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ON THE ISSUE OF INCREASING THE DURABILITY OF EXPANSION JOINTS OF BRIDGES: ANALYSIS AND MODELING

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ABSTRACT

Introduction. Expansion joints are one of the most important elements of bridge structures that ensure the perception of temperature, shrinkage, creep and operational movements of superstructures. The practice of operating road bridges shows that a significant part of defects in road clothing and load-bearing structures develop precisely in near-collision areas due to the effects of dynamic wheel loads, climatic factors, moisture penetration and deicing agents. Premature destruction of expansion joints leads to a decrease in the transport and operational performance of structures, an increase in maintenance and repair costs, as well as a reduction in the service life of bridges. **Materials and Methods.** The paper analyzes modern designs of expansion joints of road bridges, including open, finger, elastomeric, modular, asphalt concrete (mastic) and integrated systems. The classification of these structures is carried out taking into account the range of perceived movements, operating characteristics, tightness, noise level and operational reliability. Special attention is paid to the causes of characteristic damage, such as the destruction of the edges of the coating, loss of tightness, wear of sealing elements, corrosion of metal parts and the formation of ruts in transition zones. **Results and Discussion.** A scheme of physical modeling of the deformation seam operation on a laboratory bench with reproduction of the effects of wheel loading and control of the stress-strain state of structural elements is proposed. Based on the analysis of operational characteristics, a comparative ranking of the main types of seams was performed in terms of durability, wear resistance, tightness, ride comfort and resistance to operational impacts. An algorithm for selecting a deformation seam system has been developed, taking into account the range of movements, climatic conditions, traffic intensity, tightness requirements and the cost of the life cycle of the structure. **Conclusions.** The results obtained can be used in the design, reconstruction and operation of bridge structures to increase the durability of expansion joints and reduce the cost of their maintenance during the standard service life..

KEYWORDS: deformation seams; bridge structures; durability; operational damage; physical modeling; near-seam zones; tightness; life cycle.

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1 INTRODUCTION

The expansion joints of road bridges are among the most stressed and at the same time the most vulnerable elements of the bridge structure [1]. Their purpose is to ensure free movement of the superstructure relative to the supporting parts and mating sections, to compensate for temperature deformations, shrinkage and creeping changes in concrete, rotary and longitudinal movements, as well as to maintain the operability of the bridge crossing under conditions of repeated dynamic impacts from vehicles [2-6]. At the same time, it is the zone of the deformation seam that most often turns out to be a source of increased noise, local wear, shock loads and coating destruction [7, 8].

Operational practice shows that defects in the seam area are formed not only due to structural flaws in the seam itself, but also as a result of inconsistencies between the type of seam, the level of transport load, climatic conditions, installation quality and the actual maintenance scheme. The most typical types of damage are discoloration of the coating edges, cracking in the transition zone, depressurization, loosening of anchors, loss of elasticity of seals, corrosion of metal elements and local rut formation. In conditions of high traffic intensity and the use of heavy vehicles, these phenomena accelerate and lead to a significant increase in life cycle costs [9, 10, 21-24].

A separate problem is the acoustic effect of passage through the seam. The impact of the wheel on an unevenness formed by a structural difference or wear of the seam elements causes vibration of the superstructure and road surface, increasing the noise level for the driver and the surrounding area. In urban environments, this becomes not only an operational but also an environmental problem [11, 12].

Modern engineering practice requires the deformation seam to perform several contradictory functions simultaneously: ensuring significant movement, maintaining tightness, reducing the dynamic impact on the coating, minimizing noise, high maintainability and durability [13]. In this regard, a comparative analysis of the types of seams, an assessment of foreign experience in experimental modeling, and the development of integral selection criteria are of particular importance, allowing informed decisions to be made at the design and reconstruction stages.

The purpose of this article is to summarize the requirements for expansion joints of road bridges, present a modern classification of structures, systematize foreign experience in physical modeling and experimental approaches to improving the durability of near-seam zones, as well as formulate criteria for choosing seam systems and technological solutions aimed at reducing noise, track formation and wear. The work of Kozlachkov et al. is used as a basis. [1, 5], Valieva et al. [3], Bondareva et al. [7], as well as applied research on OP-DSH-K2 nodes of the C80/F80/E80 class [10].

1.1. Requirements for expansion joints of road bridges

The works of Russian researchers rightly emphasize that the deformation seam cannot be considered as an isolated element. It is part of the unified system "superstructure - transition zone - coating - waterproofing - plate edges - support elements". Therefore, the requirements for it are formulated not only in terms of permissible displacement, but also in terms of interface reliability and operational safety.

The basic requirements include:

- compliance with the range of longitudinal, transverse and angular movements;
- resistance to cyclical effects of transport loads;
- tightness and protection of structures from penetration of water, deicing agents and abrasive particles;
- minimization of dynamic impact during driving;
- absence of unacceptable noise and vibrations;
- adaptability of installation and repair;

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- resistance to climatic and corrosive influences;

- Compatible with the pavement and transition plate system.

Kozlachkov et al. [1] emphasized that the quality of the transition zone, in which the greatest gradients of stiffness and stress are formed, is not so much the determining factor for durability. Efanov and Ovchinnikov [5] emphasized the need to coordinate the seam with the slab structure and the edge sections of the superstructure, since destruction often begins precisely with the edges and the anchoring part.

1.2. Modern classification of seams

The modern classification of expansion joints can be performed for several reasons: according to the principle of operation, the amount of allowable displacement, the degree of tightness, the design scheme and the nature of the interface with the coating. In practice, the most useful classification is performance-oriented.

There are:

1. Open seams - simple in design, but accompanied by strong impact and high noise levels.

2. Closed elastomeric seams – provide smoother passage and tightness, suitable for limited movement.

3. Modular seams - used for large movements, allow significant deformations, but require high accuracy of installation.

4. Asphalt concrete and mastic transition joints - they are characterized by low noise and good smoothness of passage, but they are sensitive to overloads and temperature.

5. Integrated and semi-seamless solutions - aimed at maximum smoothing of the transition and reducing stress concentration.

Valiev, Smolenkin, and Rybnikova (2016) noted that the trend in recent years has been to move from a "point-based" perception of the seam as a mechanical rupture to a systematic approach in which the seam is designed as part of a transition system with controlled rigidity.

1.3. Foreign experience of physical modeling

Foreign research on expansion joints traditionally relies on two complementary approaches: field and bench tests [15, 16]. Field tests allow us to assess the actual behavior of the seam under the influence of traffic flow and climatic factors, but they require a long time. Bench and laboratory tests, in turn, make it possible to rapidly simulate thousands of loading cycles, monitor temperature conditions, humidity, penetration of water and reagents, as well as record changes in stiffness and residual deformations [18-20].

The following types of stands are most common:

- cyclic installations with simulated seam opening and closing;

- wheel-load stands for wear and track formation assessment;

- climate chambers with alternating freezing and thawing;

- combined stands combining mechanical and climatic effects;

- stands for acoustic testing and vibration acceleration measurement.

Bondar et al., (2025), considering the OP-DSH-K2 (C80/F80/E80) nodes, showed that not only the anchoring strength and the quality of the elastomeric element have the greatest effect on durability, but also the stability of the transient stiffness in the near-seam zone. For such systems, it is critical to ensure an even distribution of stresses in the area adjacent to the pavement.

1.4. The main mechanisms of failure

The analysis of literary sources allows us to identify the following dominant failure mechanisms:

- fatigue failure of anchors and connecting elements;

- discoloration and cracking of the transition zone;

- loss of sealing ability;

- accumulation of residual deformation

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and formation of a track;

- separation of sealing materials;
- corrosion of metal parts;
- violation of the adhesion between the joint and the asphalt surface.

The most dangerous is a combination of several mechanisms. For example, if there is insufficient tightness, water and reagents penetrate the structure, accelerating corrosion and weakening the bond between the layers, and then the cyclical action of transport leads to the opening of cracks and accelerated track development.



Fig. 1. Modern classification of expansion joints of road bridges

2 METHODS AND MATERIALS

2.1. Research materials

The material for the study was:

1. domestic publications on deformation seams and bridge transition zones [1; 5, 3, 7];
2. Applied work on OP-DSH-K2 nodes of class C80/F80/E80 [10];
3. generalized information about foreign bench tests and approaches to accelerated modeling;
4. regulatory and technical principles of bridge crossing design used in engineering practice.

The article did not carry out its own field experiments; the work is of a review and analytical nature using comparative analysis,

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expert ranking and normalization of performance indicators.

2.2. Methods of analysis

The following methods were used to achieve this goal:

- comparative analysis of structures and seams according to operational characteristics;
- structural and functional analysis of the seam-transition zone-coating system;
- expert normalization of indicators on a dimensionless scale;
- integrated reliability assessment using weighting factors;
- generalization of the results of poster and field studies based on literature data. The following are accepted as the main evaluation criteria:
- the range of permissible movements;
- Water resistant;
- noise level;
- resistance to rutting;
- wear resistance;
- maintainability;
- durability;
- sensitivity to installation errors.

2.3. The approach to the formation of the integral criterion

An integral indicator of operational suitability is proposed for comparing joint systems:

$$K\int = \sum_{i=1}^{n} w_i \cdot x_i \qquad (1)$$

where x_i – is the normalized score according to the i-th criterion, w_i – is the weighting coefficient, $\sum w_i = 1$.

If the goal is to minimize the risk of failure, then the reverse form is introduced:

$$R_{joint} = \sum_{i=1}^{n} w_i \cdot (1 - x_i) \qquad (2)$$

where a lower value of *R*joint corresponds to a more reliable solution.

The weighting factors are selected based on the importance of the factor for a particular object. For bridges with high traffic intensity and strict requirements for driving comfort, noise, track formation and tightness gain more weight. For objects with large movements, the ability to perceive deformations and maintainability.

2.4. The scheme of physical modeling

Summarizing foreign experience, we can single out a typical test sequence.:

1. production of a seam fragment on a scale of 1:1 or 1:n;
2. imitation of the bearing base and edges of the plate;
3. cyclic opening/closing of the seam;
4. Wheel loading;
5. Introduction of temperature cycles;
6. Exposure to water, salt solutions and abrasives;
7. Measurement of residual deformations, acoustics, stiffness and tightness.

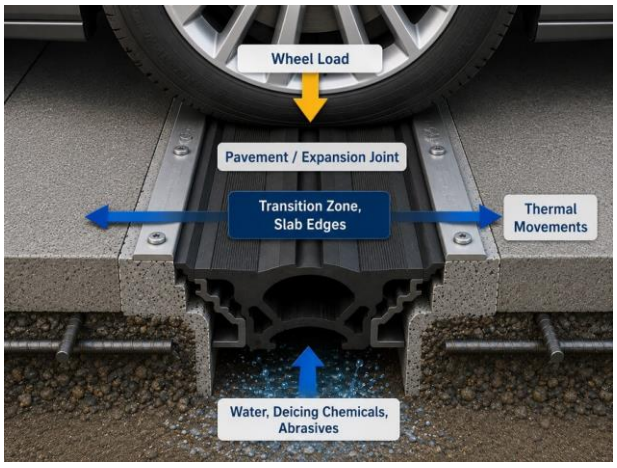


Fig. 2. Diagram of the main impacts on the near area

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Key effects:
- impact during the passage;
- local shifts;
- bending and opening of edges;
- accumulation of fatigue;
- moisture penetration

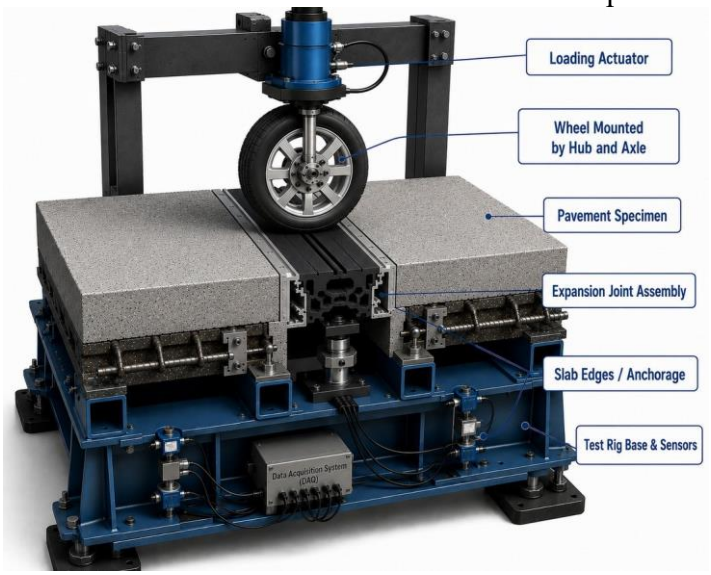


Fig. 3. Typical bench diagram of the physical modeling of a deformation seam

2.5. Parameters to be monitored

During the tests and comparative evaluations, the following are monitored:
- vertical edge movements;
- dynamic accelerations;
- acoustic level;
- track width and depth;
- residual deformation;
- coefficient of water permeability;
- loss of mass or wear of materials;
- rigidity of the transition zone;
- resistance of joints to delamination and tearing

3 RESULTS AND DISCUSSION

3.1. Summary classification and operational properties

A generalization of the literature data has shown that no type of suture is universal. The choice always depends on the range of movements, the durability of the coating, the climatic zone, the permissible noise level and the availability of maintenance.

Table 1. Modern classification of expansion joints of road bridges

Joint Type	Allowable Movements	Watertight-ness	Traffic Noise	Main Application Area	Key Disadvantages
Open Gap Joint	High	Low	Very High	Temporary solutions, auxiliary structures	Impact loads, noise, water penetration
Finger Joint	High	Low to Moderat e	High	Large move en ranges	Complex maintenance, high noise levels
Elastomeric Strip Joint	Low to Moderate	High	Low	Urban and highway bridges	Limited movement capacity

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Modular Joint	High	High	Moderate	Long-span bridges, large movements	High cost, demanding installation requirements
Asphaltic Plug Joint	Low	High	Low	Locations requiring high ride comfort	Sensitive to overloading and temperature variations
Integrated (Semi-Seamless) Joint	Low to Moderate	High	Very Low	Bridge rehabilitation and new bridge construction	Increased requirements for transition zone design

It follows from the table that an increase in operational quality is achieved primarily by reducing the hard gap in the road pavement. The smoother the transition between the slab and the seam, the lower the dynamic load and noise.

3.2 Comparative assessment of systems based on key indicators

To normalize the results, a conditional scale of 1-5 was used, where 1 is the worst value, 5 is the best. The assessment is of a generalized expert nature and reflects the typical behavior of systems.

Table 2. Comparative assessment of expansion joint systems based on performance indicators

Joint System	Noise Level	Rutting Resistance	Wear Resistance	Waterproofing Performance	Maintainability	Overall Score
Open Gap Joint	1	1	1	1	2	1.2
Finger Joint	2	2	2	1	2	1.8
Elastomeric Strip Joint	4	3	3	5	4	3.8
Modular Joint	3	3	4	4	2	3.2
Asphaltic Plug Joint	5	4	3	4	3	3.8
Integrated (Semi-Seamless) Joint	5	5	4	4	3	4.3

The results show that, based on a combination of characteristics, integrated and asphalt concrete solutions are the most attractive if the range of movements and operating conditions allow their use.

Modular systems remain indispensable for large movements, but their effectiveness directly depends on the accuracy of installation and the quality of subsequent maintenance.

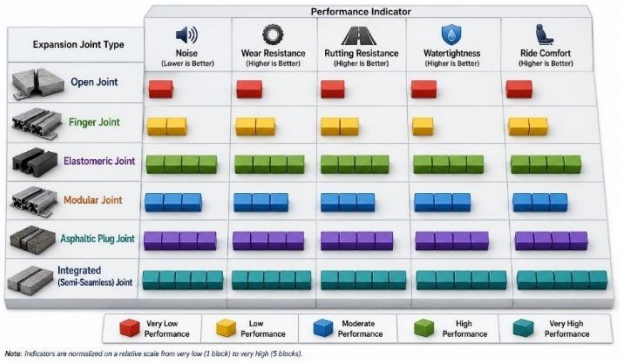


Fig. 4. Comparison of normalized performance indicators of the main types of seams

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3.3 Summary of Bench Test Designs

Analysis of foreign and applied research allows us to identify the most informative schemes for accelerated testing

Table 3. Summary of test bench schemes for expansion joints

Test Setup	Primary Objective	Loading Type	Monitored Parameters	Advantages	Limitations
Cyclic Joint Opening/Closing Test	Assessment of fatigue performance and water-tightness	Linear displacement cycles	Residual deformation, crack formation, watertightness	Accurately simulates thermal movements	Does not account for wheel impact loads
Wheel-Loading Test Rig	Evaluation of wear and rutting resistance	Rolling wheel load	Rut depth, vibration, noise	Closely represents real traffic conditions	Requires complex calibration
Climatic Chamber with Mechanical Loading	Evaluation of frost resistance	Freeze–thaw cycles	Mass loss, cracking, water permeability	ncorporates environmental effects	Time-consuming preparation
Combined Water–Salt –Load Test Rig	Durability assessment under aggressive environmental conditions	Repeated combined loading cycles	Corrosion, delamination, watertightness	Reflects actual winter service conditions	High labor intensity
Impact-Dynamic Test Rig	Evaluation of ride comfort and noise generation	Short-duration impact loading	Accelerations, acoustic response	Effectively identifies peak dynamic effects	Limited representation of overall performance

Physical modeling shows that the combination of dynamic load with moisture penetration and the subsequent temperature cycle is the most destructive. It is this combination that accelerates the development of latent defects in the anchoring, transition layer and edge zone.

3.4. Durability of near-seam zones and the role of structural parts

According to the data of the reviewed works, the durability of the seam is determined not only by the gap closure element itself, but also by the quality of the plate edges, anchor nodes, transition layers and waterproofing [14, 17]. They are particularly sensitive:

- areas with a sharp change in stiffness;
- zones of local stress accumulation;
- places where the sealing material does not fit properly;
- insufficiently compacted layers of asphalt concrete;
- areas where the installation sequence is disrupted.

The following engineering tasks are relevant for OP-DSH-K2 type nodes

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(C80/F80/E80):

1. stabilization of the contact surfaces in the abutment area;
2. Reduction of micro-movements leading to abrasion;
3. Ensuring reliable drainage;
4. Increased resistance to repeated deformation cycles;
5. Reducing stress concentrations in anchors and edge elements.

In applied research on such systems, it is emphasized that even a relatively "strong" seam loses its functionality due to insufficient preparation of the substrate or poor sealing of joints. Therefore, durability should be assessed as a property of the entire coupled system, rather than as a characteristic of a single product.

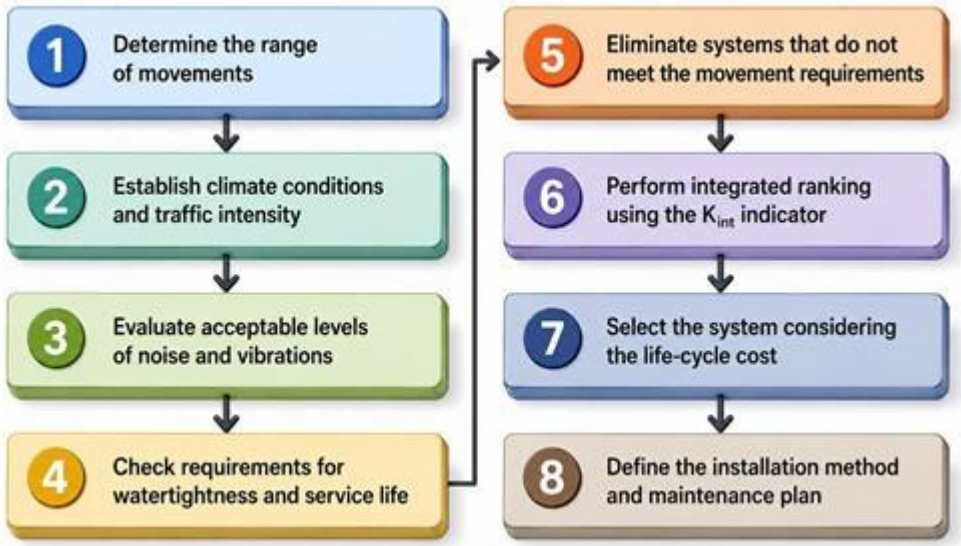


Figure 5. Algorithm of selection of the deformation seam system

3.5 Integral metrics of operational reliability

For practical purposes, it is proposed to use a set of integral metrics combining various durability factors. The most informative were:

- coefficient of operational suitability K_{int};
- risk of failure R_{joint};
- travel comfort index I_{comf};
- Water protection index I_{seal};
- the index of repair availability I_{maint}.

Table 4. Integral evaluation criteria and recommended weighting factors

Performance Indicator	Symbol	Normalization	Weight (w_i)	Comment
Compliance with Movement Range Requirements	x_1	0–1	0.20	Mandatory design constraint
Waterproofing Performance	x_2	0–1	0.20	Critical for deck protection
Noise Level	x_3	0–1	0.10	Important in urban environments
Rutting Resistance	x_4	0–1	0.15	Affects ride quality and service life
Wear Resistance	x_5	0–1	0.15	Determines long-term durability
Maintainability	x_6	0–1	0.10	Influences life-cycle cost

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Compatibility with Installation Technology	x_7	0–1	0.10	Reduces the risk of installation defects

Recommended interpretation of the integral indicator:

- Kint ≥0.80 is a highly reliable solution;
- 0.65 ≤Kint <0.80 is a satisfactory solution;
- 0.50 ≤Kint <0.65 – solution of limited applicability;
- Kint <0.50 – not recommended for responsible facilities.

The results obtained confirm that the key problem of deformation seams of road bridges is not the presence of a gap as such, but the method of its engineering "smoothing". It is the abrupt transition of stiffness that causes a dynamic impact, which then transforms into noise, vibration, coating destruction and accelerated wear of the seam elements.

A comparison of the types of seams shows that open and finger designs remain relevant only where increased noise and maintenance costs are acceptable, or where large movements do not allow the use of softer systems. For modern urban and mainline facilities, the priority is shifting towards solutions with a smooth transition: asphalt, mastic, elastomeric and integrated. However, such a choice is possible only if the device technology and quality control are strictly adhered to.

The issue of track formation in the transition zone deserves special attention. The track observed in practice is formed not only from the actual vertical load, but also from the local "swing" of the edge, due to which the load on the coating is unevenly distributed. Therefore, reducing fracture stiffness and increasing joint stability are more important than simply increasing the strength of the coating material.

From the perspective of foreign experience, the most valuable is the systematic nature of the tests. On the stands, not one factor of destruction is reproduced, but a combination of loads: displacement, wheels, moisture, temperature and reagents. This makes it possible to identify hidden degradation mechanisms that are difficult to notice in a short field observation. This approach is especially important for Russian conditions, since bridge crossings operate in a wide range of climatic zones, including freeze-thaw cycles and the use of deicing materials.

When analyzing the OP-DSH-K2 (C80/F80/E80) nodes, it can be concluded that a further increase in durability is primarily due to:

- more precise adjustment of the transient stiffness;
- improvement of anchoring nodes;
- reduction of micro-movements;
- improving the sealing quality;
- the introduction of constructive measures to dampen the impact.

In other words, the durability of the seam should be ensured not only by the material, but also by the architecture of the system. This is the main conclusion that unites domestic and foreign studies [25, 26].

The proposed integral criterion, although based on expert normalization, is useful as a pre-selection tool. It allows you to filter out solutions that do not correspond to a given range of movements, and then compare the remaining options based on a set of lifecycle parameters. This is especially important for the designer, since the cost effectiveness of the seam is actually determined not by the initial price, but by the total costs of maintenance, repair and time restrictions on movement.

It is also practically significant that noise and durability are often interrelated. Solutions that ensure smooth travel typically simultaneously reduce dynamic peaks and thus extend service life. Therefore, noise reduction is not only an environmental, but also a constructive measure to increase the resource.

At the same time, it should be emphasized that there is no completely "universal" seam. Integrated and asphalt-concrete solutions are excellent in terms of comfort, but limited in movement. Modular

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systems are indispensable for large openings, but they are sensitive to installation and require careful monitoring. Therefore, optimization should be carried out not by one indicator, but on the basis of a multifactorial assessment.

4 CONCLUSION

The performed analysis showed that the deformation seams of road bridges should be considered as a key element of the bridge crossing, which simultaneously affects the bearing capacity, durability of the coating, noise and traffic safety.

The main conclusions are as follows:

1. The modern classification of expansion joints should be based on their operational properties: displacement, tightness, noise, maintainability and resistance to dynamic influences.

2. The greatest problem is near-seam zones, where a sharp drop in stiffness, shock loads and exposure to water, reagents and abrasives are combined.

3. Foreign experience confirms the effectiveness of physical modeling on stands where mechanical and climatic factors work together.

4. The most promising solutions are those that ensure a smooth transition and reduce local stiffness, including asphalt, mastic, elastomeric and integrated seams.

5. To select a seam system, it is advisable to apply an integral criterion that takes into account movement, tightness, noise, rut formation, wear resistance, maintainability and compatibility with the installation technology.

6. The priority in the design should shift from the assessment of the seam itself to the assessment of the entire coupled system "seam - transition zone - coating - plate edge".

Thus, an increase in the durability of expansion joints of road bridges is achieved not by a single constructive measure, but by a combination of rational choice of the type of seam, high-quality preparation of the seam zone, strict adherence to installation technology and regular monitoring in operation. This is especially important for objects with high traffic intensity, including OP-DSH-K2 (C80/F80/E80) type nodes, where the requirements for tightness, comfort and resource are particularly high.

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