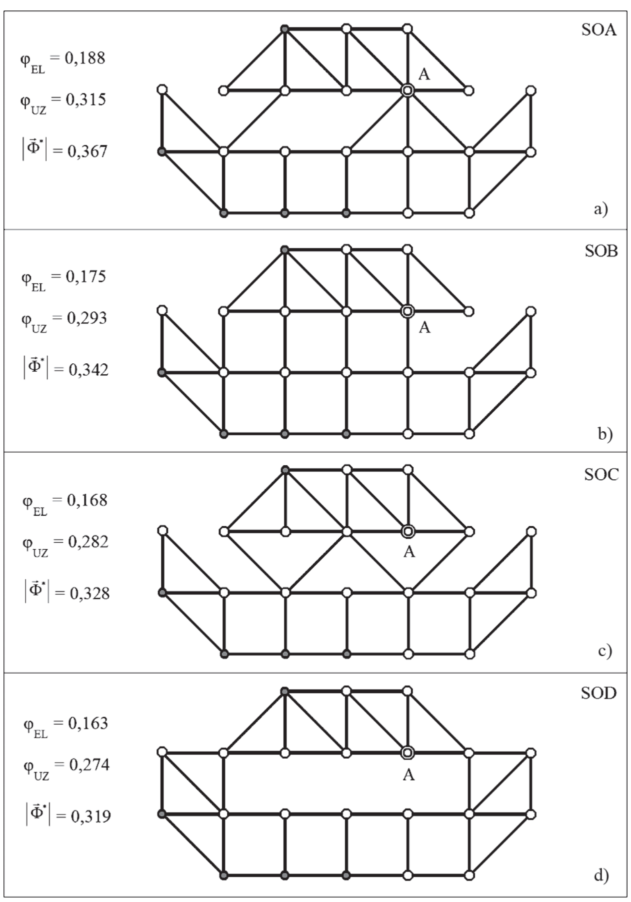


Fig. 6. Structure diagrams of pipeline systems SOA (a) … SOD (d) with various locations of the coupling pipelines

All of them have the same number of nodes, linear elements and product consumers, therefore in case of mixed damage with cyclogram T(1.1) the corresponding resilience characteristics can be correctly compared. The calculation data obtained for the above network structures using samples of the size of 10^4 elements are shown in Fig. 6.

It can be seen that the highest value of $\left|\vec{\Phi}^*\right|$ is observed in case of mixed damage to network structure SOA. For the examined extension options the highest value of $\left|\vec{\Phi}^*\right|$ exceeds the lowest one by 1.15 times. Thus, the structure diagram shown in Fig. 6 (a) should be considered as the solution of the synthesis problem.

Conclusions

1. Mixed damage is a hazardous development scenario of an emergency situation and is associated with rapid degradation of the transportation capacity of pipeline systems.

2. Various network structures vary in terms of their ability to resist mixed damage, while their resilience characteristics should be identified using computer simulation.

3. Comparison of the mixed damage resilience characteristics φ_{EL}, φ_{UZ}, $\left|\vec{\Phi}^*\right|$ is only possible for comparable network structures with equal numbers of nodes, linear elements and end product consumers. Additionally, the same cyclogram of mixed damage must be used.

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The author’s contribution

The author analyzed the specificity of mixed damage in network structures of pipeline transportation systems. The paper proposes to describe the dynamics of a system’s stationary random exposure with a damage cyclogram. Resilience characteristics and conditions of comparability of network structures under mixed damage were identified.

A comparative analysis was conducted of the ability of various network structures to resist mixed damage as part of standard designs.