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ANALYSIS OF DESIGN DEPENDABILITY OF CRITICAL UNITS OF ARCH SPANS OF PEDESTRIAN OVERPASSES BASED ON NUMERICAL AND SIMULATION METHODS

The paper deals with the design dependability of the grip-arm interface "arch – bowstring – jack beam" in spans of pedestrian overpasses. Dependability estimation required the performance of a number of simulation procedures that include five basic steps. Exhaustion of weight strength in one of the critical element of the arch – bowstring – jack beam joint was the criterion of making a decision about failure.

Keywords: *design dependability, simulation, pedestrian overpass, load, confidence interval.*

Introduction

The level of constructive system dependability is usually selected at the concept and requirements specification stage. Designing bridges for large cities generally involves the requirement of aesthetic expressiveness that inevitably leads to the intentional complication of junctions. That, in turn, requires comprehensive substantiation of the adopted design decisions, design flaws can lead to catastrophic consequences with large casualties.

This paper presents the results of dependability analysis at the stage of arrangement of the critical joint "arch – bowstring – jack beam" in spans of a designed pedestrian overpass on a road of the first engineering category in the Moscow Region. According to the construction solution, a span of the pedestrian overpass is implemented as a single-span inclined arch of variable box-shaped section with dimensions from 1600x500 mm to 1000x500 mm with pipe hangers of 203x10 mm. In cross-section, the two planes of arches have an inward tilt of 14 degrees to vertical. The jack beam is box shaped and measures 750x1000 mm. The length of arch span of the pedestrian overpass is 77 m, the walking part is 4 m in width. Structural components of the critical joint "arch – bowstring – jack beam" are made of 15HSND steel as per GOST 6713. The designed service life of the structure is not less than 100 years.

The analysis of the design dependability of the critical arch – bowstring – jack beam joint in spans of a designed pedestrian overpass required the performance of a number of procedures that included five basic steps.

At the first step, using determined input parameters, an estimation of expected boundaries of loads' variability was carried out based on the method of confidence intervals with validity $\beta = 0{,}995$. Statistical characteristics of individual load components were obtained based on statistical information generalized in studies [1, 2], as well as the general rules of application of normative values and system of factors in the allowing equations of the limiting conditions method stated in studies [3, 4].

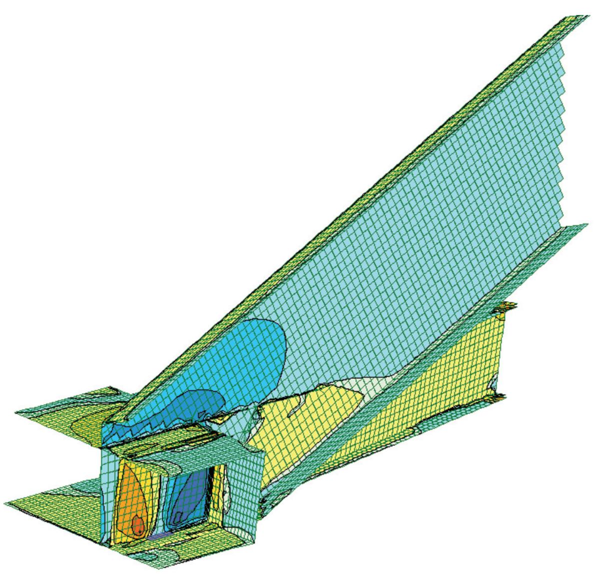
In order to identify the boundaries of variation of the total constant load, the authors carried out a series of simulations. Over a number of repeated simulations, in order to create samples of realizations of random variables of constant load components, MathCAD random numbers generators and program modules developed by the authors were used along with rational algorithms of line-by-line transformation of numerical sets the advantages of which are outlined in [5]. Upon the performance of the series of simulations, the most disadvantageous boundaries of variation of total constant load $[q_{\Sigma,\, inf}; q_{\Sigma,sup}] \sim F_{q\Sigma}$ [60,69; 83,91] кN/m were chosen for subsequent calculation.

The expected boundaries of variation of live load from pedestrians are presented by an interval $[p_{inf}; p_{sup}] \sim F_p$ [3,15; 28,85] N/m. The expected boundaries of variation of other loads [6, 7] are estimated within the following intervals: wind pressure in the construction area $[w_{0,inf}; w_{0,sup}] \sim F_w$ [0,000; 1,581] кN/m^2; weight of snow $[S_{0,inf}; S_{0,sup}] \sim F_S$ [0,096·μ; 1,864·μ] кN/m^2, μ being the factor of transit from weight of snow cover to snow load.

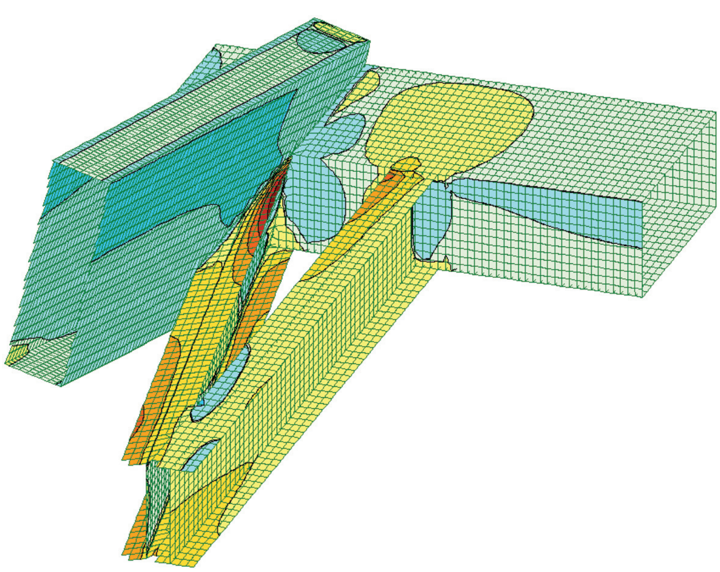
At the second step, using the expected boundaries of variation of loads obtained at the first step, as well as finite element displacement method in the LIRA software system, a set of static calculations of spans of pedestrian overpass was executed. In order to evaluate the stress-strain state (SSS) of the arch – bowstring – jack beam joint, account was taken of stress components in elements of the joint and in adjacent elements: top and bottom booms of the arch, top and bottom chords of the bowstring, bottom zone and the wall (diaphragm) of the jack beam, elements of bowstrings in the supporting section. 138 most typical combinations of loading are involved in the set of static calculations, both individual loads, and their possible combinations within the limits of expected boundaries of variation.

Fig. 1 shows fragments of individual loadings with stress izofields in elements of the arch – bowstring – jack beam joint.

At the third step, a statistical analysis of SSS estimation results of the arch – bowstring – jack beam joint is carried out based on the selective data obtained from the loading combinations at the second step.



a) Stress izofields by T_{xy} over the range from –71 to +68,4 MPa



b) Stress izofields by N_x over the range from –82,4 to +306 MPa

Fig. 1. Fragments of individual alternative loadings with stress izofields in elements of the arch – bowstring – jack beam joint

Table 1. Statistical characteristics of individual components in the arch – bowstring – jack beam joint

Item number	SSS components	Statistical characteristics						
		Sample size	Arithmetic mean value	Root-mean-square deviation	Coefficient of variation	Set excess	Least value	Largest value
1.	Normal stress along vertical axis	138	122,4 MPa	23,9 MPa	0,195	–0,857	90,0 MPa	155,6 MPa
2.	Normal stress along horizontal axis	138	130,1 MPa	27,1 MPa	0,208	–0,832	102,0 MPa	174,9 MPa
3.	Shear stresses	138 MPa	82,3 MPa	17,3 MPa	0,210	–0,838	58,0 MPa	90,4 MPa

The general view of the obtained statistical characteristics of individual SSS components (table 1) shows the deformation of the form of final distribution of probabilities regarding its comparison with statistical characteristics of random variable for the normal distribution law.

The authors have developed logic and analytical MathCAD program modules in order to estimate the probability of a possible «surge» of the random variable of each k-th intermediate parameter (individual SSS components) beyond the level of disadvantageous boundary in uncertainty entropic interval. For this purpose, the frequency $\varphi_k|N$ of the expected "surge" of k-th parameter random variable, which was determined by registration of cases with individual excess of i-th realizations of k-th parameter $\sigma_{k,i}\ (N)$ in the level of the upper boundary of uncertainty entropic interval $\sigma_{k,sup}$, for the same parameter during simulation of volume N:

$$\phi_k \left| N = \frac{n_k \left| \left(\sigma_{k,i}(N) > \sigma_{k,\sup} \right) \right.}{N} \right., \qquad (1)$$

$$\sigma_{k,\sup} = \bar{\sigma}_k + \varepsilon_{k,\beta}, \qquad (2)$$

where $\varepsilon_{k,\beta}$ is the estimation accuracy of k- th parameter calculated with confidence β.

Test runs of simulation models were carried out for definition of the required amount of stress simulation in calculated sections using statistical characteristics of individual SSS components in arch – bowstring – jack beam joints (table 1). The volume of initial numerical sets (individual SSS components) is specified at the level of $N \sim 10^4 \ldots 10^7$ realizations. As the criterion confirming the adequacy of accepted simulation model, convergence by probability P_β is accepted:

$$\phi_k \left| N \xrightarrow{P_\beta} Q_{k,\lim}(t),\ t \le T_\Theta \right., \qquad (3)$$

where $Q_{\lim}(t)$ is the limit value of the risk factor, estimated based on the requirements of system dependability during operation *t* within the limits of expected designed service life T_Θ of construction.

Test runs of simulation models have shown that meeting the requirements to adequacy of the simulation plan, it is required to artificially regulate the volume of initial numerical sets N that depends on the accepted confidence level of the calculated parameter. For the purpose of the research task, the plan of simulation featured the volume of initial numerical sets $N = 10^7$ realizations at confidence level $\beta = 0{,}995$. The requirement to the limit risk factor of $Q_{\lim}(t) = 5 \cdot 10^{-6}$ is observed.

At the fourth step, a set of simulations to estimate the design dependability of an arch – bowstring – jack beam joint was carried out according to the criterion of failure due to exhaustion of weight strength. Failure is the event consisting in the excess value of random realization of individual or simultaneous stresses in design sections over the random realization of the weight strength value of the material.

Initially, after studying the results of statistical research of the mechanical properties of the used structural material, it was decided to further use statistical data regarding 969 control tensile tests of standard samples presented in study [8]. In the set of simulations aimed at estimating the dependability of the arch – bowstring – jack beam joint, the used 15HSND steel features the following statistical characteristics: selective average yield stress of 386,9 MPa, variation coefficient of 0,0835, mean difference of 32,4 MPa; selective average breaking strength of 558,5 MPa, variation coefficient of 0,0745, mean difference of 41,7 MPa.

Table 2. Calculated interval estimates for joint SSS components

Item number	SSS components	Calculated interval estimates	
		Lower boundary (inf)	Upper boundary (sup)
1.	Normal stresses along vertical axis, $\sigma_x \sim f[\sigma_{x,\inf};\sigma_{x,\sup}]$	90,0 MPa	280,9
2.	Normal stresses along horizontal axis, $\sigma_y \sim f[\sigma_{y,\inf};\sigma_{y,\sup}]$	102,0 MPa	590,6
3.	Shear stresses, $\tau_{xy} \sim f[\tau_{xy,\inf};\tau_{xy,\sup}]$	58,0 MPa	183,5

Solving the tasks of this step with the use of the results of statistical analysis of junction SSS evaluations obtained at the third step involved the generation of interval estimates for SSS components according to the accepted simulation plan (table 2). The lower border is specified as the least value of the respective SSS component (see table 1) that corresponds to constant loads only, while the upper boundary is calculated based on the characteristics of the simulation plan (at the upper boundary of the confidential interval with the probability of 995, sample size of 138, quantile of 2,853 and number of model runs of 400).

The condition of estimation according to the criterion of failure due to exhaustion of weight strength is follows:

$$Q_\Omega \Rightarrow \begin{cases} R_y(j) < \sigma_x(j) \\ R_y(j) < \sigma_y(j) \\ R_s(j) < \tau_{xy}(j) \\ R_y(j) < \sqrt{\left|\sigma_x(j)^2 - \sigma_x(j)\cdot\sigma_y(j) + \sigma_y(j)^2 + 3\cdot\tau_{xy}(j)^2\right|} \end{cases}, \text{ for } j \in [1;N], \quad (4)$$

where $R_y(j)$, $R_s(j) = 0,58 \cdot R_s(j)$ are sets of random realizations of yield point and shear resistance of steel, $\sigma_x(j)$, $\sigma_y(j)$, $\tau_{xy}(j)$ are sets of random realizations of individual SSS components (normal and shearing stresses).

Simulations of design dependability of the arch – bowstring – jack beam joint according to the criterion of failure due to exhaustion of weight strength did not identify the values of random realizations of individually simulated normal and shearing stresses to exceed random realizations of values of material weight strength. It was established, that subject to composite action of stresses during the estimation according to the fourth model in condition (4), there was a consistent registration of failures with the maximum frequency of $2{,}4\cdot10^{-6}$ that does not contradict the limiting value of risk factor at $Q_{lim}(t) = 5\cdot10^{-6}$.

Thus, from the standpoint of sufficient dependability parameters for the design stage, the accepted design solutions can be left unchanged.

At the fifth step, a series of simulations was carried out to estimate the possible variability of dependability parameters of the arch – bowstring – jack beam joint at the stage of operation.

Obviously, in the course of systems operation, the effects of various adverse processes are inevitable (i.e. deterioration of elements, substandard and/or untimely maintenance). As a rule, at the design stage, the designer has to face certain seemingly insurmountable difficulties that are caused, in particular, by the fact that the designed structure or sometimes even comparable projects are nonexistent. In this situation it is difficult or even impossible to provide an accurate assessment of system dependability evolution over the course of design life time. In order to solve the tasks of this step, analytical models for formalization of variability process of dependability parameters outlined in [9] and the model for description of deterioration processes of steel structures from allied sciences (for example, [10]) were used.

In the development of the variability model of dependability parameters during designed operation life time one of the more important indicators is the final value of dependability determinative parameter (for example, failure probability) by the moment of exhaustion of safe operation life. Let's write down the condition at which the technical system has not exhausted the life during operation time *t*:

$$Q_{\Omega}(t) \leq \left[Q(t)\right],\ t \leq T_{\Theta}, \tag{5}$$

where $Q_{\Omega}(t)$ is the probability of hazardous failures according to limiting state with the condition Ω; $[Q_{\Omega}(t)]$ is the acceptable value of probability of the failure in question.

In view of condition (5), the formula of estimation (4) by failure criterion due to exhaustion of weight strength is rewritten as follows:

$$\left\{Q_{\lim}(t)\right\} \leq Q_{\Omega}(t) \Rightarrow \begin{cases} R_{yt}(j) < \sigma_{xt}(j) \\ R_{y}t(j) < \sigma_{yt}(j) \\ R_{st}(j) < \tau_{xyt}(j) \\ R_{yt}(j) < \sqrt{\left|\sigma_{xt}(j)^2 - \sigma_{xt}(j)\cdot\sigma_{yt}(j) + \sigma_{yt}(j)^2 + 3\cdot\tau_{xyt}(j)^2\right|} \end{cases}, \tag{6}$$

where $R_{yt}(j)$, $R_{st}(j)$ are the areas of random realizations of yield point and steel shear resistance with time-base sweep *t;* $\sigma_{xt}(j)$, $\sigma_{yt}(j)$, $\tau_{xyt}(j)$ are the same for individual SSS components.

Now let's consider a simple linear model describing variability of individual i-th calculated parameter, included in formulas (4):

$$\Phi_i(t) = \Phi_{i,0}\cdot\left(1 + t\cdot\Delta_t\right), \tag{7}$$

where $\Phi_{i,0}$ is the initial-time value of an individual i-th calculated parameter (t= 0);$\Delta_t = \frac{d}{dt}\Phi_i(t)$ is the composite indicator that takes into account the effects of various adverse processes in time *t* within the limits of expected designed life time of a structure.

Various values of a complex parameter Δ_t adopted in the range of $1\cdot10^{-4}$ … $5\cdot10^{-5}$ are examined using the example of the arch – bowstring – jack beam joint in spans of pedestrian overpasses. The values of the composite indicator Δ_t were used in simulations to define the variability of probability of system failures in time (by a fig. 2).

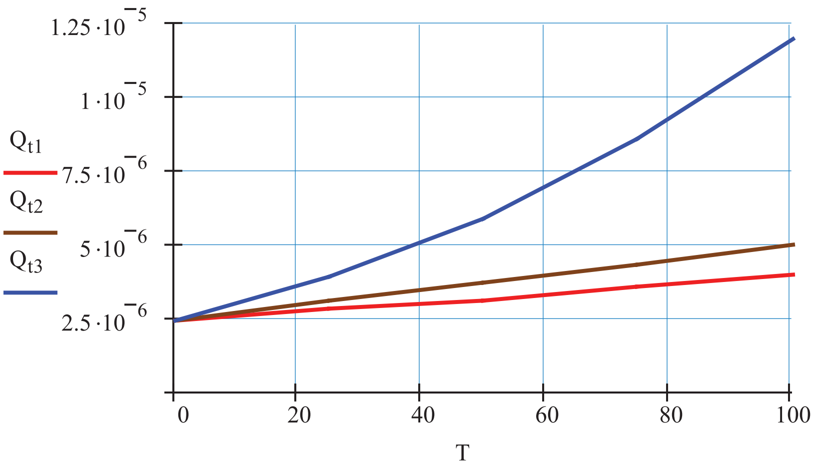


Fig. 2. Variability diagrams of probability of system failures in time T depending on the accepted value of the composite indicator Δ_t, for $\Delta_{t1} = 5\cdot10^{-4}$ the probability of failures is Q_{t1}, $\Delta_{t2} = 2{,}5\cdot10^{-4}$, the probability of failures is Q_{t2} and for $\Delta_{t3} = 1\cdot10^{-4}$ the probability of failures is Q_{t3}

The obtained results show, that in order to retain the dependability parameters in operation, provided that the accepted design solutions remain unchanged, the variability of calculated parameters in time (increase of stresses) must not exceed $\Delta_t = 2{,}5\cdot10^{-4}$ per year.

Conclusions

According to the results of dependability analysis of the critical arch – bowstring – jack beam joint in spans of a designed pedestrian overpasses, it was established, that subject to confidence level of calculated estimations $\beta = 0{,}995$, a failure under criterion of one of the elements exhaustion appears to be practically improbable.

For the criterion of weight strength exhaustion from cumulative action of stresses in the simulation of typical combinations of external loadings in the arch – bowstring – jack beam joint, there was a consistent registration of failures with the maximum frequency of $2{,}4\cdot10^{-6}$ that does not contradict the limiting value of risk factor of $Q_{lim}(t) = 5\cdot10^{-6}$.

The authors have developed and practically tested special dependability estimation algorithms based on structural, statistical and simulation methods, as well as regression analysis techniques that allow both estimating design dependability and predicting the acceptable level of dependability parameters variation over the course of system operation subject to the criticality of the function.

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