18th International Conference
ENGINEERING MECHANICS 2012
Svratka, Czech Republic, May 14 – 17, 2012

pp. 1465–1471
Paper #231

THE METHODOLOGY OF FATIGUE TEST SIMPLIFICATION

J. Vágner*, B. Culek jr.**, B. Culek***

Abstract: *The contribution is focused on the issues of experimental determination of fatigue characteristics of structural nodes of rail vehicle parts on a dynamic test stand. The aim of the contribution is to describe a methodology allowing simplifying the experiments. The proposed methodology uses FEM computation, correlation analysis and estimation based on specific stress response. In order to validate the methodology, an experiment with a physical specimen was performed.*

Keywords: ***Rail vehicle, structural node, fatigue testing, FEM analysis, dynamic test stand.***

1. Introduction

The aim of this contribution is to describe a methodology which allowing simplify experimental testing of fatigue strength of structural nodes of rail vehicle bogie frames. The purpose of the proposed methodology is to reduce the number of cylinders (and thus also other equipment) necessary for fatigue testing for determining the fatigue properties of structural nodes, especially structural nodes of rail vehicle constructions.

The methodology contains particular points listed below:

1. Finding a suitable set of criteria for assessment of the equivalence of two modes of loading of the structural node.
2. Finding the relation between the evaluated component of the material response and the loading mode.
3. Defining the procedure leading to simplification of the loading mode (reduction of number of the loading cylinders).
4. Verifying the above points at theoretical models with use of FEM analysis.
5. Experimental validating (demonstrating) the methodology at a physical specimen.

Although the work is focused at the simplification of experimental testing of fatigue strength, many theoretical techniques and methods also had to be used to reach the aim. In order to prove the theoretical methods (and thus also their result) acceptable, the methods were to be validated by experiments in each step. For this purpose, a specimen representing a characteristic structural node used with bogie frames of rail vehicles was designed. The methodology was validating by FEM analysis and testing on real specimens at an electrohydraulic stand.

2. The proposed methodology

The method assumes that the loaded assembly is linear. Further assumption is that the sample, subjected to the applied loading, has one critical point. Fig. 1 shows a block diagram of the theoretical model of the original and the simplified loading sets including three levels of checking of equivalence

* Ing. Jakub Vágner, Ph.D.: University of Pardubice, Jan Perner Transport Faculty, Department of Transport Means and Diagnostics, Studentská 95, 532 10 Pardubice, Czech Republic, e-mail: Jakub.Vagner@upce.cz

** doc. Ing. Bohumil Culek, Ph.D.: University of Pardubice, Jan Perner Transport Faculty, Department of Transport Infrastructure, Studentská 95, 532 10 Pardubice, Czech Republic, e-mail: Culek@upce.cz

*** Prof. Ing. Bohumil Culek, CSc.: University of Pardubice, Jan Perner Transport Faculty, Department of Transport Means and Diagnostics, Studentská 95, 532 10 Pardubice, Czech Republic, e-mail: Bohumil.Culek@upce.cz

of both sets. Both models are identical as to the included modules; however the transfer functions between the modules are different.

In order to enable utilising of the method, not only that the simplification system itself had to be designed, but also a way of assessment of the equivalence of the simplified loading mode had to be found. It was necessary to find a hypothesis which would not be much conservative and allowed to compare the effects of two loading sets, with regards to the material fatigue, as precisely and simply as possible.

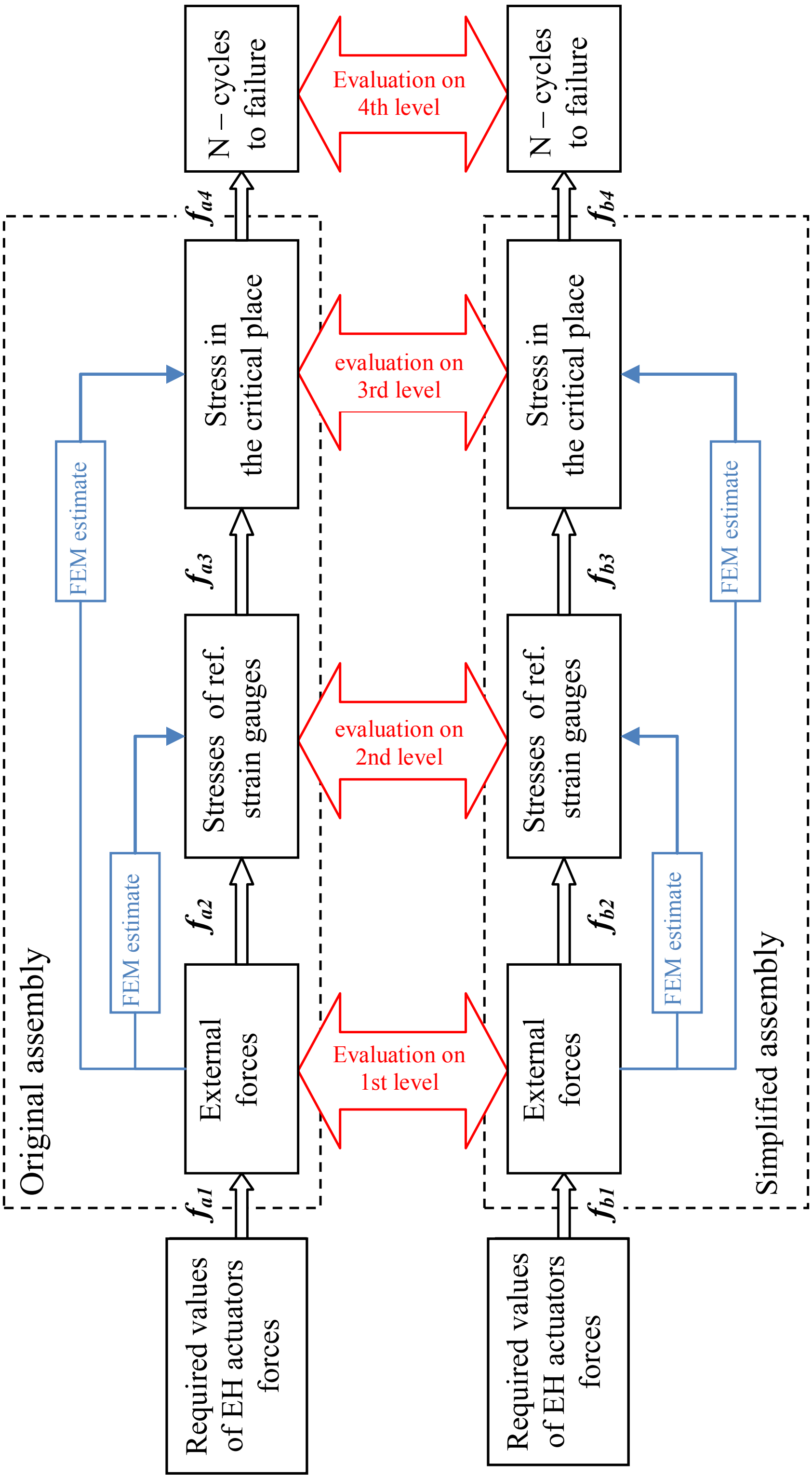

Fig. 1: Block diagram of the theoretical model of the assembly.

3. The criteria for assessment of the equivalence of two modes of loading

The aim is to reach the same number of cycles to failure (the 4th level on Fig.1), but another requirement has still to be fulfilled, that the same mode of failure occurs at the same point as with the original loading set. In an extreme case it may also happen that the specimen is loaded in a completely different way but the failure occurs at the same (almost the same) number of cycles. Based on the aforementioned information, several assessment methods were proposed (which does not exclude other methods):

One-parameter methods

a) The value of σ_1 – only the magnitude of the principal stress is evaluated, its direction is not taken into account!

b) The value of τ_{max} - only the magnitude of the maximum tangential stress is evaluated, its direction is not taken into account!

c) The value of σ_{HMH} – the directions and relation of the shear and tensile components are not taken into account; negative values of stress are not taken into account either.

d) Reference stress σ – one or more strain gauges are positioned at a suitable place of the construction. The assumption may be made that there is a relationship between this stress and the maximum stress in the notch. The value of the stress in the direction of the strain gauge is evaluated and subsequently transformed to the stress in the notch (critical point).

Two-parameter methods

e) The values of σ_1 and τ_{max} – Magnitudes of both stresses are evaluated, with regard to the fatigue limit ellipse in the σ–τ diagram. The direction in relation to the critical point is not taken into account.

f) The values of σ and τ – The values of tensile stress and shear stress in a selected reference direction are evaluated. The direction must be chosen with regards to the supposed direction of the crack. The direction in relation to the critical point is thus taken into account.

The loading modes are equivalent if the points of both compared situations are located on a common ellipse of constant fatigue strength in the σ–τ diagram.

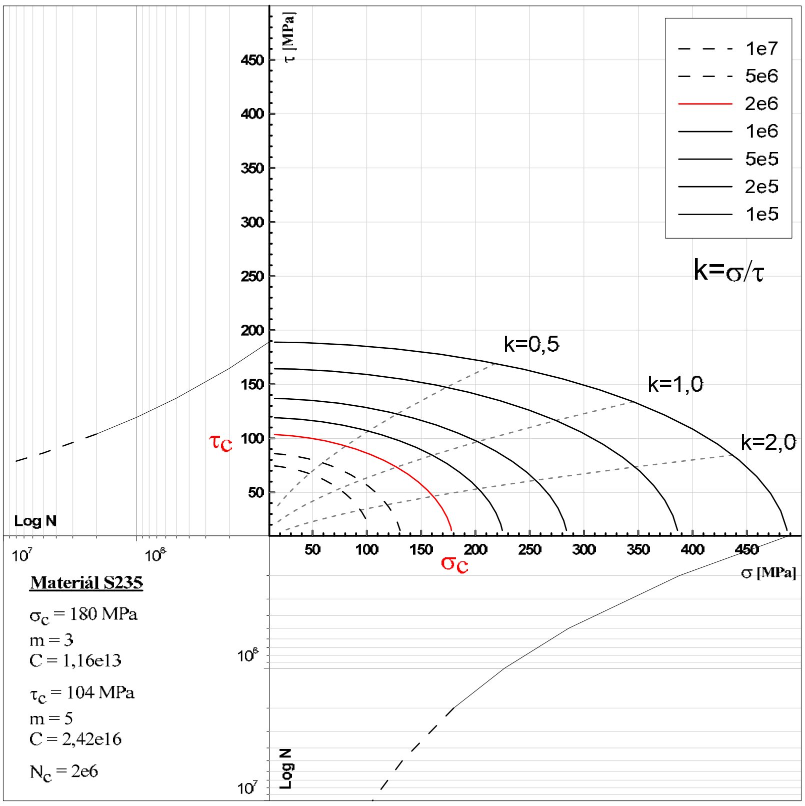

Fig. 2: Extended σ–τ diagram.

4. The specific stress response metho

As the stress in the critical point may not be experimentally verified, a method for estimating the stress on the basis of specific stress response was created. It comprises the following steps:

1) An appropriate FEM model is created.

2) All load components are applied with the magnitude of 1.

3) All variants for only one component at a time are computed.

4) All components of stress in the nodes are exported for further processing.

The stress in a selected point (FEM node) is then:

$$\begin{bmatrix} k_{\sigma x\,1} & \dots & k_{\sigma x\,n} \\ k_{\sigma y\,1} & \dots & k_{\sigma y\,n} \\ k_{\sigma z\,1} & \dots & k_{\sigma z\,n} \\ k_{\tau xy\,1} & \dots & k_{\tau xy\,n} \\ k_{\tau yz\,1} & \dots & k_{\tau yz\,n} \\ k_{\tau zx\,1} & \dots & k_{\tau zx\,n} \end{bmatrix} \cdot \begin{bmatrix} F_1 \\ . \\ . \\ . \\ F_n \end{bmatrix} = \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{zx} \end{bmatrix} \quad (1),$$

where the coefficients k represent values of the specific stress response. These values may also be obtained experimentally.

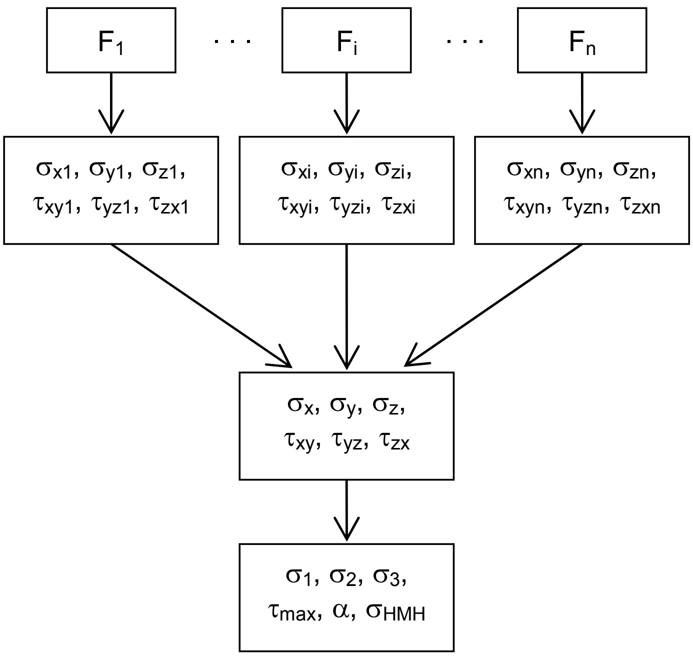

Fig. 3: Schema of application of the specific stress response method.

5. Typical process of simplification

Typical process of simplification is as follows:

1) The time histories of external forces assumed in operation (experiment) serve as input.

2) Another input is constituted by the data necessary for assessment of equivalence of the loading – stresses from the FEM analysis calculated under the loading specified in the previous point.

3) The experiment loading set is designed. It is required that the dominant component(s) of the original loading be preserved. This loading set will be henceforth referred to as „simplified“.

4) Design of the assembly with the structural node (specimen), fastening equipment and system of applying the loading forces.

5) FEM analysis of the sample loaded in the designed assembly with unit loading from external forces (specific stress response).
6) Finding the suitable location for reference strain gauges so that the measured values correlate sufficiently with the stress in the critical point.
7) Based on the original loading, the stress response to the dominant force is calculated.
8) The difference between the original stress and the stress resulting from the dominant force will be compensated for by other forces remaining in the loading set.
9) The values of other forces are calculated using the superposition principle so that required effect is achieved.
10) After the calculation of the new loading, new stress histories in the critical point are calculated.
11) The original and the new histories are compared following a selected criterion for assessment of load equivalence. If the agreement is not sufficient, the proposition must be modified.
12) Before the experiment is started, a check is made whether the responses from the reference strain gauges, with respect to the loading forces, are accurate enough compared with the FEM calculation.

The process may be slightly different with regard to the purpose of simplification and with regard to the character of the test specimen. In particular, the range of input parameters may differ.

6. Achieved results

The methodology was applied on an actual specimen. A steel weldment was constructed, representing the structural node of connection of a sideframe and a transom. It was loaded by three EH cylinders; the simplified assembly was loaded by two EH cylinders. There are two potential critical places on the specimen (CP1, CP2) but with regard to load system only one of them is critical.

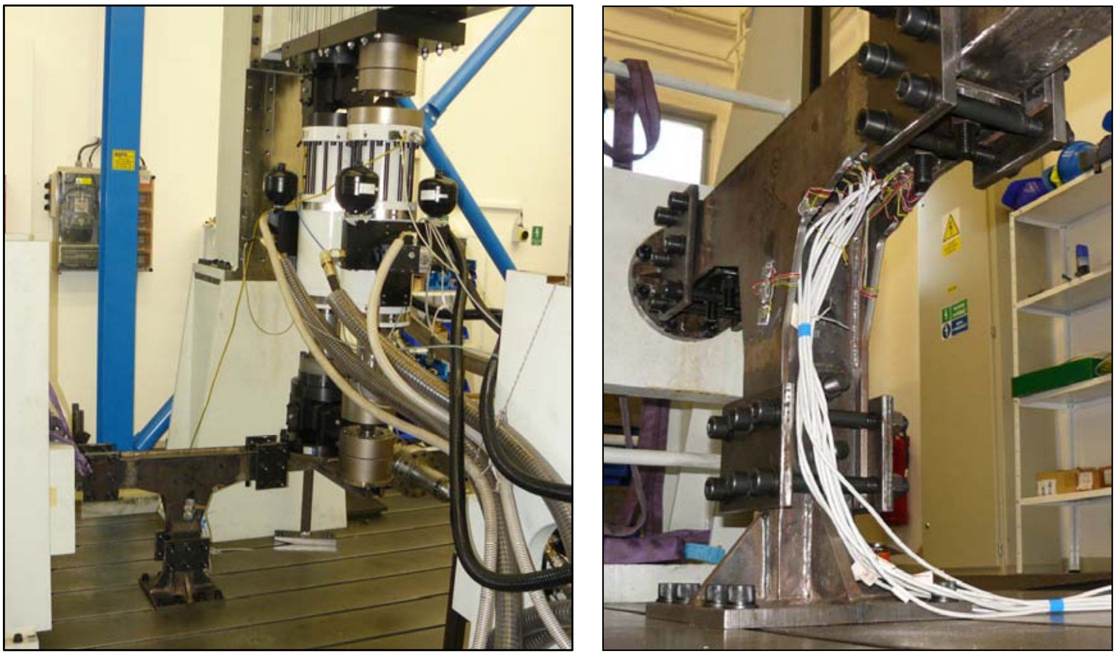

Fig. 4: The experimental assembly and the specimen with strain.

Results of comparison between theoretical and experimental determination of specific stress response are listed in Tab. 1. The presented results were obtained under one cylinder loading conditions.

Tab. 1: Comparison between theoretical and experimental determination.

Strain gages	FEM [MPa/kN]	Experiment [MPa/kN]	Difference
T3	4.97	5.07	2%
T4	4.97	4.97	0%
T5	4.85	4.85	0%
T6	4.85	4.58	-6%
R1A	1.23	1.26	3%
R1B	4.44	4.57	3%
R1C	2.16	2.21	2%
R2A	2.16	2.15	0%
R2B	4.44	4.50	1%
R2C	1.24	1.25	1%

Following variants of load have been proposed for verification of the methodology (Tab. 2):

a) Original version: This is the basic version for comparison.

b) Version A: In this version, the force *F2* was omitted and compensated by other forces. The resulting tensile component for the secondary critical point decreased; the shear component remained without significant change for all values.

c) Version B: In this version, the force *F2* was omitted and compensated by remaining cylinders. The resulting tensile component for the secondary critical point was lower again; the shear component remained similar for all values.

d) Version C: In this version, the forces *F1* and *F2* were both omitted and compensated only by the force *F3*. The tensile component was maintained, the ratio of the tensile and shear components was not (difference 7.5 %).

e) Version C1: This version differs from the version C solely by the fact that, besides varying the loading intensity, the ratio of amplitude and mean value of the force also varied in order to attain the appropriate loading. The ratio was changed from original 1:0,25 to 1:0,6.

f) Version D: In this version, the forces of the cylinders *F*2 and *F*3 were omitted and compensated only by the force *F*1. The tensile component was maintained, the ratio of the tensile and shear components was satisfactory. In this case it was observed that the stress state in the in the secondary critical point (CP2) was the same as in the primary critical point (CP2). Although this loading is apparently suitable according to the comparison of numbers of cycles to failure, the failure might occur in another place than in the assumed primary critical point (CP1)!

Tab. 2 – Load forces (two-parameter simplification).

Version	F1 [kN]	F2 [kN]	F3 [kN]
Original	+/- 4.3	-/+ 1.3	8.5 +/- 2.10
Version A	+/- 3.5	0	7.1 +/- 1.75
Version B	+/- 2.9	0	5.8 +/- 2.90
Version C	0	0	19.3 +/- 4.80
Version C1	0	0	10.6 +/- 6.40
Version D	+/- 5.5	0	0

Results of stress responses obtained by proposed variants of load are listed in tab. 3. Results of the **σ/τ** ratio are listed in tab. 4.

Tab. 3: Stress response (two-parameter simplification).

Version	CP1		CP2	
	σ	τ	σ	τ
Original	64.9	28.4	49.7	28.6
Version A	64.8	30.7	40.8	30.9
Version B	65.0	31.0	33.5	31.1
Version C	64.7	28.3	-1.0	28.3
Version C1	64.4	30.0	-1.3	30.0
Version D	64.9	31.6	64.9	31.9

Tab. 4: The σ/τ ratio (two-parameter simplification).

Version	CP1	CP2
	σ/τ	σ/τ
Original	2.12 (0%)	1.61 (0%)
Version A	2.11 (-0.65%)	1.32 (-18.22%)
Version B	2.1 (-1.17%)	1.08 (-33.29%)
Version C	2.28 (7.52%)	-0.03 (-102.09%)
Version C1	2.15 (1.17%)	-0.04 (-102.61%)
Version D	2.05 (-3.35%)	2.03 (26.05%)

7. Conclusions

The described methodology allows simplifying the loading of a structural node of a rail vehicle for the purpose of simulation of its operational loading at a dynamical test stand. However, the methodology should be taken only as a starting point of further research, since it still has many limitations in the present stage. For simple structural nodes loaded by external loading components with the same phase it is applicable, though. It is also difficult to use for tests, which are conclusively defined by standards.

Acknowledgements

This work has been supported by the project of Research Centre of Rail vehicles No. 1M0519 and Competence Center of Railway Vehicles No. TE01010038.

References

Vágner, J. (2012) *Simulace provozního namáhání částí kolejových vozidel na zatěžovacích standech*. Pardubice. Disertační práce. Univerzita Pardubice, Dopravní fakulta Jana Pernera.

Vágner, J., Culek ml., B., Culek, B. (2011) *Simulace rozhodujících složek provozního namáhání částí kolejových vozidel na multiaxiálních zatěžovacích standech.* Přehledová zpráva VCKV č. B8-01-2011-UPa. Pardubice.

Vágner, J., Culek ml., B., Culek, B. (2010) *Simulace rozhodujících složek provozního namáhání částí kolejových vozidel na multiaxiálních zatěžovacích standech*. Přehledová zpráva VCKV č. B8-01-2010-UPa. Pardubice.