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Practical notes for assessing the fatigue life of bodyworks of buses and trolleybuses

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Abstract

When developing a new vehicle, the prescribed fatigue criteria must be met in all important structural nodes of the vehicle bodywork. Maximum stress amplitudes (stress ranges) must be lower than permissible values when the vehicle crosses significant road unevenness. The development stages are: 1) projecting and design of vehicle; 2) investigation of vehicle function sample on test stand; 3) measurement of vehicle prototype. In case the prescribed condition is not fulfilled, it is necessary to recommend a modification of the vehicle bodywork. In any case, it is necessary to know the fatigue properties for various structural and technological variants of the body sections. These properties can be determined in advance by laboratory fatigue tests. The paper describes the assessment of fatigue life in successive phases of vehicle development and presents the results of fatigue tests of several variants of welded nodes used in body constructions.

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Keywords: bodywork; bus, trolleybus; service life; welded nodes; MBS; FEM; stand test; strain gauge measuremet; stress-time history; laboratory fatigue tests; fatigue life calculation.

1. Vehicle development process

When developing new vehicles, a majority of manufacturers combine computer modelling and sequences of experiments at various levels, involving the structure of the entire vehicle or its components, down to structural details. A development route which has been used for new Skoda buses and trolleybuses was presented several times in professional literature, for instance by Kepka and Rehor (1992) and Kepka (2009).

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In order to predict fatigue life, the following input data is required: The S-N curve of the structural detail in question and a stress spectrum in the form of a histogram of stress cycle frequencies as a representative sample of service loads acting on the vehicle.

Normally, test samples of characteristic structural details of the body (most often they are welded joints of thin-walled sections) can be manufactured at early stages of the vehicle development process and used for finding the relevant S-N curves in laboratory fatigue tests. Reliable measurement and evaluation of the service stress spectra is only possible at later stages: during tests of a roadworthy prototype. However, in the early phases of vehicle development, one can use what is known as design stress spectra, as outlined by Kepka and Kepka Jr. (2017) and earlier by Heuler and Klätschke (2005).

The vehicle development process involves checking the compliance with the following condition:

$$S_{a.max}(J) \leq S_{a,max,p} \tag{1}$$

$S_{a.max}(J)$ – Maximum amplitude of stress response determined for the structural detail when the vehicle rides over a standardized obstacle which simulates a severe irregularity in a road surface;
$S_{a,max,p}$ – Maximum acceptable amplitude of dynamic load acting on the structural detail;
J – Index of the vehicle development stage, J = 1, 2, 3.

The permissible maximum stress amplitude can be the same value as the fatigue limit of the detail under investigation. However, it is typically defined in terms of the prescribed service life with the aid of the linear cumulative damage rule, Kepka and Kepka Jr. (2016). In long bars in the body structure, uniaxial stress examination is sufficient as there is no need for multiaxial fatigue criteria suggested by Margetin et al (2016), for instance.

1.1. Vehicle design stage

Alternative design variants are compared using computational models. For a variety of reasons, only a limited number of variants are considered.

Dynamic models of the vehicle are constructed on the basis of drawings. Key assemblies of the vehicle (body, axles, wheels and tyres, suspension and guiding elements and others) are modelled using multibody simulation (MBS) software. The characteristics of tyres, shock absorbers and air springs are very important. The choice of these suspension elements (and their combinations) has a strong impact on dynamic properties of the vehicle and the levels of dynamic stresses in the body structure.

Using a dynamic MBS model of an empty and fully-loaded vehicle, vehicle ride over standardized obstacles (with left wheels, right wheels, both wheels on a single axle simultaneously) at a chosen speed is simulated. Combinations of different variants lead to a wide range of load states. A prominent obstacle on the road surface (kinematic excitation) is simulated using a cylinder segment 500 mm in width and 60 mm in height. First, the relative movements and velocities between the body and axles in response to excitation of this kind are examined. Then, using the known suspension characteristics, force-time histories in individual suspension elements are derived.

A computational model of the body structure is constructed using a finite element method (FEM). It should provide a sufficiently accurate description of the stress state in the structure, and facilitate dynamic calculations within reasonable computing times.

The FEM model of the vehicle body is then subjected to variable forces acting on suspension elements, as determined using MBS. Stress response time histories are then found for all crucial structural details of the body (for load states under investigation). Maximum peaks and stress amplitudes are identified and compared to tentative maximum acceptable values. The procedure is shown schematically in Fig. 1.

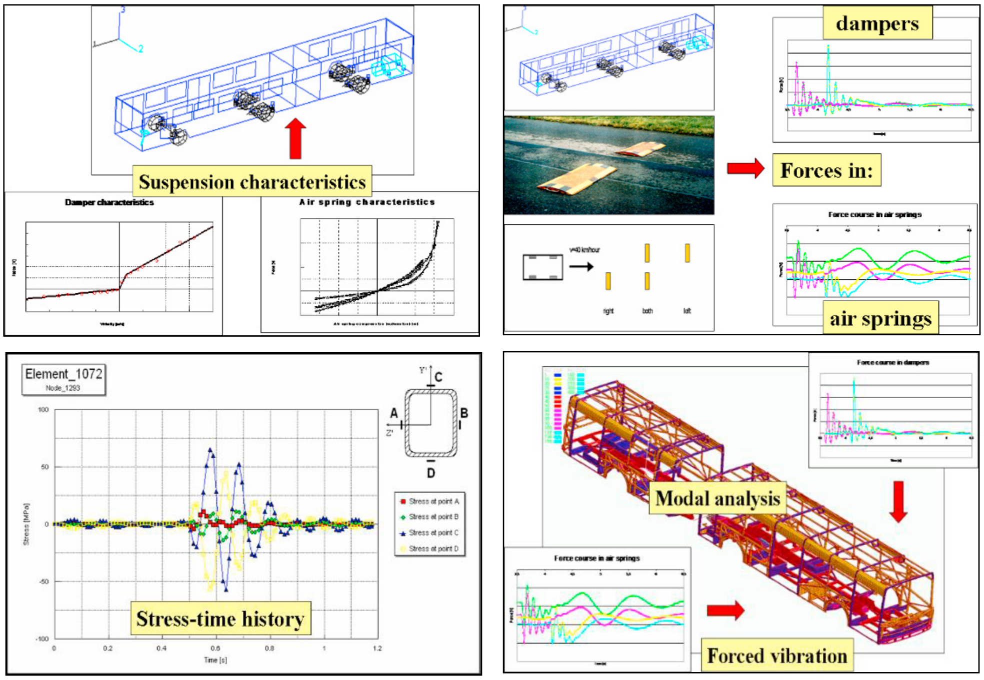

Fig. 1. Computation of dynamic stresses as part of conceptualization and design of a vehicle.

1.2. Testing a functional sample of vehicle on test stand

Tests of a functional sample of the vehicle on a test stand provide effective means of validation of computational models, validation of alterations to the body structure, and means for choosing the best variant in terms of service strength and fatigue life.

The vehicle is placed onto cylinders of a computer-controlled electrohydraulic test stand. The vertical dynamic behaviour of the vehicle is of major interest. Shock loads are simulated (using controlled vertical movement of the cylinder piston rod), which represent the vehicle driving over a standardized irregularity in the road surface. Stress responses are recorded using strain gauges attached to the functional sample of the vehicle in up to hundreds of locations. The largest recorded stress amplitudes are compared against pre-determined acceptable values.

Testing in an electrohydraulic loading stand can be performed in a highly flexible and versatile manner, as the equipment can replicate relevant load states at any time and to full extent.

The “vehicle” under test need not be roadworthy. The weight of its special units and components, which may be still under development, is applied by dummy weights, as is the payload. In the course of functional sample testing on the test stand, alterations to the design of the structure, application of loading to only selected parts of articulated vehicles, and replacement of suspension elements can be made relatively easily. Two photographs of test set-ups for functional samples of vehicles in test stands are shown in Fig. 2.

1.3. Measurement on a functional sample or prototype vehicle on a test track

These experiments involve generation of dynamic stresses by driving on a simulated test track, Fig. 3. The simulated test track includes standardized artificial obstacles placed on a smooth asphalt road surface. Usually the stress response of an empty and fully-loaded vehicle to driving is measured using strain gauges. The number of measuring locations has already been reduced in order to focus on those locations in the body which had been identified as “unsafe”. The principle of evaluation is the same as in the previous stages.

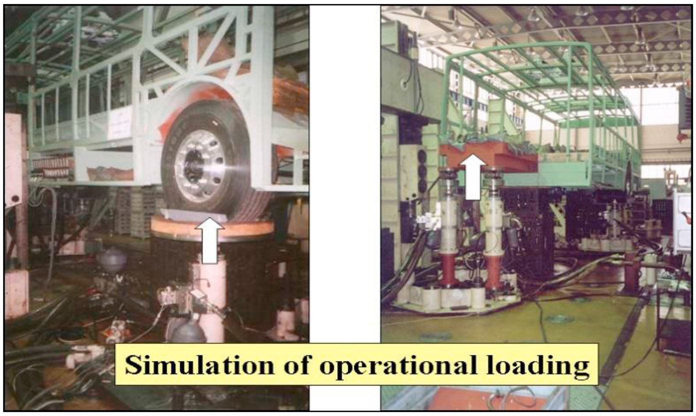

Fig. 2. Measurement of stresses during the investigation of a functional sample of a vehicle on a test stand.

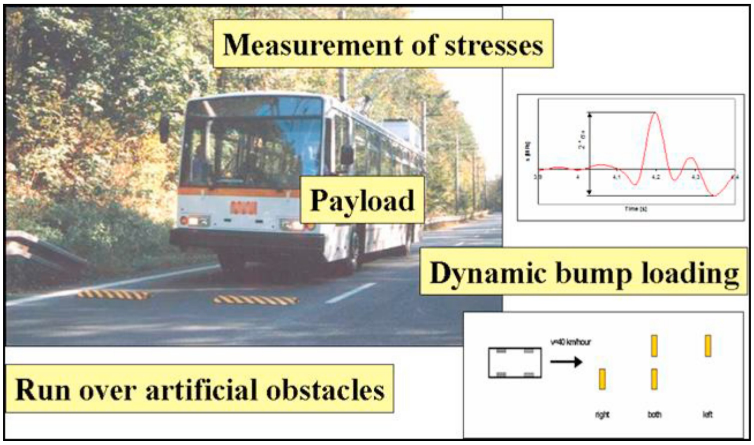

Fig 3. Measurement of stresses during the run of a vehicle prototype over artificial obstacles.

2. Modifications of bodywork structure

Failure to meet the above-defined condition calls for alteration to the design of the body. Alterations to the body design fall into three major groups, Fig. 4. Understandably, various combinations of design interventions can be considered as well.

Reasonable local reinforcement applied to several structural details of the body only affects stress states in the structural details. However, it may also alter its fatigue properties (S-N curve, fatigue strength). Dynamic properties of the body as a whole (natural frequencies and mode shapes) do not change appreciably. Hence, this design intervention has no impact on the other locations within the body.

Added structural elements reinforce the body structure primarily in their location and the immediately adjacent region. An added diagonal member is one example. With structural elements of this kinds, the orientation of the element plays a greater role than its stiffness. Its orientation causes changes in stress distribution in its vicinity. At the same time, dynamic properties of the entire body do not change substantially.

Natural frequency, natural mode shapes, and therefore the stress distribution may be altered profoundly by changing the cross-sections of the key sections of the body structure, adding sheet reinforcement etc. Alterations of this kind can even be seen as new designs of the body structure.

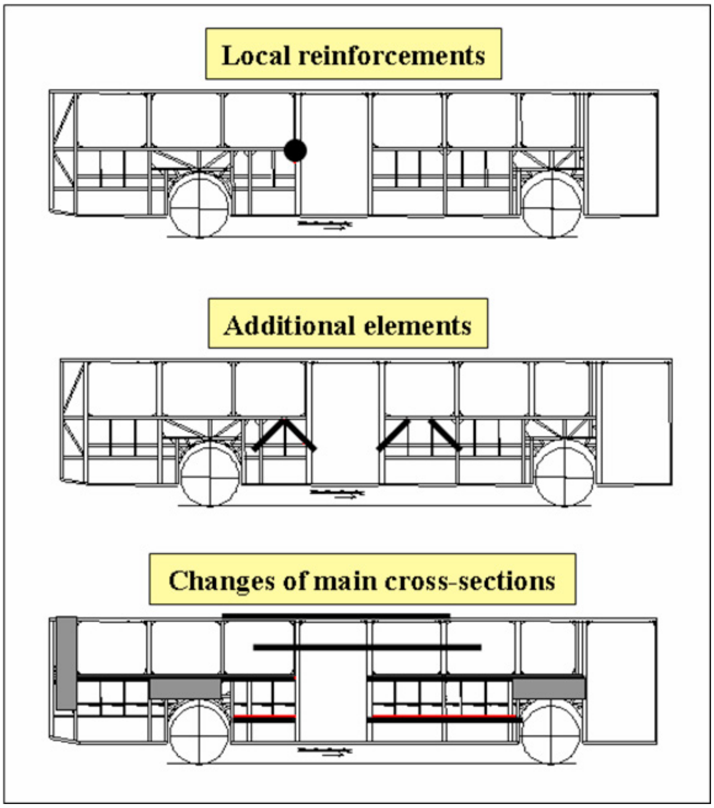

Fig. 4. Types of structural modifications – shown schematically.

3. Fatigue tests of several variants of welded joints

The fatigue properties of individual design and manufacturing variants of body sections need to be known for the design process. They can be determined beforehand using laboratory fatigue tests. This section describes some results of fatigue tests of several variants of welded structural details used in the body structure.

3.1. Test stands in dynamic testing laboratories

In Pilsen Region in the Czech Republic, there are three facilities capable to carry out fatigue tests on various scales. They are the test laboratories of Vyzkumny a zkusebni ustav Plzen s.r.o. (Research and Testing Institute Pilsen, VZU), the company COMTES FHT a.s. (COMTES) and Regional Technological Institute (RTI), a research centre affiliated with the Faculty of Mechanical Engineering of the University of West Bohemia.

Fig. 5 is a photograph of a test stand which was used for many years at VZU. COMTES developed a test arrangement within a frame of a testing machine, as seen in Fig. 6. RTI is working on incorporating the probabilistic approach into assessment of fatigue life of vehicle bodies. To make this viable, a body of fatigue test data is required. For this purpose, RTI designed a test stand which applies multiple loads to joints between members of the body structure, Fig. 7.

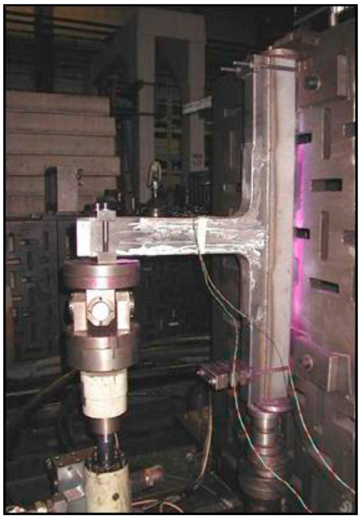

Fig. 5. VZU test stand.

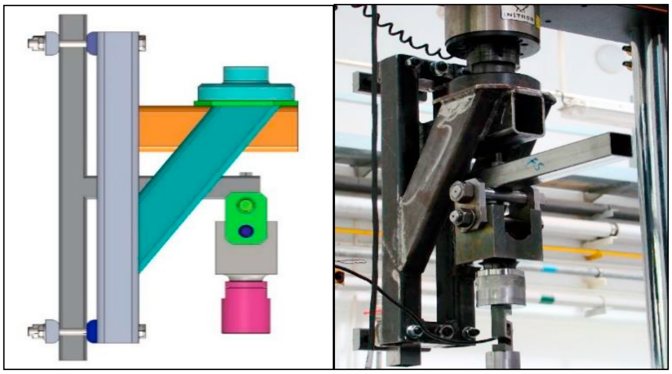

Fig. 6. COMTES test setup.

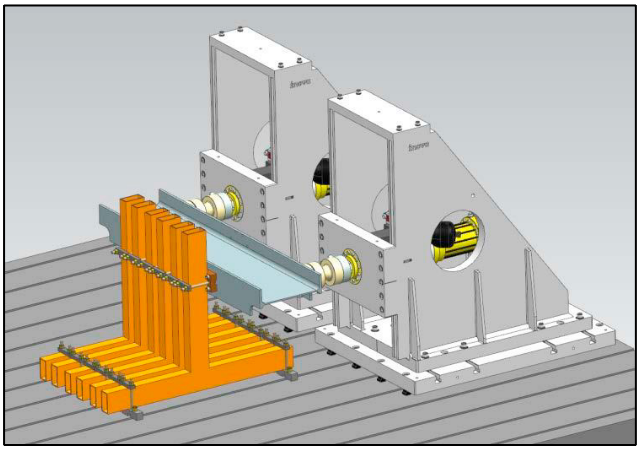

Fig. 7. Design of a new RTI test stand.

3.2. Results of fatigue tests

Test laboratories are approached by vehicle manufacturers to perform tests, usually as contract research jobs. This is why the present paper cannot include full interpretation of the results. Material, design and process specifications of the structural details have been omitted.

Fig. 8 shows sketches of structural details in question; and Fig. 9 includes results of individual fatigue tests with mean S-N curves. Tests were performed with symmetrical alternating loading and the stress amplitudes in S-N curves are valid for locations in which a technical fatigue crack was initiated on the test specimens. The stresses were monitored by strain gauge technics during the tests.

The graphs indicate differences between the results, depending on whether the structural detail has been reinforced or not. The authors are allowed to disclose that metallographic examination of the fatigue fractures revealed a major role played by the quality of welded joints and the base material (thin-walled closed sections).

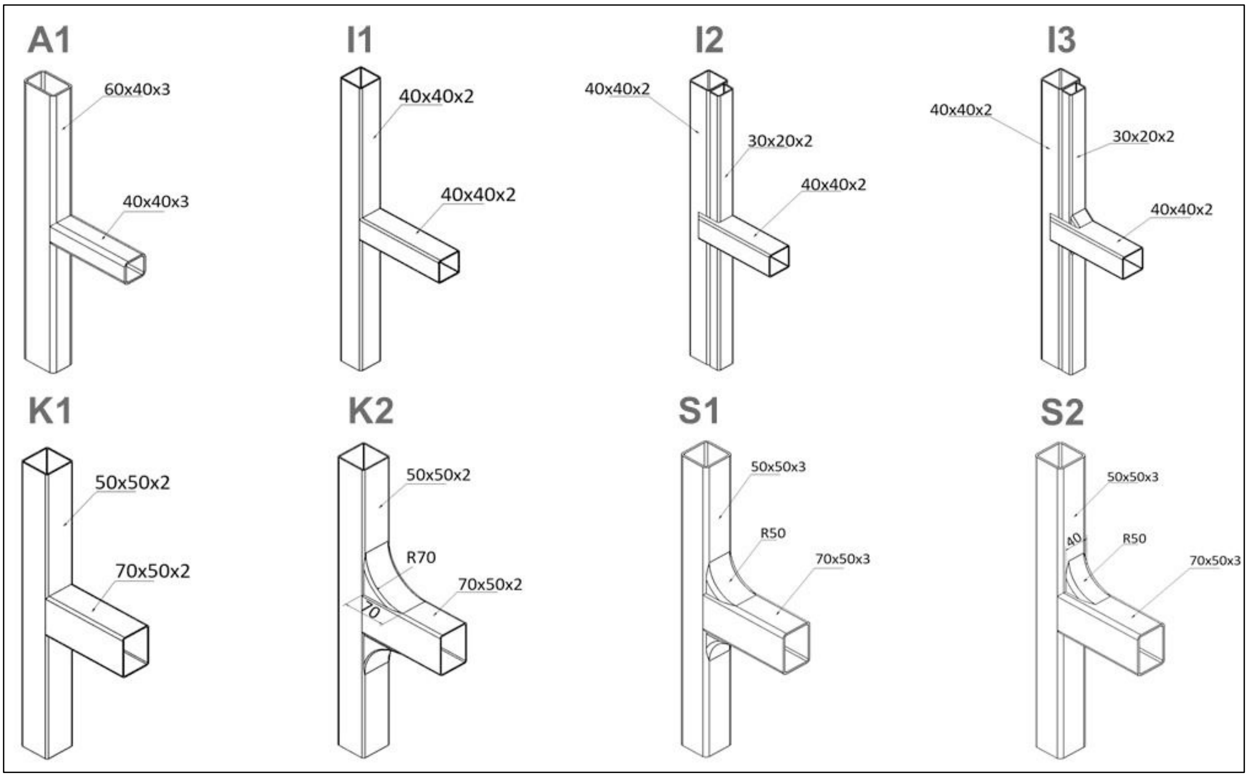

Fig. 8. Welded bodywork nodes – shown schematically.

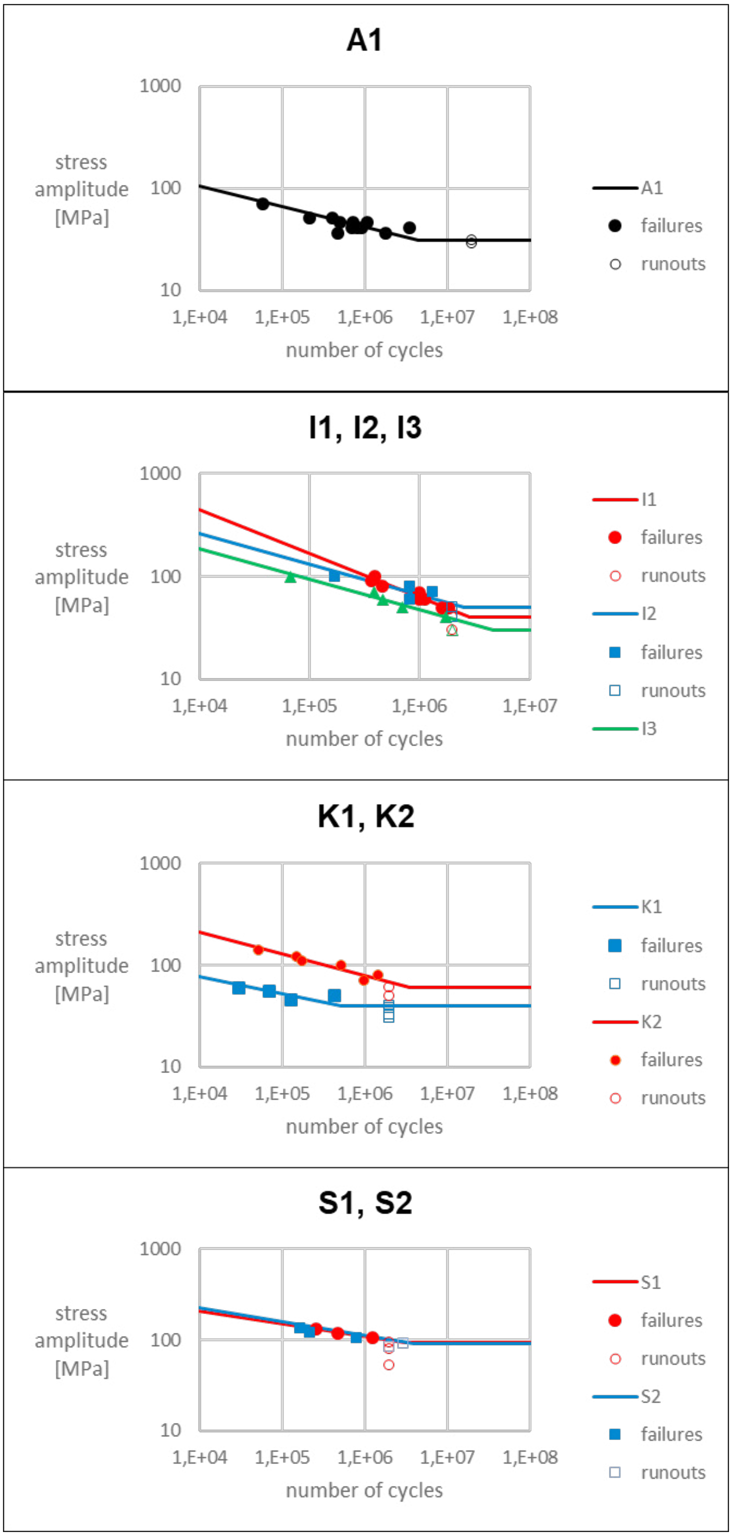

Fig. 9. Results of individual fatigue tests with mean S-N curves.

4. Conclusions

This paper outlines one of the possible approaches to designing a bus (trolleybus, battery bus) body structure for fatigue resistance. Contributors to the development of this methodology include authors of this paper, one of their contributions being the performance of laboratory fatigue tests of structural details of vehicle bodies. Based on results of these fatigue tests, one can determine maximum acceptable service stress amplitudes to meet the desired life of the vehicle body. Under certain conditions, one can also find the fatigue life distribution function for critical structural details of the body, and assess their reliability, Kepka and Kepka (2018).

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