Resilience of Above-ground Arctic Pipelines

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doi: https://doi.org/10.21467/abstracts.93.99

ABSTRACT

The paper first introduces and describes the basic concepts of structural resilience on the example of the simplest structural element - a rod subjected to centrally applied tensile force. The very fact of the possibility of such a method of introducing fundamentally new concepts indicates that resilience is one of the *intrinsic* properties of mechanical systems, such as strength, durability, reliability, and can be described in quantitative terms. The novel method of structural resilience analysis used in the paper is based on two consecutive applications of the classical reliability apparatus to assessing the individual and ensemble-wise structural resilience of a physical object. First, an estimate is made of the system reliability, designed in accordance with current design standards, using the design values of loads/impacts. After that, the reliability of the same structure is examined when it falls into a beyond-the-design state. The second step analysis is nothing but testing the ability of the safety cushion, provided by the used design norms, to withstand forces that are beyond the design limits. This analysis clearly shows that resilience is conditioned by the design code used to create the system. A very conservative design code will provide the system with a large safety cushion, and with it, high resilience. A riskier code will provide the designed system with a smaller resilience. This situation can be vividly illustrated by the case of resilience analysis of pro-sportsmen: they use their capabilities to the extreme, which makes them very vulnerable to different kind of infectious diseases: their resilience to additional stressors is very low. All the above permits proposing following definition of structural resilience: *structural resilience is the reliability of a structure/system operating under the influence of beyond-the-design loads and/or effects*.

Structural resilience is always conditional, since it depends on the type of load/stressor applied to the structure, material properties, configuration and structure of the system itself (discrete, distributed, statically determinate or in determinate strut system, plate, shell, three-dimensional body) and type of failure (i.e. loss of bearing capacity/functionality). With an increase in the inherent strength of the material and the degree of the structure static indeterminacy, the resilience will obviously increase. The *intrinsic resilience* (IR) of an *individual* construction is its ability to maintain its integrity (and, therefore, performance) when exposed to loads greater than the design loads, in the absence of: (1) any devices and subsystems for load control, (2) maintenance subsystems.

The load on the construction and the minimal yield (ultimate tensile) strength of its material are considered as random variables, i.e. the true yield strength of steel used in a particular structureis not known in advance; only its distribution is known. Therefore, resilience is of stochastic nature. In the considered case of resilience of an arctic above ground oil pipeline it is necessary to move from the load as a random variable (RV) to the random stresses it causes and find the joint probability that characterizes the state of system resilience: current stresses are larger than their ultimate permissible design values, while, at the same time, the strength of the structure material is greater than this current value.

DOI: 10.21467/abstracts.93

A comprehensive algorithm that accounts for all specific loads on the pipeline (dead loads, pumped oil weight, wind, soil summer subsidence and winter upheaval) was developed for the case of an above ground Arctic oil pipeline. Let the acting loads and impacts induce stresses *x*, that belong to the resilience domain, when the structure is used beyond its design purpose), i.e., in the interval $\left[R_y;R_{0.997}\right]$, where R_y is the structure material design resistance according to the minimum yield (ultimate tensile) strength; $R_{0.997}$ is the material strength PDF quantile of level 0.997. Then, under the normal law of distribution of the yield strength and the stresses in the structure, the IR at an arbitrary point $x \in \left[R_y;R_{0.997}\right]$ will be equal to the probability that the stresses will be less than this value of *x*, and the yield strength will be greater, i.e. these two events are existing simultaneously:

$$\operatorname{Re}s_{ind} = P\begin{Bmatrix} S < x \\ R > x \end{Bmatrix} = \int_0^x \frac{1}{\sigma_S\sqrt{2\pi}} \exp\left[-\frac{(t-\mu_S)^2}{2\sigma_S^2}\right]dt \cdot \int_x^{+\infty} \frac{1}{\sigma_R\sqrt{2\pi}} \exp\left[-\frac{(t-\mu_R)^2}{2\sigma_R^2}\right]dt =$$
$$= \Phi\left(\frac{x-\mu_S}{\sigma_S}\right)\left[1-\Phi\left(\frac{x-\mu_R}{\sigma_R}\right)\right], \quad x \in \left[R_y;R_{0.997}\right] \tag{1}$$

where $\mu_S, \sigma_S \left(\mu_R, \sigma_R\right)$ are respectively, the expectation and the standard deviation of the stresses (yield strength).

Based on formula (1), the problem of assessing the resilience of a linear section of an Arctic aboveground oil pipeline was solved. Stochastic IR of the considered section of the pipeline is estimated by the formula (1), which for the pipeline will take the form

$$\operatorname{Re}s_{ind} = P\begin{Bmatrix} \sigma_e < x \\ R > x \end{Bmatrix} = \int_0^x f_e(t)dt \cdot \int_x^{+\infty} \frac{1}{\sigma_R\sqrt{2\pi}} \exp\left[-\frac{(t-\mu_R)^2}{2\sigma_R^2}\right]dt = \Phi\left(\frac{x-\mu_R}{\sigma_R}\right)\int_0^x f_e(t)dt,$$
$$x \in \left[R_y;R_{0.997}\right],$$

where σ_e - are the equivalent stresses in the pipeline; $f_e(t)$ is the PDF of equivalent stresses.

When $x = R_y$ the pipeline section resilience is equal to its reliability. With an increase in the acting stresses (for example, from excess subsidence/upheaval of supports) in the pipeline, its resilience decreases monotonically to a value close to zero (corresponding to stresses equal to the yield stress quantile $R_{0.997}$, after which failure is inevitable).Thus, the obtained pipeline resilience is related to the strength and stability criterion, and the stresses are caused by excessive subsidence / upheaval of the pipeline supports.

In the general case, equivalent stresses σ_e are a nonlinear function of random variables (circumferential and longitudinal axial stresses), the inverse function of which is implicit, which does not allow applying the theorem on the distribution density of a monotonic function of a random variable to obtain the PDF of σ_e. Since the equivalent stresses are non-negative, the Laguerre polynomials can be used as the system of basic orthogonal functions for approximating the PDF.

This statement of the problem allows considering such factor as the effect of changes in the loads on the structures, including changes due to global warming and/or degradation processes, on the change in its resilience. Indeed, if climate changes lead to an increase in loads (e.g., wind, snow, wave) or impacts (e.g.,

 DOI: 10.21467/abstracts.93

seasonal upheaval/ subsidence of permafrost soil), then the right tail of the load PDF becomes heavier (fatter) and, as a result, the resilience of functioning systems correspondingly decreases.

The described type of structural resilience fully characterizes the system when the load is the only possible cause of failure. If the failure can occur due to material degradation or changes in the design scheme, it is necessary to additionally assess the resilience of object, considering these circumstances. In general, the above results can be interpreted as basic components of the consistent theory of stochastic resilience of structures and as an example of its application to real life case resilience assessment of a pipeline system.

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