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Specificity of the development and characteristics of mixed damage to network structures of pipeline transportation systems

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Abstract. *Pipeline transportation systems are used in various industries for the purpose of delivering various substances and materials to consumers. If, as the result of an accident development, a certain number of random linear elements (pipelines) consecutively fail, such scenario of events is called progressive damage. If several pipelines converging at a node fail simultaneously, such point element of the system is blocked. Progressive blocking of a certain set of nodes of a pipeline system in random order is called a progressive blocking. Simultaneous development within a system of progressive damage to linear elements and blocking of transportation nodes represents mixed damage. Mixed damage is a hazardous form of emergency, and its development causes fast degradation of a system's transportation capabilities. The* **Aim** *of the paper is to study the characteristic properties and patterns of the progress of mixed damage affecting network structures of pipeline systems, as well as evaluating such systems' capability to resist its development.* **Methods of research.** *The characteristics of network entities' resilience to the development of mixed damage were identified by means of computer simulation. The nature of the effects to which a system is exposed was defined with a cyclogram, whose integer parameters indicate the alternation of the process of sequential damage of linear elements and nodes of a network structure.* **Results.** *It has been established that a correct comparison of the resilience of various network structures to mixed damage is only possible with regard to comparable facilities. For that purpose, the analyzed systems must have identical numbers of nodes, linear elements and end product consumers. Additionally, such systems must be exposed to effects with identical cyclograms. It is shown that the correlation of the resilience of comparable network structures does not depend on the specific type of mixed damage cyclogram, but is defined by the nature of the connections within a particular system.* **Conclusions.** *Mixed damage is a hazardous development scenario of an emergency situation that is associated with rapid degradation of the transportation capacity of pipeline systems. The ability of network structures of pipeline systems to resist mixed damage is evaluated based on indicators that are defined by means of simulation. A correct comparison of the resilience of various structures to mixed damage is only possible in case they are comparable. For that purpose, they must have identical numbers of nodes, linear elements and product consumers. Additionally, such systems must be exposed to damage procedures with identical cyclograms. The correlation of the resilience of network structures that comply with the comparability conditions does not depend on the adopted damage cyclogram, but is defined by the existing set of connections within a particular system.*

Keywords: *system, pipeline, structure, mixed damage, resilience.*

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Pipeline transportation systems are used in various industries for the purpose of delivering various substances, products and materials to consumers [1-4]. Normally, such engineering facilities have complex network structures, a large number of possible states and functional elements [5]. The transition of some structural elements into the down state is of potential hazard, both for the end product consumer, and for the environment [6-9]. If, as the result of processes occurring in the system or the environment, a certain number of random linear elements (pipelines) consecutively fail, such scenario of events is called progressive damage [10].

In case several pipelines converging at a node fail simultaneously, such point element of the system is blocked. It is obvious that a blocked node becomes unable to handle transport streams, while the blocking process can do significant harm to a system's transportation capabilities. Consecutive blocking of system nodes in random order is called progressive blocking [11, 12].

In real operating conditions adverse effects affecting a system may be associated with the simultaneous development of both progressive damage of linear elements, and blocking of transportation nodes. However, the ability of network structures to resist mixed damage that occurs in accordance with the above mechanism is not understood, while in technical literature there is no organized information regarding the dynamics of this process.

The aim of this paper is to study the characteristic properties and patterns of the process of mixed damage affecting network structures of pipeline systems, as well as to evaluate such systems' capability to resist its development.

Let us assume that the process of mixed damage is stationary, i.e. the rates of failure of various structural elements are known (or specified) and do not change over time.

Then, the network entity damage process can be described with an elementary cycle T, that repeats many times over the course of an accident until all connections between the source and end product consumers are disrupted. In these circumstances, for each moment of system time we can easily identify the total number of damaged linear elements and blocked transportation nodes.

Thus, if the process dynamics are characterized by the damage to first α linear elements, then blocking of β transportation nodes, the cyclogram of mixed damage process $T(\alpha.\beta)$ provides a complete picture of the effects the analyzed system is affected by.

Thus, characterizing a stationary random process of mixed damage of a network structure using a cyclogram only requires specifying its integer parameters α and β. For instance, if damage occurs by the mechanism of transportation node blocking, such model of action is characterized by cyclogram $T(0.1)$. If the scenario involves progressive damage of linear elements, the above mechanism of system exposure is characterized by cyclogram $T(1.0)$.

The ability of a pipeline system to resist the development of mixed damage was assessed using computer simulation software, similarly to [13, 14].

For the specified network structure and adopted damage cyclogram the following statistical characteristics were specified:

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

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

Paired values φ_{EL} and φ_{UZ} are projections of vector $\vec{\Phi}^*$ on the coordinate axis. The vector characterizes the ability of the analyzed system to resist the development of mixed damage. High values of module $\vec{\Phi}^*$ correspond with high ability of the system to resist the development of such process.

Computer simulation [15-17] of mixed damage was performed using MathCAD [18] according to the following procedure:

1. The initial network structure of a pipeline system is determined by a square incident matrix, similarly to [19, 20].

2. If at a specific moment of system time a linear element is damaged, in the corresponding binary incident matrix all elements in a randomly selected i-th line are set to zero. If at the specified moment of system time a transportation node is blocked, all elements in a randomly selected i-th line and i-th column of the corresponding incident matrix are set to zero.

3. For each moment of system time corresponding reachability matrices are constructed, that are required for the identification of connection between the source node and each of the end product consumers. The network entity damage process ends after all consumers have lost connection with the source node.

4. As the mixed damage process is specified with a cyclogram with known values of parameters α and β, the identification of the moment of system time, when the connection between the source and all product consumers is disrupted, allows identifying the total number of both damaged linear elements, and blocked transportation nodes.

Their respective shares are random values, that were generated as the result of a single system exposure to mixed damage. In order to identify the statistical characteristics of the damage process, the above exposure process must be repeated numerous times in accordance with the adopted cyclogram.

For the purpose of calculation, samples with the size of 10^4 were assigned average values φ_{EL} and φ_{UZ}, as well as the measure of scatter. The adopted sample size allows evaluating the obtained resilience characteristics as having 2 significant decimal figures, which proves to be sufficient for comparing the properties of the network structures examined in this paper [21].

Let us note that a comparison of the resilience to mixed damage is only possible with regard to comparable facilities.

The requirements for comparability of structures are associated with the fulfillment of the following requirements:

1. The network entities must have identical numbers of nodes, linear elements, as well as end product consumers.
2. The compared entities are to be exposed to mixed damage in the same way, i.e. must have the same damage cyclogram.

In this context, let us examine the characteristic features of a set of comparable network structures.

Thus, Figure 1 shows structure diagrams of pipeline systems SMA, …, SMF with a source of the end product *A* and consumers *B*, …, *I* that differ in terms of resilience to mixed damage.

They all include the same number of nodes *R*, edges *Z* and end product consumers *U*. Correct comparison of the resilience characteristics requires creating identical damage conditions.

The specified values φ_{EL} and φ_{UZ} allow estimating if the analyzed systems are able to resist mixed damage. The resilience characteristics obtained for various damage conditions are shown in Figure 2.

A comparison of structures' resilience to mixed damage is only possible along the directions shown with arrows in the graph, as in this case the parameters of the corresponding cyclograms α and β remain unchanged. We can see that from SMA to SMB and to SMF the resilience of the analyzed structures progressively declines regardless of the used damage cyclogram.

That means that for a random set of comparable network structures the correlation between their resilience does not depend on the specific conditions of mixed damage. Therefore, we can argue that any structural variations aimed at improving systems' resilience to mixed damage have a positive effect on its behaviour in the event of accidents regardless of the specific type of implemented cyclogram. Additionally, the data in Figure 2 allow concluding that the blocking of transportation nodes is the most hazardous scenario of network entity failure.

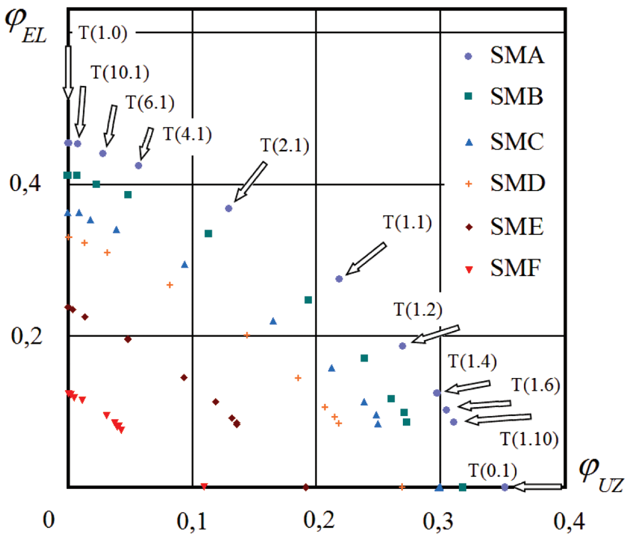

Figure 2 – Values φ_{EL} and φ_{UZ} specified for the sets of structures SMA, …, SMF.

In this context, of interest is the estimation of the variation of values φ_{EL} and φ_{UZ} of the set of comparable network structures with various resilience to mixed damage, for instance, as they change from SMA to SMF.

In order to trace such dynamics, it is required to choose for structure SMA that has the high resilience, such damage cyclogram that complies with condition $\varphi_{EL} = \varphi_{UZ}$. In this

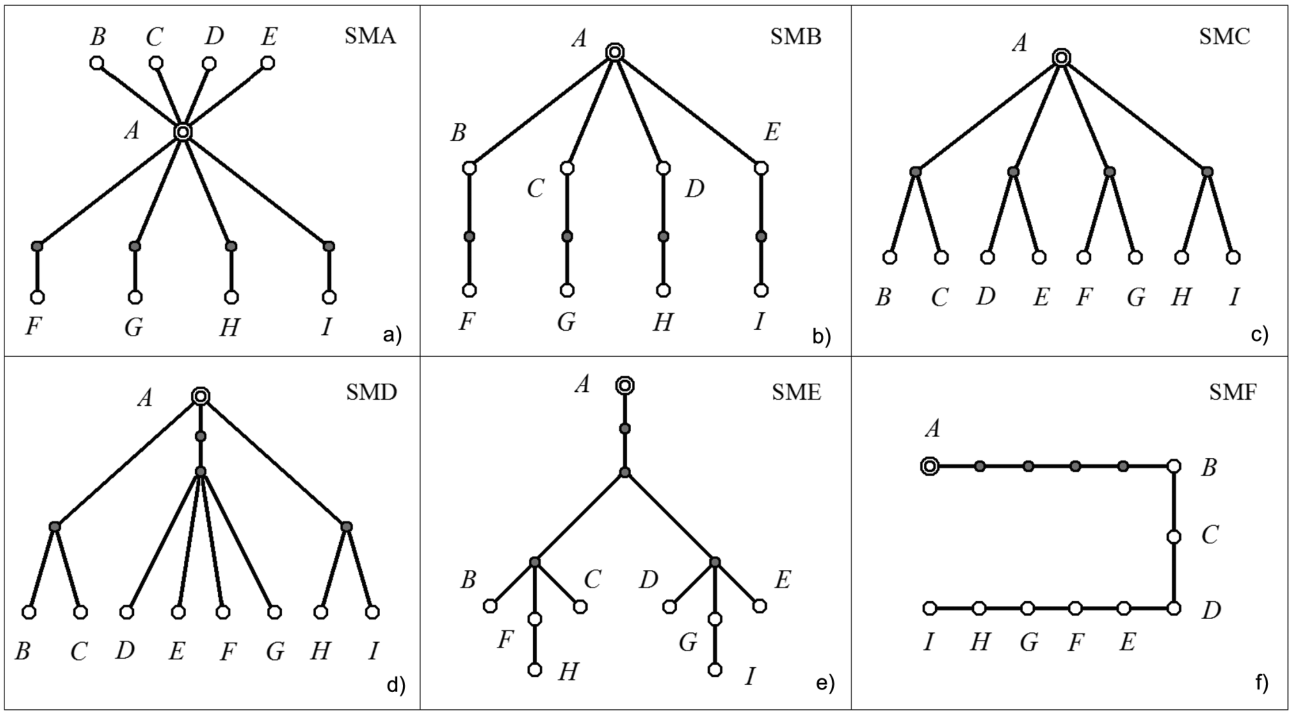

Figure 1 – Structure diagrams of SMA (a), … SMF (f) pipeline transportation systems.

case the deterioration of the systems' resilience characteristics from SMA to SMF will occur from the same starting positions. If that condition is fulfilled, we can clearly see how structural variations reflect on the variation of the contribution of individual components to the final resilience of network structures to mixed damage.

A series of simulation experiments on the SMA structure allowed concluding that near equality $\varphi_{EL} \approx \varphi_{UZ}$ is achieved in case cyclogram $T(3.8)$ is used. The variation of the position of vector $\vec{\Phi}^*$ on a plane under the mixed damage process $T(3.8)$ as regards the set of comparable network structures SMA, …, SMF is shown in Figure 3. The value of the module of vector $\vec{\Phi}^*$ is defined as:

$$\left|\vec{\Phi}^*\right| = \sqrt{\varphi_{EL}^2 + \varphi_{UZ}^2}.$$

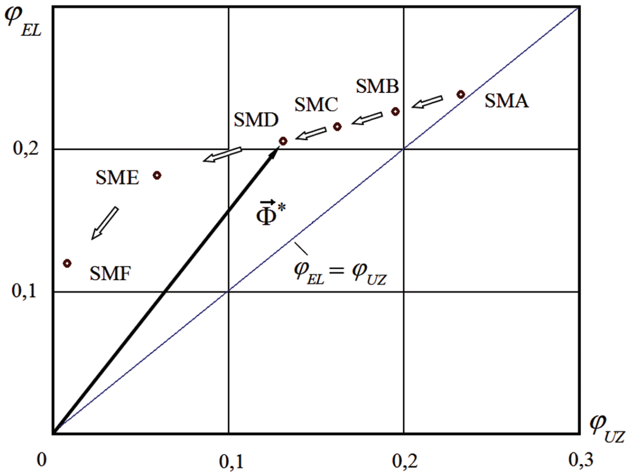

Figure 3 – Mixed damage resilience characteristic of network structures through vector $\vec{\Phi}^*$

The reduction of the values of individual components (axial projections of vector $\vec{\Phi}^*$) φ_{EL} and φ_{UZ} from SMA to less resilient network structures is shown in Figure 4. As for structure SMA, condition $\varphi_{EL} \approx \varphi_{UZ}$ is met, the height of the corresponding columns in the diagram is about the same.

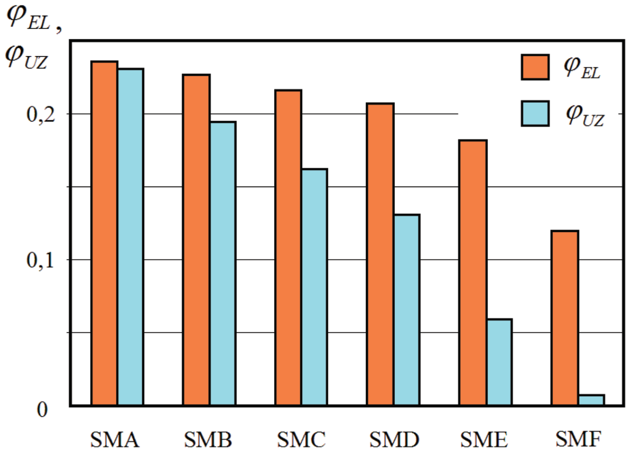

Figure 4 – Diagrams of values φ_{EL} and φ_{UZ} variation from SMA to SMF.

Additionally, it can be seen that in case of progressive transition from SMA to less resilient network structures, a relatively slow decline of value φ_{EL} can be observed. At the same time, the decline of values φ_{UZ} happens rapidly, which largely defines the observed effect of resilience deterioration.

Thus, the obtained result allows concluding that ensuring system resilience to mixed damage should be primarily based on measures aimed at improving their resilience to progressive blocking of transportation nodes.

Let us also note the following detail that was identified based on the analysis of data of Figure 2. If the mixed damage of a set of network structures proves to be similar to the process of progressive blocking of transportation nodes ($\beta >> \alpha$) or the process of linear elements failure ($\alpha >> \beta$), the respective points of the graph are placed too close to each other, which complicates the assessment of the obtained result.

For that reason, the identification of a system's ability to resist mixed damage is to be done using a test load with a cyclogram of type $T(1.1)$. Such exposure is a sequence of random damage to linear and point elements of a system and, in this sense, is balanced. Then, the resilience of comparable network structures should be compared subject to damage conditions according to cyclogram $T(1.1)$.

Let us assume that it is required to estimate the ability to resist the development of mixed damage of pipeline systems, whose structure diagrams are shown in Fig. 5. The above systems are defined by the presence of source *A*, identical number of transportation nodes, linear elements, as well as end product consumers (*B*, …, *G*). Let us evaluate their resilience for various conditions of mixed damage.

The results of conducted calculations are shown in Figure 6 and allow concluding that resilience to damage progressively declines in the course of transition from the system designated SUA to the system SUB and further from SUC to SUD.

Additionally, on plane we can define conventional boundaries of areas with different mechanisms of network structure damage. Thus, for range of Ω_E values φ_{EL} and φ_{UZ}, damage primarily occurs due to the failure of linear elements, while in area Ω_U mostly transportation nodes get blocked.

If for cyclogram $T(\alpha.\beta)$ condition $\alpha >> \beta$ is fulfilled, such nature of exposure of a network entity is associated with primarily linear element damage. Then, the comparability requirements can be somewhat reduced and we can consider as such systems with matching total numbers of linear elements and end product consumers only. If the above systems are exposed to damage with identical cyclogram, the expected values φ_{EL} should be used as criteria that allow estimating their resilience to mixed damage.

If the cyclogram features the parameter correlation $\beta >> \alpha$, such exposure is associated with the damage to primarily transportation nodes.

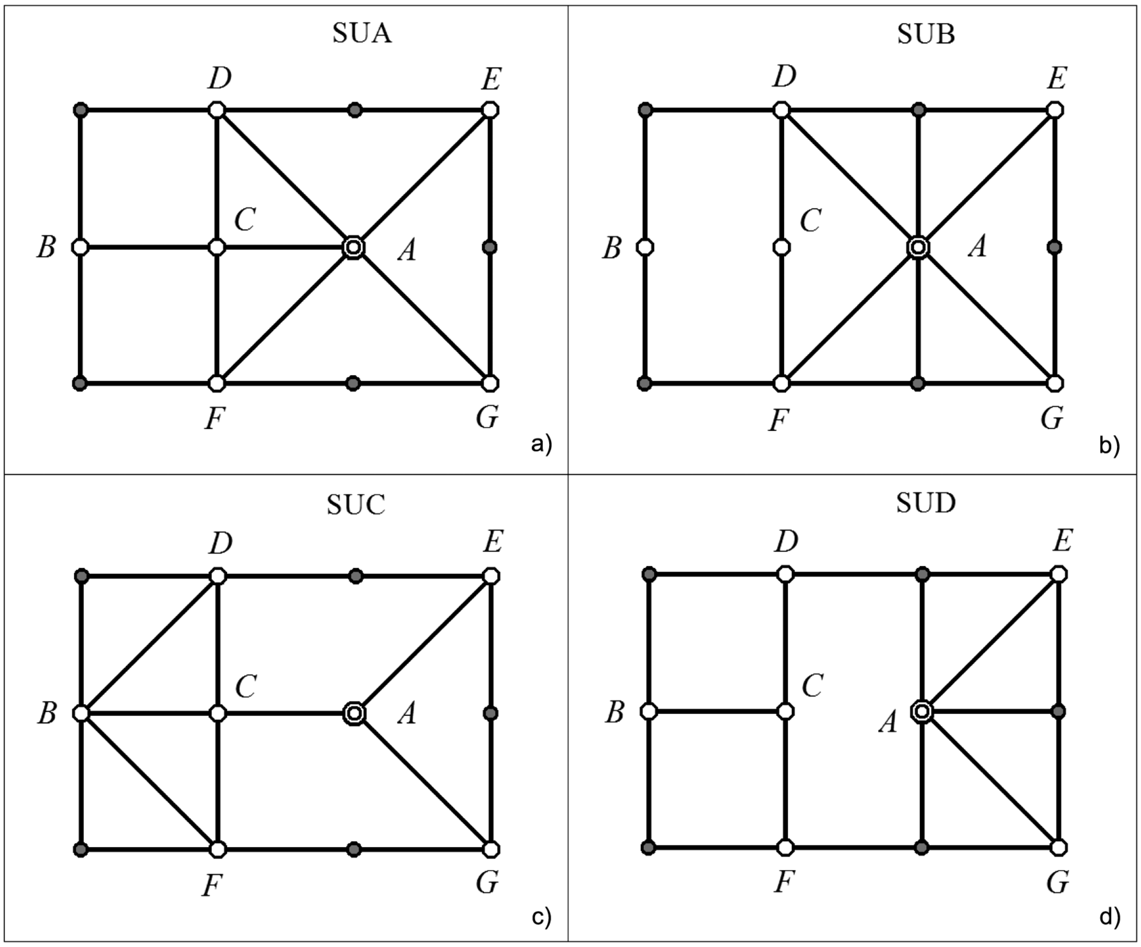

Figure 5 – Structure diagrams of SUA (a), … SUD (d) pipeline transportation systems.

Under such conditions systems with identical numbers of nodes and end product consumers will be comparable.

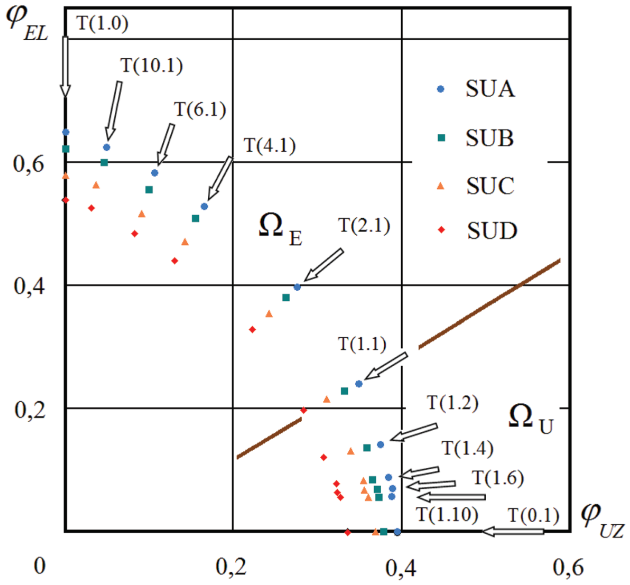

Figure 6 – Resilience characteristics specified for network structures SUA, …, SUD.

If such items are exposed to damage with identical cyclogram, the expected values φ_{UZ} are criteria that characterize their resilience to mixed damage.

Thus, the elimination of some limitations with regard to the identification of comparability of network entities for specific conditions of mixed damage enables analysis and solution of a wider range of applied problems.

Let us assume that it is required to evaluate the resilience and adopt a design solution regarding the practical application of one of the alternative network structures shown in Figure 7 subject to the threat of mixed damage.

All those facilities have identical numbers of nodes, linear elements and end product consumers (B, …, G). In case of mixed damage to the above structures with cyclogram $T(1.1)$ the comparison of values $\left|\vec{\Phi}^*\right|$ allows comparing the correlation of their resilience. This feature should be used for substantiation and adoption of design solutions.

Thus, Table 1 shows corresponding expected values that allow concluding that in case of mixed damage (regardless of the specific exposure conditions) the most resilient is the structure designated SFB that is to be regarded as the solution to the original problem.

The SFA and SFC network structures have about the same resilience, as their values of vector module $\vec{\Phi}^*$ are almost identical.

Let us now assume that the chosen SFB network structure is potentially exposed to external effects causing damage to primarily transportation nodes. Let us evaluate the feasibility of improving its resilience through structural modifications

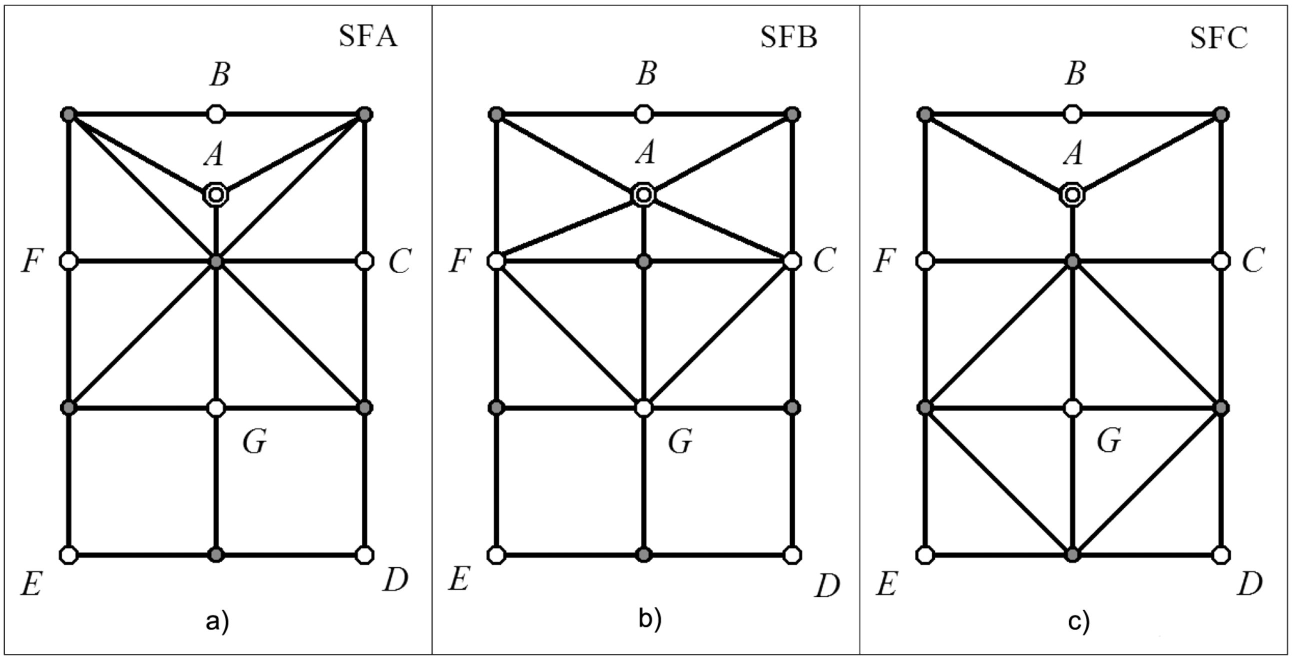

Figure 7 – Structure diagrams of SFA (a), … SFC (c) pipeline transportation systems.

Table 1. Resilience characteristics of comparable network structures for the adopted conditions of mixed damage

Designation of structure	Designation of mixed damage cyclogram	Estimated characteristics of resilience		
		φ_{EL}	φ_{UZ}	$\left\|\vec{\Phi}^*\right\|$
SFA	$T(1.1)$	0.168	0.288	0.333
SFB		0.187	0.323	0.373
SFC		0.167	0.286	0.331

and use of additional linear elements. Such derived structure designated SFW is shown in Fig. 8 (a).

The resilience characteristics of the SFB and SFW systems for the adopted damage conditions can be compared, as they have the same total number of nodes and end product consumers. Let us apply a mixed damage procedure – for instance, with cyclogram $T(1.3)$ – to the above systems. Values specified subject to the results of simulation are shown in Table 2.

As we can see, the inclusion into the SFB system of additional pipelines enables higher resilience, when damage affects predominantly point elements.

If, in the process of operation, the SFB system is exposed to damage to predominantly linear elements, we would be interested in finding a solution that would have a positive effect on its resilience to the above effects.

Let us reduce the number of nodes in the SFB system to $R = 11$, while preserving the total number of linear elements ($Z = 23$) and product consumers ($U = 6$). The structure of such pipeline system designated SFX is shown in Fig. 8 (b). The resilience of the SFB and SFX systems can be compared after the definition of the corresponding values for the specified damage conditions of predominantly linear elements. Thus, the values for each of the analyzed network structures damaged in accordance with the adopted cyclogram $T(3.1)$ obtained as the result of simulation, are shown in Table 2. It can be seen that the structural changes implemented in the SFX diagram have a positive effect on the system's resilience and are recommended for practical application.

Thus, when estimating the mixed damage resilience of a set of comparable network structures one must specify corresponding values $\left|\vec{\Phi}^*\right|$ in the test input conditions structure with characteristics $\alpha = \beta = 1$. Then the adjustment of the systems under consideration in terms of their resilience to mixed damage is to take into consideration the fact that more resilient systems have higher values of $\left|\vec{\Phi}^*\right|$. This criterion must be used as part of design solutions.

However, in some cases the specificity of the damaging effects allows slightly reducing the specified requirements

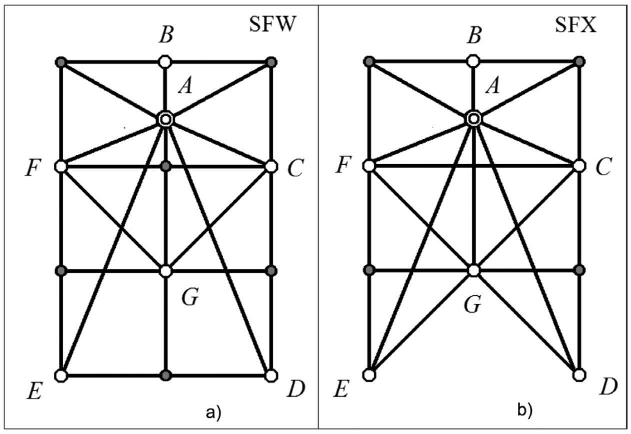

Figure 8 – Structure diagrams of systems resulting from the inclusion into SFB of additional linear elements (a) and exclusion of nodes (b).

Table 2. Estimated characteristics of network structures resilience

Designation of structure	Composition of structural elements	Designation of damage cyclogram	Resilience characteristics	
			φ_{UZ}	φ_{EL}
SFB	R=13, Z=23, U=6	T(1.3)	0.349	-
		T(3.1)	-	0.413
SFW	R=13, Z=26, U=6	T(1.3)	0.391	-
SFX	R=11, Z=23, U=6	T(3.1)	-	0.454

Table 3. Conditions of comparability and evaluation criteria network structures resilience

Specificity of damage	Cyclogram parameter	Conditions of comparability of network structures	Evaluation criteria of system resilience
Balanced damage to structural elements	$\alpha = \beta = 1$	Identical numbers of linear elements, nodes and product consumers	$\left\lvert \vec{\Phi}^* \right\rvert = \sqrt{\varphi_{EL}^2 + \varphi_{UZ}^2}$
Predominant damage to linear elements	$\alpha >> \beta$	Identical numbers of linear elements and product consumers	$0 < \varphi_{EL} < 1$
Predominant blocking of transportation nodes	$\beta >> \alpha$	Identical numbers of nodes and product consumers	$0 < \varphi_{UZ} < 1$

and thus extending the options of comparative estimation of the properties of the analyzed systems.

Thus, Table 3 shows recommendations regarding the conditions of comparability and selection of criteria of systems resilience evaluation for various procedures of mixed damage. Their practical value is associated with the feasibility of a wider use of the identified patterns and theoretical findings.

Conclusions

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

2. The ability of network structures of pipeline systems to resist mixed damage is evaluated based on φ_{EL}, φ_{UZ} and $\left\lvert \vec{\Phi}^* \right\rvert$, that are defined by means of simulation.

3. A correct comparison of the resilience of various structures to mixed damage is only possible in case they are comparable. For that purpose, they must have identical numbers of nodes, linear elements and product consumers. Additionally, such systems must be exposed to damage procedures with identical cyclograms.

4. The correlation of the resilience of network structures that comply with the comparability conditions, does not depend on the adopted damage cyclogram, but is defined by the existing set of connections within a particular system.

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The author's contribution

The author has analyzed the resilience of pipeline transportation systems affected by developing process of mixed damage to structural elements. The statistical characteristics of the process and conditions of comparability of systems in case of accidental damage to linear and point elements were defined.

Computer simulation of the process of mixed damage was conducted. The characteristics that enable the assessment of individual systems to resist the development of this process were identified. A method was proposed of comparative estimation of the resilience of comparable network structures affected by possible accident development by the mechanism of mixed damage.