EVALUATING THE LOAD CAPACITY AND DURABILITY OF BRIDGES IN OPERATION

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Abstract: *The article considers the principles of assessing the carrying capacity and longevity of operated bridge structures based on the results of full-scale studies and calculations based on the knowledge and conscious application of the principles of calculating structures for limiting states, taking into account their physical and moral deterioration.*

The durability of a bridge structure or its structural elements determines the period of time during which the structure (element) can be operated in the design mode under normal control without reconstruction or major repairs.

The durability of the structure cannot be considered in isolation from the rest of its functional properties. Therefore it is logical to determine the longevity of the structure differentially in terms of the reduction in the level of load capacity, or throughput, or traffic safety.

Criteria for longevity are associated with critical levels of load capacity, requirements for their security and measures to restrict traffic.

Keywords: *bridge structure, load-carrying capacity, durability, defects and damages, from moral and physical deterioration, full-scale inspection and testing.*

The evaluation of the load capacity and residual service life of bridges in operation is the most critical. Indeed, bridge owners should know and have the right to know how they can safely operate the structure, what kind of vehicles they can pass through the bridge in a free flow, and how to pass nonstandard heavyweight cargo through the bridge. And, finally, for how long they can stay calm for their "masterwork". And of course, they specify these questions in the terms of references for bridge examination and testing.

But after carrying out the all the tests they, having not yet received an official conclusion from the contractor, descends from the engineering level to the domestic one, and nervously fumbling with a button on the operations manager's coat while looking in his eyes, shyly asks: "Are you sure it will not fall?"

In order to make it easier to answer this kind of "Hamlet questions", let us consider the principles of estimating bridge capacities using the limit state method, as well as some actual calculation procedures in this area.

The method of obtaining such estimates based on the results of field studies and calculations is based on the knowledge and conscious application of the limit state method for structure calculation taking into account their depreciation and obsolescence (physical and moral deterioration).

The deterioration is referred to as a decrease in the level of consumer properties, in particular, the load-carrying capacity and durability, in relation to the initial parameters.

The depreciation of bridges is associated with structural defects obtained during manufacture, transportation and installation, as well as damages obtained during operation. Both may cause a decline in the level of their consumer properties to some extent.

The obsolescence of bridges is caused by the increase in the demands to their consumer properties during operation as compared to those specified in the standards and the project terms. At the same time, the design load capacity a bridge W_d stops to satisfy the real weight characteristics of the vehicles passing through the bridge ($W(t) > W_d$).

What can we do in this case? If it is a question of any specific structures, those must be strengthened. However, if we are dealing with a load increasing trend nationwide, it is necessary to increase the load standards. It is this reason that prompted the authorities to significantly increase the regulatory vehicle loads in 2008 (GOST R 52748 [1] A14 and H14 loads instead of A11 and NK-80). This provision is also specified in SP 35.13330 [2].

And then many experts have a question about what to do with bridges in operation. After all, the capacity of those is lower than that of new ones. The answer to this question is quite simple. Load standards for new bridges are appointed from a remote perspective. Existing bridges designed according to different standards have different design capacities that will be exhausted on the grounds of obsolescence or depreciation at different times. A decision will be made based on the situation only when such a moment occurs for a particular structure. Let us hope it will not come so soon.

When evaluating the bridge load capacity and durability, three criteria should be considered that determine the degree of their provision:

- **The design criterion** reflecting the level of the consumer property provided when designing structures with respect to regulatory requirements. Typically, this level is somewhat higher than that required by the standards which is due to structural reasons. For instance, when selecting cross-sections of load-bearing elements, the thicknesses of steel plates, the numbers of rolled steel, and the reinforcement diameters are selected from standard grades while approximating the required sections from above. In other words, the diagram of the materials should be enveloping in relation to the diagram of stresses.
- **The depreciation criterion** showing the maximum degree of loss of the consumer property under investigation at a given time due to depreciation. For example, the destruction of the protective layer in pier columns working in compression reduces their

carrying capacity, the corrosion of railing elements adversely affects the pedestrian traffic safety, etc.

- **The obsolescence criterion** reflecting the ratio of the design level of the consumer property and the requirements for it acting during the current period of bridge operation.

The load capacity of a bridge is a characteristic reflecting the maximum permissible weight parameters of vehicles and pedestrian traffic, as well as the modes of their passage through the bridge.

By properly normalizing the load capacity of a bridge, we thereby provide the mechanical safety of that bridge, that is, protecting it from destruction. Naturally, the capacity is determined by the ultimate limit states.

The load capacity of bridges can be characterized in various forms.

The standard capacity of road bridges is expressed in the **maximum permissible regulatory load classes** for this bridge defined by the current regulatory vehicle load diagrams - AK (corresponds to free unrestricted road traffic) and NK (a single heavy vehicle crossing the bridge in an assigned mode in the absence of other temporary loads). The AK and NK load diagrams, as well as the SK diagram of the regulatory load of railway bridges in the design standards for bridges and pipes are shown in SP 35.13330 [2].

In both cases, the symbol “K” represents a load class, that is the factor by which to the parameters of the so-called unit load have to be multiplied to obtain regulatory values. The load classes can differ depending on the traffic volume and type of traffic on the road section where the bridge is located, which is specified in the above mentioned regulatory document or in the terms of reference for design.

Currently, class K = 14 is adopted both for motor-road load and railroad loads (this coincidence is accidental).

The load capacity for pedestrian bridges is expressed in the maximum permissible load intensity per square meter.

The load capacity of bridges defined in the regulatory load classes makes it possible to evaluate the state of the bridge economy as a whole and to determine the strategy for bridge construction, maintenance and repair as part of the development and operation of a particular area. In addition, this form allows us to schedule the traffic routes of large-size and large-tonnage cargo.

In the most general form, the load capacity of bridges can be interpreted as the **maximum permissible forces or stresses** that can occur in structural elements from the effects of vehicles and pedestrians (let us call them a useful temporary load).

Let us recall that the **bearing capacity** of a structural element is the maximum force that can be transferred to this element from all the loads and impacts provided by the standards.

Therefore, the bridge element capacity W can be represented as the difference between its bearing capacity ***C*** and the effects of permanent and other temporary loads D, that is:

$$W = C - D \tag{1}$$

The bearing capacity and, hence, the load capacity are functions of load standards, as well as actual values of the material strengths and geometric parameters of bridge elements.

The load capacity of a bridge can be determined most accurately by forces in the elements, for which a spatial calculation of the bridge is most likely required. This method is typically used when testing the bridge capability to take multiaxle heavy vehicles that do not satisfy the regulatory load diagram.

Finally, the load capacity of road bridges can be expressed by the **critical masses** of various types of vehicles (for example, determined by the number of axles) that can safely cross the structure in a free (AK diagram) or special mode (NK diagram).

When knowing the maximum permissible masses of various types of vehicles, the operational staff can determine the possibility of passing a particular vehicle through a particular bridge right on site.

The Guidelines for determining the load capacity of bridges on motor roads of ODN 218.0.032 [3] show permissible masses of motor vehicles for different lengths of bridge span structures.

However, it should be noted that the possibility of passing of road trains weighing more than 45 tons through bridges requires a special design check.

In the process of bridge operation, its load capacity may not be sufficient due to both depreciation and obsolescence. That is, the force W_i **(t)** occurring in its **i**-th structural element from the impact of real useful temporary loads after **t** years after the start of operation may exceed its actual load capacity at that moment.

Thus, the provision criteria for the load capacity of bridges can be formulated as follows:

$$\text{design} - W_{regul} < W_d$$

$$\text{obsolescence} - W(t) < W_d$$

$$\text{depreciation} - W(t) < W_{act},$$

Where W (t) is the forces arising in the structural elements from the effects of useful temporary loads at the time of operation (t);

W_{regul} is the regulatory load capacity;

W_d is the design load capacity;

W_{act} is the actual load capacity.

The reason for the decrease in the actual load capacity of bridges as compared to the design value can be depreciation, including single mechanical or power damages of load-bearing elements resulting in a decrease of the values of their geometric parameters. In addition, the strength of concrete in reinforced concrete structures can change due to changes in its structure. Another factor contributing to the decrease in the load capacity is an increase in the permanent load; for example, due to additional layers of asphalt concrete laid during the operational period. We will discuss further how to take these factors into account.

How can we estimate the load capacity of a bridge in operation and determine the possibility and conditions to pass a particular heavy vehicle (weighing over 45 tons) through it? The following methods are available:

If a bridge is built for AK and NK load (class "K" is equal to 11 or 14), we have to to compare the forces in the load-bearing elements arising from the vehicle under consideration with their actual load capacity at the moment. Also, we select a controlled traffic mode corresponding to the minimum effect on the structure.

If a bridge is calculated using the limit state method for N30 and NK-80 (N10 and NG-60) loads, its class in the AK or NK diagrams is defined as the class of the most loaded load-bearing element using the formula:

$$K = \frac{S_{st}}{S_1}, \quad (2)$$

where S_{st} is the force from the N30 (NK-80) load;

S_1 is the force from the A1 (N1) load.

The class of a particular heavy vehicle is defined in a similar way, as a ratio of the force from the vehicle to the force from the load N1. If it happens that its value is less than the design value, passing this load will not cause any problems. Otherwise, measures will be required to control the traffic mode or even to reinforce the bridge.

The most difficult task is estimating the load capacity of an old bridge designed using the method of permissible stresses, Since the stress diagram in relation to the height of the cross-section of bent elements is built under the assumption of the elastic work of the structure in this method and differs from the diagram adopted in the limit state method (Fig. 1)

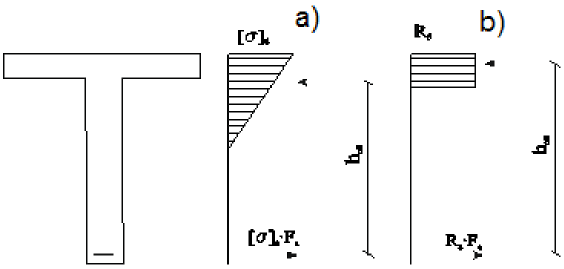

Fig.1. *Stress diagrams in the cross section of a reinforced concrete beam with conventional reinforcement; a) using the method of permissible stresses; b) using the limit state method*

If the dimensions of the cross-section and its reinforcement (for reinforced concrete structures) are known, then its bearing capacity (for span structures, it is represented by the limiting values of the bending moment and transverse force) is determined according to the modern standards. After that, the load capacity is calculated as a difference between the load capacity and the force from permanent loads.

In cases where the reinforcement is unknown and cannot be found using field methods, we can assume in the safety margin that the amount of reinforcement should exactly correspond to the calculations accepted when this bridge was being designed. We have to repeat these calculations and determine the reinforcement in this way. Further, the load capacity is calculated as shown above.

Estimates of ***the influence of various damages on the bearing capacity and, hence, the load capacity*** are given in ODM 218.0.018-05 [4]. But these estimates are of an indirect nature and are not very convincing. For example, study [4] assumes that the transverse stress cracks in the tensile zone of reinforced concrete beams located in steps of less than 0.5 m (the opening is not shown) decrease the load bearing capacity by an average of 20%, which corresponds to a decrease in the load capacity by 30% to 50%. In fact, this statement is incorrect. It is known that cracks in the tensile zone of concrete with an opening of up to 0.3 mm and even up to 0.5 mm (with this step of cracks, there can hardly ever be a larger opening) do not significantly affect the magnitude of the ultimate bending moment.

Their influence can be estimated accurately enough by the degree of reduction of the bending rigidity of the span structure. The actual rigidity is not difficult to calculate based on the results of measurements of the deflections during tests. Most typically, the reduction in the load capacity will not exceed 5% to 10%.

When detecting stress cracks in the tensile zone of concrete larger than 0.5 mm, we should expect the occurrence of a zone of flowage in the reinforcement and a reduction of the useful diameter of individual rods. It is advisable to check this by opening the reinforcement at the crack location.

In compressed elements, such as pier columns, it is advisable to exclude the concrete of the protective layer at the depth of the crack from the working cross-section.

The degree of corrosion damages to the reinforcement of reinforced concrete structures or metal structures is determined by direct measurements.

Fatigue wear cannot be measured directly. It has to be evaluated based on the retrospective analysis of the bridge traffic or based on the fact that the design fatigue durability coincides with the design life of the bridge.

The impact of mechanical damages can be evaluated "from above" by excluding the damaged element from the calculation pattern or, more accurately, by the results of the bridge tests.

The limit state method of calculation assumes that the load capacity is determined by the ultimate limit states and the durability is determined by the service limit states.

Durability is an inherent consumer property of any product. For food products and industrial products, the lower estimate of durability is determined by the warranty period. After it expires, the manufacturer of industrial products is not responsible for its performance; but as for the expired food products, these represent a threat to our health and should be immediately removed from the shelves.

Durability of a bridge or its main elements (foundations, pier columns, span structures, supporting parts, bridge) is referred to as the period of time during which the structure (element) can be operated in the design mode under normal maintenance conditions without any modification or major overhaul.

For new structures, the concept of durability coincides with the concept of design life but certainly on condition of its high-quality design, construction and operation. For structures in operation, it is the remaining time resource (residual service life) which is generally much less than the remaining part of the design life due to obsolescence and, mainly, depreciation of their elements.

The feature of this category in comparison with other consumer properties also should be noted here. The durability of a structure can not be considered in isolation from the rest of its functional properties. Indeed, bridges are multi-element structures, and different elements or groups of elements provide certain consumer properties. For example, the load-bearing elements of a bridge determine its load capacity, the elements of the carriageway determine the traffic capacity and traffic safety. But all these elements, in turn, have different design lives, deterioration rates, and degrees of maintainability. Therefore, it is logical to determine the durability of a structure differentially by the reduction in the level of load capacity, traffic capacity, or traffic safety.

Based on this, we can describe graphically the design, obsolescence, and depreciation criteria of durability for other functional properties (we denote the level of the functional property as W), see Fig. 2 [5].

Experience shows that the most variable in time consumer property and, at the same time, most often determining the nature of operation of bridges is the load capacity. It is applied to the load capacity that the diagrams in Figure 2 are the most evident.

Indeed, when we estimate the trends of increasing the operating loads in time (W_{req} (t) diagram) and determine the economically optimal life T_{regul} of load-bearing structures based on these trends, we obtain the required level of regulatory loads W_{regul} (T_{regul}).

As we have already noted above, during design, some reserves of load capacity are generally added, that is $W_d > W_{regul}$.

Hence, the design life is usually greater than the regulatory one, that is,

$$T_d > T_{regul}.$$

During the operational period, depreciation of structures takes place, and, accordingly, their load capacity decreases, as shown in the W_{dep}(t). Naturally, at the same time their service life T_{dep} is reduced. Besides, the increase in operational loads may be faster than anticipated ($W_{req.ref}$ (t) diagram). A premature obsolescence occurs which reduces the service life to the value of T_{obs}. And finally, the cumulative effect of accelerated growth of operational loads and depreciation results in an even larger reduction in the service life ($T_{dep.obs}$).

When we determine the indicated service life in relation to the load capacity using the results of field studies and calculations, we have an opportunity to choose the strategy of operation of the structure, as well as its repairs and modifications.

The durability criteria are defined as follows:

- design - a regulatory service life is provided;

- obsolescence - the required load capacity does not exceed its design value during the service life;

- depreciation - the required load capacity does not exceed its actual value during the service life.

The residual service lives of structural elements at the time of the research serve as a quantitative evaluation of their durability. It is design life for new bridges.

Thus, in order to evaluate the durability of bridge structures, it is necessary to plot the increase in the operational loads and depreciation of structures in time and extrapolate these diagrams for the entire design life of the bridge.

Let us get into some more detail on the second one of these diagrams.

To date, the ROSDORNII methodology developed by V.I. Shesterikov [3], is relevant.

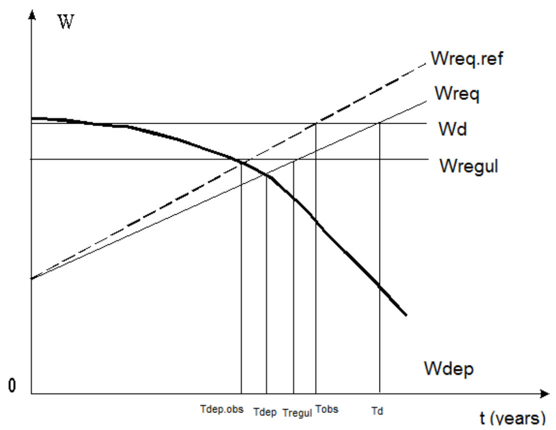

Fig. 2. *The service lives of bridge structures based on different criteria*

W - load capacity; W_{regul} - regulatory; W_d - design; W_{req} - required according to operating conditions; $W_{req.ref}$ - required according to operating conditions, refined; W_{dep} - taking depreciation into account; T_{regul} - regulatory service life; T_d - design life; T_{obs} - service life taking obsolescence into account; T_{dep} - service life taking depreciation into account; $T_{dep.obs}$ - service life taking both depreciation and obsolescence into account.

The depreciation of structures U according to this version is a loss of the load-bearing capacity and is determined by the formula:

$$U(t) = e^{\lambda(t-T)} - 1, \quad (3)$$

Where U(t) is the deterioration in fractions of the bearing capacity at the time t;

λ is the index of deterioration intensity which according to V.I. Shesterikov's data ranges from 0.008 to 0.012;

T is the period of “running-in” (in years), i.e. the initial period of operation when there is no deterioration yet;

t is the current time from the start of operation (in years).

Using this formula, we can determine the residual service life ΔT at the moment t from the condition $U(t) = U_{cr}$, where U_{cr} is the critical deterioration that causes the operation to stop and t_{cr} is the period corresponding to the critical deterioration. If we convert formula (3), we obtain:

$$t_{cr} = \ln(U_{cr} + 1) / \lambda + T ;$$

$$\Delta T = t_{cr} - t. \tag{4}$$

The theoretical value of λ can be refined within the scope of the survey at the moment t_{surv}, if it is possible to fix the actual deterioration U_{surv}. For that, expression (3) should be presented as follows:

$$\lambda = \ln(U_{surv} + 1) / (t_{surv} - T). \tag{5}$$

The durability criteria are associated with critical levels of load capacity, the requirements for their provision and the measures for traffic restriction. There is no single opinion on how to form them yet. The estimates are of an expert nature.

For example, in [3], the threshold deterioration levels are determined depending on the span lengths and the degree of maintainability of the structural elements as follows (table 1).

Table 1. *Threshold deterioration levels for reinforced concrete beams*

Threshold deterioration levels I_{thr} (%) for the elements of span structures overlapping spans L (in light), m				**The parameters of the level**
L ≤ 30	30<L≤60	60<L≤80	L >80	
30	25	20	15	The margin of permissible deterioration which means that the repair of the element is required (the operability limit).
60	50	40	30	The limit of ultimate deterioration, which means that the element is not repairable and its replacement is required

The above methodology does not take into account the possible reduction in load capacity due to single mechanical damages. If any of those exist, then this reduction should be deducted from the threshold levels of deterioration.

References

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