The article deals with the issues of vehicle traffic safety on artificial constructions. Ensuring safety in the field of rail transport is an essential element in the activities of all subjects of the market of railway services, including passenger carriers. To fully study the issues of the deformed state of beam superstructures, it is necessary to conduct static and dynamic tests. Before the start of the tests, it is mandatory to check the technical condition of the artificial structure:

1) visual inspection, special checks with verification of necessary parameters;

2) carrying out control linear measurements;

3) selective determination of concrete strength by non-destructive methods.

First, the static tests is conducted to determine the total deformations of each beam of the superstructure at the control point with maximum deformations of ½ L. Then dynamic tests with determination of periods of natural oscillations and deformations (stresses). Processing of the results of surveys and tests of the overpass with an assessment of the possibility of passing design loads on the road bridge, after which a dynamic passport of the transport structure is compiled. The study of the stressed state of vehicles gives a clear idea of the causes of deformations in the structural elements when analyzing the work of the span of the automobile bridge in conditions of increasing axial loads and traffic flow speeds. Deformation processes lead to defects, structural failures and accidents on the vehicle, which leads to premature wear, material damage and environmental damage. Periodic measurements of deformations (stresses) of the superstructure structure over several years will make it possible to predict changes in its condition over time and determine the remaining resource in terms of load-bearing capacity and load capacity. As a result of experimental studies, it was proved that the presented technique, developed in the classical version for detecting structural defects between a single-layer coating and a base of various types, can also work effectively in the case of non-destructive testing of multilayer structures

Keywords: safety, road bridge, stress condition, technical inspection, static and dynamic tests

UDC 624.21:620.178:534

DOI: 10.15587/1729-4061.2022.255275

INFLUENCE OF THE DEFORMED STATE OF A ROAD BRIDGE ON OPERATIONAL SAFETY

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Received date 21.02.2022
Accepted date 18.04.2022
Published date 28.04.2022

How to Cite: *Bondar, I., Kvashnin, M., Aldekeyeva, D., Bekzhanova, S., Izbairova, A., Akbayeva, A. (2022). Influence of the deformed state of a road bridge on operational safety. Eastern-European Journal of Enterprise Technologies, 2 (7 (116)), 29–34. doi: https://doi.org/10.15587/1729-4061.2022.255275*

1. Introduction

Artificial structures of the transport industry in terms of strength, reliability, stability, cost-effectiveness of maintenance and timing must meet current modern technical requirements and ensure the passage of modern loads with established speeds. This is ensured when organizing and performing work on their current maintenance and major repairs.

In recent decades, the current maintenance of artificial structures has been mainly aimed at eliminating existing malfunctions, and work to prevent the appearance and further development of new malfunctions and defects has not been carried out enough.

In addition, the long-term operation of artificial structures, many of which serve for about 100 years, despite the ongoing work, has led to significant physical wear of their structures and elements, and, ultimately, to the loss of design operational parameters, i.e., to a decrease in operational loads, restrictions on permissible speeds. Many artificial structures are designed according to the regulatory documents previously in force for the construction period for other operational loads and erosion phenomena.

A significant number of artificial structures need a comprehensive assessment of their operational reliability due to increased operating loads and speeds of rolling stock.

Numerous cases of deformation of artificial structures in the transport industry under conditions of increased operating loads determine the need to solve the problems of timely identification of the nature and causes of deformations in the elements of structures. This is due to the fact that the destruction and accidents occurring due to deformation processes cause enormous economic, social and environmental damage, incomparable with the funds spent on protective measures.

In the world practice there are many cases when due to incorrect maintenance and operation of artificial constructions, in particular bridges, their poor quality repair or repair with deviations from construction standards and rules their destruction and collapse occurred. Sometimes with human casualties.

Therefore, studies devoted to the study of the deformed state of the road bridge during the acceptance tests are relevant.

The issues of safe operation of artificial structures of transport infrastructure are of paramount importance for the transportation of goods and passengers. A significant number of man-made structures need a comprehensive assessment of their operational reliability due to the increase in traffic loads and speeds [1].

In addition, at present, in accordance with the strategy for the development of the transport system of the Republic of Kazakhstan until 2030, the construction of new and reconstruction of existing railways, as well as infrastructure modernization are being carried out. One of the directions of the strategy is to ensure the necessary level of reliability of artificial structures, which have a significant impact on road safety [2, 3].

Numerous cases of deformation of artificial structures in the transport industry under conditions of increased operational loads determine the need to solve the problems of timely identification of the nature and causes of deformations in structural elements. [4, 5].

The necessity of this experiment lies in the fact that destructions and accidents occurring due to stressful processes cause enormous economic, social and environmental damage, incomparable with the funds spent on protective measures [6].

2. Literature review and problem statement

The article [1] shows the device and equipment used to inspect and test bridges and diagnose the soil of the railway embankment in order to ensure their safe operation. The method of vibration diagnostics of the upper structure of the track, girder spans of railway bridges and access embankments to bridges, high railway embankments and embankments on weak foundations is described.

The paper presents some results of measurements of bending deformations of reinforced concrete bridge spans during train traffic with an analysis of the influence of the rolling stock on its stress-strain state. Ensure the safety of rail transport infrastructure in accordance with the requirements of technical regulations, increase the service life and reduce the cost of routine maintenance of track and artificial structures.

A random reduction algorithm is used to estimate the impulse response of the tower displacement, to extract the dynamic characteristics. Dynamic properties and analysis of statistical time series of measurements show that transport loads have a significant impact on semi-static and dynamic characteristics [2].

In [3, 4] the procedure of damage identification in bridge structures equipped with insulators and/or energy dissipation devices is considered, and the method of damage detection in bridge structures equipped with insulators (energy dissipation devices) is discussed. The technique is based on accelerometer sensors installed on existing bridges, which provides an assessment of the deterioration of the characteristics of structural elements, as well as installed insulators and energy dissipators obtained by changing the characteristics of the modal response of the structure. This information can be used to develop plans for inspection and maintenance of man-made structures.

The article [5] describes standards covering most of the in-situ monitoring methods and defines appropriate technical parameters for monitoring high-rise structures, spatial structures with large spans, bridges and structures with isolated foundations. The article presents a comprehensive overview and a linear comparison of existing norms and standards for monitoring the condition of structures.

A brief overview foreign publications on accidents of bridge structures is given and examples of accidents on bridges are given, the main causes of which were: underestimation of wind load and aerodynamic instability; loss of stability of elements; errors in the technology of construction, installation and repair work [6].

The paper [7] presents some results of instrumental measurements of dynamic coefficients and fiber stresses of reinforced concrete girder superstructures of railway overpasses under mobile load. The appearance of defects in bridge structures during operation is inevitable, therefore, the issue of strengthening damaged bridge structures is relevant for civil engineers at present. The purpose of these studies is to monitor the stress-strain state of the railroad overpass to detect and correct defects in the early stages. The results of calculations performed by the finite element method (FEM) in the ABAQUS/Standard program correlate well with the experimental data.

The article [8] presents some results of instrumental measurements of dynamic coefficients and stresses in the fibers of reinforced concrete girder spans of railway overpasses under moving load. The article [9] shows the need to use mobile measuring computer systems when performing bridge diagnostics, and also provides an analysis of the amplitude-phase-frequency characteristics of frame reinforced concrete and metal spans of railway bridges during train movement. Comparing the width of the obtained ranges with the ranges of new (undamaged) superstructures, it is possible to assess the degree of wear and the degree of damage to structural elements. According to the results of calculations, it was confirmed that the inclusion of elements of the bridge bed and the upper structure of the track in interaction with the main load-bearing structures increases the accuracy of solving the problem of determining natural frequencies.

The article [10] discusses the results of the computational analysis of the load-bearing structures of overpasses with a single-track railway line. The stress-strain states obtained in the elements of reinforced concrete superstructures and intermediate supports at specified loads using spatial finite element models allow them to be compared with the normalized range of loads and the level of real stability and reliability of bridge objects. At the same time, there is also a need to monitor such conditions in order to maintain the viability of the operated structures.

The purpose of the article [11] is to analyze the reinforced concrete railway overpass as a whole and its elements separately. The article presents calculated and experimental data on the forms and frequencies of natural vibrations of reinforced concrete railway trestles under constant loads and removal of rolling stock from the superstructure. These studies can be further used in the design of artificial structures, as well as to identify defects in the structural elements of railway bridges.

In [12], the stress-strain state in the structural elements of reinforced concrete superstructures of railway overpasses under the influence of their own weight and time load was investigated on the basis of experimental and numerical methods. The results of the study of the stress-strain state in the girder reinforced concrete superstructures of the overpass can be used to calculate the seismic resistance and stability of similar structures with an increase in the operational load on railway bridges. The need for periodic monitoring of the stress and strain state of artificial structures under operational loads in order to determine the actual technical state of the structures, effectively assess the reliability of bridge structures and establish compliance between the design scheme and the actual operation of transport structures, which will improve operational safety.

In the design of new bridges, operation and reconstruction of existing bridges, to ensure the necessary reliability of structures, assessment of the dynamic effects of loads on the beam spans of bridges has a great importance.

There are methods and technical means designed to assess the actual condition of the structure. In practice, there are various ways of loading the tested structure using appropriate devices and equipment based on digital technology, constantly improving for the purpose of obtaining the most complete and reliable information.

Dynamic tests are studies that allow the actual stress and strain state in the existing load-bearing structures of bridges under the dynamic effects of temporary moving loads on the beam spans.

These studies are carried out with the help of experimental methods using hardware-software systems, in which measurements of the parameters of the bridge state are made while moving over the bridge of the moving load, as well as using theoretical methods simulating the impact of moving loads on the girder spans of bridges.

3. The aim and objectives of research

The aim of research is to identify the influence of the deformed state of a road bridge on operational safety

To achieve this aim, the following objectives are being solved:

– the calculation values of natural vibration frequencies for metal spans with defects and without defects;

– study the deformation processes in structural elements.

4. Materials and methods

Before inspecting and testing the girder spans, it is necessary to perform finite element calculations. The calculated values of the controlled parameters, for example, stresses in the structural elements of the superstructure, can be determined both by engineering methods and with the help of specialized computational software systems implementing finite element methods (MIDAS Civil, APM Civil Engineering). The advantage of using finite element models is the ability to simulate various malfunctions in the structure, adapting the calculation results to real operating conditions. By the deviation of the actual stresses from the calculated values, it is possible to judge the degree of damage to the bridge superstructure structures.

Then the following main supporting structures and structural elements were inspected and undergone special examination: superstructure beams, support parts, shore and intermediate supports including extensions and sub-frameworks, road floor and expansion joints.

After the inspection, random control measurements are made in several cross-sections along the length of the structure to obtain average measurement values. No defects were detected that reduce the durability, load-bearing capacity and limiting load-bearing capacity of the main structural elements of the spans and supports.

Static tests: during static tests, the deflections of the span structures were measured in the middle of the span. The purpose of the tests was to investigate the compliance of the deformed state of the structure with the design assumptions and to assess whether the bridge can be accepted for operation under the design loads.

Dynamic tests: the purpose of the tests was to determine the periods of natural vibrations of the spans in the vertical and horizontal planes and assess the influence of roadway irregularities on its dynamic characteristics. Disturbing dynamic forces in the form of periodically repeated pulses were created by passing the thresholds of a three-axle truck.

Numerous cases of deformation of objects of the transport complex in conditions of constant increase in transport, including heavy, which directly affects the causes of deformations in structural elements. This can lead to internal damage due to deformation processes. In order to avoid accidents on artificial structures, it is necessary to take into account the technical characteristics that affect the strength, reliability and stability of the transport structure as a whole.

Upon conducting a man-made construction examination as a whole, bridge spans tests over the river Yessil were conducted. Static tests of the span No. 2 in the axes of supports No. 2 and No. 3. The testing was conducted in December 2017. The work was carried out during the daytime in light windy weather, at air temperature of minus 12 °C, the duration of tests – 5 hours.

In order to specify the deflections during loading and unloading of the span structures, "Maximov" system PM mechanical deflectometers were used. Scale interval of the testing devices is 0.1 mm, the indication accuracy is ±0.1 mm. The layout of the test instruments is shown in Fig. 1.

For test load the loaded HOWO dump trucks with a gross weight of more than 38 tons loaded with crushed stone were used, Table 1.

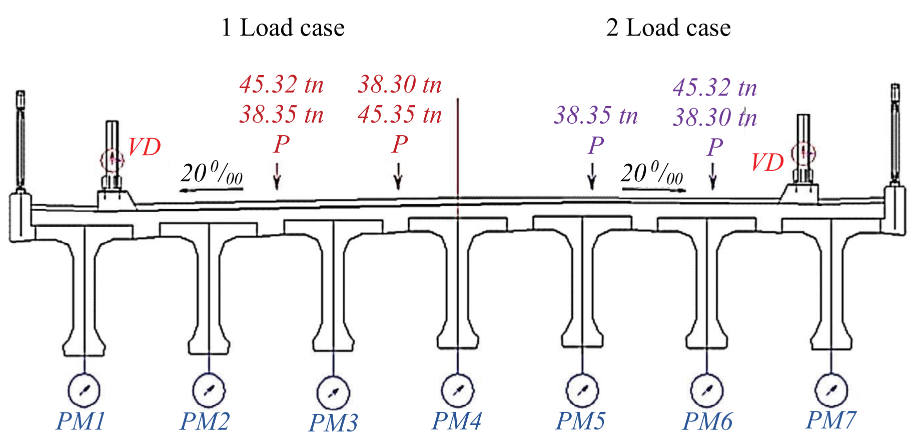

Fig. 1. Testing instruments Layout PM1...PM7 – mechanical deflectors of "Maximov" system; VD – sensitive vibration sensor – 2-axis accelerometer; P – test load, loaded HOWO dump trucks loaded with crushed stone

Table 1

Weight of each test load vehicle

Vehicle License Plate	Actual weight of the test vehicle, kg
869 AN 04	38 350
269 ADA 03	45 350
851 AN 04	38 300
993 AN 04	45 320

The total actual weight of the test load is 167.32 t. The discrepancy between the calculated and actual load does not exceed 1 %, which corresponds to p. 6.2.4 ST RK1856-2008. Test load was set according to previously developed loading schemes:

Case 1. Four trucks were installed with a collision with the safety lane on the right side of the traffic.

Case 2. Three trucks were installed with the safety lane collision on the left side of the travel direction (Fig. 2).

Fig. 2. Scheme of loading the bridge span with test load Case 2. Three trucks are installed on the left side in the direction of travel with a collision with the safety lane

The test load intensity was 70–80 % of the design load with a full dynamic coefficient, as it is stipulated by SP RK 3.03-113-2014.

At carrying out bridge structures static tests acceptance, the main criterion for the positive operation of the spans is the compliance of the elastic deflections of the beams measured under the test load with the values of deflections determined by calculation from the action of the same test load [7–9].

Such an indicator of span girder performance is the structural coefficient determined by the formula:

$$K = \frac{S_e}{S_{cal}}, \quad (1)$$

where S_e – the deflection measured under the test load; S_{cal} – the deflection determined by calculation from the test load.

Pursuant to the static tests results, the structural coefficient K values for the main load-bearing structures are, as a rule, from 0.7 to 1.0.

Calculation of the span on the action of the test load was carried out by the spatial design scheme using the multiparametric method of finite elements with the Midas Civil 2016 for Windows software package [10, 11].

Calculated loads according to ST RK 1380-2005 "Loads and impacts", A14; NK-120 and NK180 on the road III technical category, the load from pedestrians was accepted according to SP RK 3.03-112-2013. The calculation model consists of rod finite elements of the "Beam" type and nodes (Fig. 3).

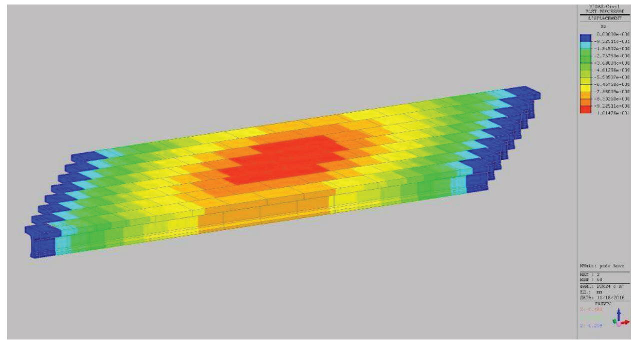

Fig. 3. Calculation model of the bridge superstructure

In the span cross-section is a diaphragmless structure, for the construction of the influence lines, the cross-section will be considered as a continuous beam on elastic settling supports, which are the main beams. Lines of influence of pressures on the beams should be plotted as lines of influence of support reactions of beams on elastic supports.

Dynamic tests. To record vibrations of the span structure in the middle of its span on the roadway, a sensitive vibration sensor – 2-axis accelerometer VD, which is part of the multifunctional measuring complex TENZOR (Fig. 4), which recorded its vibrations in the vertical direction and in the horizontal – longitudinal and transverse directions, was installed. The oscillations of the span were recorded at vehicle speeds of 5, 10 and 20 km/hour.

Fig. 4. General view of the measuring complex "Tensor MS"

The method of monitoring a road bridge is based on a set of indicators that determine the amplitude-phase-frequency characteristics under the dynamic impact of vehicles. Monitoring algorithms provide for the possibility of developing a solution to reduce or increase the speed of traffic flow if the prevailing frequencies fall into the "dangerous" range. This has a positive effect on the safe operation of the transport infrastructure as a whole.

5. Research results of the influence of deformed state of a road bridge on operational safety

5. 1. The calculation values of natural vibration frequencies for metal spans with defects and without defects

The use of digital technologies in the measurement and analysis of stresses in the elements of bridge spans from the effects of various heavy traffic flow makes it possible to identify the most defective superstructure and reduce the speed limit on this transport facility in advance.

The calculated values of natural vibration frequencies for metal spans of 27 m and 33.6 m with defects and without defects are presented in Table 2.

Table 2

Calculation values of natural frequencies of girder metal spans

No.	Design span, m	27.0	33.6
	Existence of the defect	Frequency, Hz	Frequency, Hz
1	No	6.27	5.86
2	Ulcerous corrosion	5.38	4.61
3	Corrosion damage of main span girder links	4.32	4.25
4	Disorder or lack of rivets and high-strength bolts 10%	5.22	4.66
5	Fatigue cracks or pitting cracks	3.68	3.71

5. 2. Influence of deformation processes in structural elements on the strength, reliability and stability of the structure

Table 3 shows the design characteristics of metal girder spans with and without defects.

Table 3

Comparison of design characteristics of defect-free and defective metal girder spans

Characteristics of the girder span structure		Stress in the upper belt, MPa	Stress in the bottom chord, MPa	First natural frequency, Hz/Period, s
Metal girder 27.0 m	Flawless	–53.81	51.14	6.27/0.159
	Fatigue cracks	–87.21	85.84	3.68/0.272
Metal girder 33.6 m	Flawless	–78.45	81.24	5.86/0.171
	Fatigue cracks	–99.93	101.25	3.71/0.270

The measured deflections in the spans under the heaviest loads and their corresponding theoretical values with design factors are given in Table 4.

Table 4

Values of the measured deflections and design factor K for the main load-bearing structures

Test object	Deflections for the most loaded beam, in mm		Coefficient, K
	Measured	Theoretical	
Bridge over the Yessil River Case 1	5.2	6.0	0.86
Bridge over the Yessil River Case 2	1.7	1.9	0.89

Depending on the nature of defects in the load-bearing structure of the bridge, it is possible tomake decisions about the possibility of passing heavy moving loads on the structure with or without limiting the speed of traffic.

During the tests, as parameters that characterize the technical condition of the span structures were proposed:

– first frequency (period) of natural vibrations of girder metal and reinforced concrete bridge spans;

– relative deformations (stresses) of bridge girder spans in the middle of the span.

6. Discussion of the research results of the stress-strain state of the overpass

The result of using the techniques is the assessment of the technical condition of girder spans of railway bridges, defined by two types of condition – defect-free (when the girder spans have no defects that reduce its carrying capacity, i.e. serviceable) and defective (when according to the results of the examination and testing, the measured values: natural frequencies (periods), the coefficient of relative damping and relative strains (stresses), made in accordance with the requirements of regulatory documents can diagnose the presence of the defect).

The results obtained (Table 3) can be explained by the presence of defects (cracks) in the compressed zone of the span.

In particular, the compressive stress (87.21 MPa) in the upper chord of the metal beam with a calculated span of 27 m in the presence of fatigue cracks is 38 % higher than similar stresses (53.81 MPa) for an undefective structure. The presence of fatigue cracks in the structure of a metal beam with a calculated span of 33.6 m leads to an increase in the corresponding compressive stresses (78.45 and 99.93 MPa) by 21 %. The tensile stresses (85.84 MPa) in the bottom chord of a 27 m long steel beam with fatigue cracks are 40 % higher than those in a zero-defect structure. The presence of fatigue cracks in the steel beam design span of 33.6 m leads to an increase in the corresponding tensile stresses (81.24 and 101.25 MPa) by 20 %.

The peculiarity of the proposed method is the use of strain gauges based on foil with an enlarged base. It should be noted that the strain gauge method of measuring strains and stresses in structures is the most accurate and proven method, and in determining small deformations under dynamic influences is virtually the only one and is used in all developed countries of the world. This method should not be used if there is limited access to the installation site of load cells and mounting equipment, as well as in case of possible violations of safety rules and protection during the work.

The disadvantage is electromagnetic interference, which creates interference when recording the process of transport cargo impact at a frequency of 50 Hz, which must be taken into account when processing the results using mathematical filters.

The development of this study makes it possible to conduct periodic monitoring of superstructures with an assessment of the dynamics of its change. Naturally, there is no data on the initial condition for old structures, but complex monitoring can already be carried out on newly constructed structures and structures after major repairs or reconstruction. In the future, a system of continuous automated monitoring can be deployed on large and extracurricular facilities, especially in unsatisfactory or emergency condition. The most time-consuming process affecting the accuracy of measurements is the protection of load cells from external climatic influences.

The analysis of the deflection growth graphs shows that the growth in straining occurs in degrees proportional to the applied load that indicates the joint work of the elements of the span structure in the elastic stage [12].

However, after removal of the loads, insignificant residual strainings – no more than 0.5 mm – were observed immediately, the possible causes of their occurrence could be compression of polyurethane support parts at negative temperatures. But within 5 minutes the residual deformations did not exceed 0.2 mm, which indicates the elastic work of polyurethane support parts.

Pursuant the requirements of the applicable standards SP RK 3.03-112-2013 in the spans of the city bridges, the periods of natural vibrations in the girder systems should not be within the range from 0.45 to 0.60 seconds in the vertical and from 0.9 to 1.2 seconds – in the horizontal plane. The results of dynamic tests showed that the periods of natural vibrations of the span in the horizontal plane are: across the axis of the bridge to 0.15 sec, along the axis of the bridge – 0.11 sec, and in the vertical direction of about 0.2 sec.

The results of dynamic tests showed that the periods of natural vibrations of the span do not fall into the forbidden ranges and meet the requirements of applicable regulations.

The assessment of the possibility of the structure operation under the design loads is based on the results of the tests on the following factors: the increase of deflections occurs in proportion to the applied load; the design factor K of the deflections is less than unity; the periods of natural vibrations of the span do not fall within the forbidden range and meet the requirements of the current regulations; there were no incomplete works preventing the operation of the structure.

7. Conclusions

1. The analysis of quantitative values of natural vibration frequencies for metal spans of 27 m and 33.6 m showed:

– the greatest drop of quantitative values of natural vibrations (from 6.27 to 3.68 Hz for the beam of 27.0 m and from 5.86 to 3.71 Hz for the beam of 33.6 m) occurs in the presence of fatigue cracks or piercing cracks in the span (by 41 % and 37 %, respectively, for the beams with designed spans of 27.0 and 33.6 m);

– the lowest drop in the quantitative frequency values (from 6.27 to 5.38 Hz) of natural vibrations for the 27.0 m girder was observed in the presence of ulcerated corrosion in the span, and the vibrations for the 33.6 m girder when 10 % of rivets and high strength bolts were disturbed or missing. The frequency drop was 14 % and 20 %, respectively, for the 27.0 m and 33.6 m spans.

2. Compressive stress in the upper chord of the metal beam with a calculated span of 27 m in the presence of fatigue cracks is 38 % higher than similar stresses for an undefective structure. The tensile stresses in the bottom chord of a steel beams this length with fatigue cracks are 40 % higher than those in a zero-defect structure. The presence of fatigue cracks in the structure of a metal beam with a calculated span of 33.6 m leads to an increase in the corresponding compressive stresses by 21 %. The presence of fatigue cracks in the steel beams this length leads to an increase in the corresponding tensile stresses by 20 %.

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