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Fatigue life of a bus structure in normal operation and in accelerated testing on special tracks

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Abstract

Over the last twenty years, the Research and Testing Institute in Pilsen has been developing a methodology of computational and experimental investigation of strength and fatigue life of bodies of road vehicles for mass passenger transport. The methodology includes multibody dynamic simulations, strength FEM calculations, test bench tests, stress measurements during vehicle prototype operation, evaluation of measured data and fatigue life calculations. One co-operating bus manufacturer plans to include accelerated fatigue tests on special testing grounds into this procedure. In real urban traffic and on the test circuit extensive stress measurements on a number of structural nodes and components has been carried out and analysed. In collaboration with the Regional Technological Institute, which is the research center of the Faculty of Mechanical Engineering of the University of West Bohemia, the fatigue life was calculated for the critical nodes and components of the different parts of the bus. Based on these calculations, it was possible to assess the development potential and problem of planning accelerated tests on the testing polygon.

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Keywords: bus bodywork; stress measureent; real urban road; polygon track; fatigue life calculation.

1. Introduction

Research and Testing Institute Pilsen (VZU, https://www.vzuplzen.cz/en) collaborates on a long-term basis with the University of West Bohemia in Pilsen.

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Recently, its main partner has been the Regional Technological Institute (RTI, http://rti.zcu.cz/en), which is the University's new research center affiliated with the Faculty of Mechanical Engineering.

Active cooperation has been established between the Dynamic Testing Laboratory at VZU and the Strength and Fatigue Life Testing Laboratory at RTI. This cooperation includes systematic development of assessment methods for service strength and fatigue life of road and rail vehicle frames.

The methods for both aspects have been published multiple times. An interdisciplinary approach to the design and sizing of bus and trolleybus bodies for fatigue life was presented for the first time by Kepka and Rehor (1992). Most recently, Kepka and Spirk (2015) were discussed in relation to development of battery-powered buses. A comprehensive approach to assessment of service strength of a tram bogie frame was published by Kraus et al. (2018).

In the present paper, the authors discuss and explore the feasibility of accelerated fatigue life testing of a bus at the testing ground of Tatra a.s. (a Czech manufacturer of trucks). Given the commercial nature of this project, certain facts and data are only outlined in a general form. Nevertheless, the methods are documented in a detailed and lucid manner.

A manufacturer, which develops a new bus, has chosen a virtual prototyping-based assessment of the fatigue strength and durability of the bus body and chassis structures. Load analysis involved computer simulations of various loading states and determination of the stress response in the vehicle's load-bearing structure to driving on roads with various profiles and roughness, as illustrated schematically in Fig. 1.

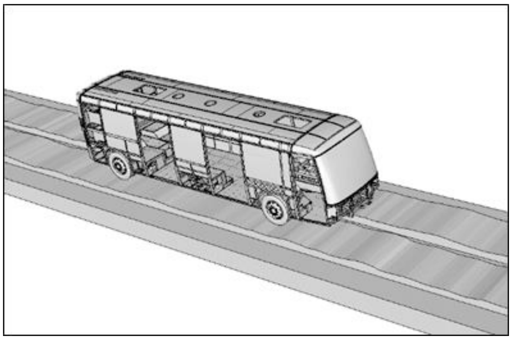

Fig. 1. Simulation of a virtual vehicle prototype riding along an irregular road surface.
(http://www.caesupport.cz/cae.php)

Using computational analysis, the manufacturer identified 50 most severely-loaded structural details in the body and chassis structures for subsequent strain gauge measurement. Strain gauges were bonded onto these critical structural details. Two examples of strain gauge locations of the body structure are shown in Fig. 2.

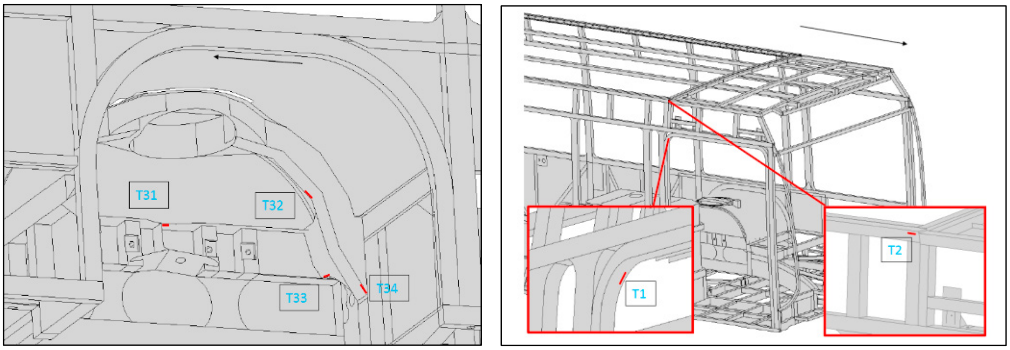

Fig. 2. Examples of strain gauge locations.

The bus manufacturer supplied parameters of S-N curves for all the structural details to be monitored, from which fatigue damage was calculated and fatigue service life predicted. As the manufacturer's data must be kept confidential, Table 1 lists these parameters while omitting any details on materials, design and technologies. Only critical structural nodes are listed in the table. The in-service measurements, fatigue life calculations and analyses were provided jointly by VZU and RTI.

Tab. 1. Parameters of S-N curves for critical structural nodes.

Structural node	σ_{ac} (MPa) fatigue limit	N_c (cycles) knee point	w slope	Vehicle part
T31	58	2.00E+06	4.5	chassis frame
T49	69	4.94E+06	5.7	chassis frame
T48	115	4.94E+06	5.7	chassis frame
T3	43	2.00E+06	4.5	side wall
T10	69	4.94E+06	5.7	side wall
T25	43	2.00E+06	4.5	side wall
T20	69	4.94E+06	5.7	side wall

2. Accelerated fatigue tests

Essentially, fatigue life testing of a vehicle can be accelerated in two ways. Under laboratory conditions, a pre-defined (severe) loading cycle can be imposed in electrohydraulic test rigs, Halfpenny (2006). However, accelerated fatigue testing can also take the form of a test ride along special tracks at a testing ground. Chmelko et al. (2019) analyzed the axle loadings of the trailers for various road reliefs like asphalt, panel road, paving blocks, pavements.

In both cases, the correlation between cumulative fatigue damage under real-world service loads and under test loads is typically established through the fatigue damage hypothesis. According to this hypothesis:

$$D_{m,x,y} = \sum_i \frac{n_{i,x,y}}{N_i} = D_{lim} \tag{1}$$

$D_{m,x,y}$ - fatigue damage caused by the stress spectrum (σ_{ai} versus $n_{i,x,y}$) imposed (track of the length $L_{m,x,y}$),

$n_{i,x,y}$ - number of cycles applied at the *i-th* level of stress with the amplitude σ_{ai},

N_i - limit life under identical loading σ_{ai} (number of cycles derived from S-N curve of an investigated structural node at the amplitude σ_{ai}),

D_{lim} - limit value of fatigue damage,

x - index of service conditions ($x = C$ or TG; C = city, TG = testing grounds),

y - index of vehicle payloads (y = *empty* or *full*).

Various boundary conditions can be used for fatigue damage calculations. A schematic representation of these boundary conditions is shown in Fig. 3. Account is taken of the damage caused by cycles with small amplitudes ($\sigma_{ath} < \sigma_{ai} < \sigma_c$), which occur very frequently. A threshold value σ_{ath} is applied to the conversion of stress to damage, and therefore the damage caused by cycles with amplitudes of $\sigma_{ai} < \sigma_{ath}$ is neglected. A limit value is set for the fatigue damage. According to Miner, $D_{lim} = 1$. In the present case, the Haibach-modified version of the Palmgren-Miner rule was chosen for calculating fatigue damage. The limit number of cycles N_i was determined as follows:

- $\sigma_{ai} \geq \sigma_c$: $$N_i = N_c \cdot \left(\frac{\sigma_c}{\sigma_{ai}}\right)^w \quad (2)$$

- $\sigma_c > \sigma_{ai} \geq \sigma_{ath}$: $$N_i = N_c \cdot \left(\frac{\sigma_c}{\sigma_{ai}}\right)^{w_d} \quad (3)$$

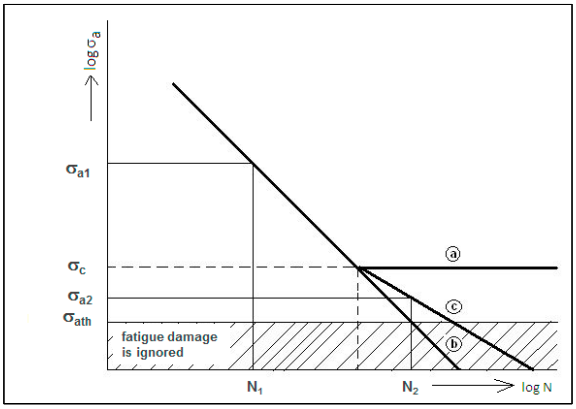

Fig. 3. Boundary conditions for fatigue damage calculations.
a – Palmgren-Miner, b – Corten-Dolan, c - Haibach

Haibach recommends the exponent for the lower part of the S-N curve to be set as $w_d = 2w\text{–}1$. The threshold stress amplitude for taking the fatigue damaging into account was given as $\sigma_{ath} = 0.5 \cdot \sigma_c$ in the present case.

3. Case study

Two loading states y were used for the measurement (Fig. 4):

- empty vehicle, carrying only the driver, test instruments and their operators,
- fully-loaded vehicle, in which the weight of passengers was applied by vessels filled with water.

Fig. 4. Simulated payload on a vehicle.

At first, measurements were performed during rides along a chosen urban test line which the manufacturer considered as a representative example of mechanical loading on the vehicle. In ordinary service, time histories of stress were recorded for all structural details along a total of $L_{m,C,y} \approx 39.4$ km ride.

In the second stage of this project, measurements were performed on an empty and fully-loaded vehicle at the testing grounds shown in Fig. 5.

Fig. 5. Special roads at testing grounds.

The test polygon offers sections, tracks and roads with various longitudinal road profiles and different types of surfaces. Table 2 specifies the composition of the proposed test route. The measurement was repeated tree times with an empty vehicle and three times with a fully loaded vehicle. The total length of the measured route was $L_{m,TG,y} \approx$ 35.5 km.

Table 2. Composition of test route on testing grounds.

Section	Length (km)
slope circuit	3.80
speed circuit	2.80
arrival to special roads	0.07
panel road	0.45
exit/arrival	0.13
sine resonance road	0.40
exit/arrival	0.15
paved road	0.40
exit/arrival	0.15
paved road	0,40
exit/arrival	0.15
paved road	0.40
exit/arrival	0.16
Belgian paving	0.40
exit from special roads	0.08
speed circuit	1.90
TOTAL	11.84

For both type of vehicle operation (x = C or TG) and for both type of vehicle loading (y = *empty* or *full*) representative stress-time histories were acquired. These random stress-time processes were transformed by the rain-flow method into stress spectra (σ_{ai} versus $n_{i,x,y}$). Fatigue life estimates $L_{x,y}$ were derived for all structural details and for all service conditions. The mileage in kilometer run is obtained from equation:

$$L_{x,y} = \frac{D_{lim}}{D_{m,x,y}} \cdot L_{m,x,y} \tag{4}$$

To obtain approximate results for actual service loads, the fatigue life $L_{x,50/50}$ was estimated for operation in fully-loaded condition for 50% of time and as empty vehicle for the other 50%:

$$L_{x,50/50} = \frac{1}{(D_{1,x,empty}+D_{1,xfull})/2} \tag{5}$$

Values $D_{1,x,empty}$ and $D_{1,x,full}$ are calculated:

$$D_{1,x,empty} = D_{m,x,empty}/L_{m,x,empty} \tag{6}$$

$$D_{1,x,full} = D_{m,x,full}/L_{m,x,full} \tag{7}$$

$D_{1,x,empty}$ - average fatigue damage caused by 1km-run with empty vehicle in operation conditions x,
$D_{1,x,full}$ - average fatigue damage caused by 1km-run with fully-loaded vehicle in operation conditions x.

The test acceleration factor $A_{50/50}$ is the ratio of the ordinary service life and the life achieved in the accelerated test. In the present case, the ratio is as follows:

$$A_{50/50} = L_{C,50/50}/L_{TG,50/50} \tag{8}$$

$L_{C,50/50}$ - estimated fatigue life under urban conditions (city),
$L_{TG,50/50}$ - estimated fatigue life under operation on special test tracks (testing grounds).

Analysis of results is most meaningful when it concerns the structural details under the most severe loads or those with the largest fatigue damage. For this reason, we focused on those structural details whose fatigue life prediction in the city environment indicated that the required design life L_{DL} = 1,000,000 km might not be met (in at least one of the loading states under assessment). The results are shown in Table 3.

Tab. 3. Summary of results of the case study.

Structural node	$L_{C,empty}$ (km)	$L_{C,full}$ (km)	$L_{C,50/50}$ (km)	$L_{TG,empty}$ (km)	$L_{TG,full}$ (km)	$L_{TG,50/50}$ (km)	$A_{50/50}$
T31	121 494	39 177	59 249	2 930	10 654	4 596	12.89
T49	417 800	162 717	234 216	22446	32 788	27 829	8.42
T48	454 373	162 886	239 805	24137	36 398	27 768	8.64
T3	> 1 000 000	174 171	348 024	15219	408 709	29 345	11.86
T10	> 1 000 000	656 103	984 388	71060	94 817	81 237	12.12
T25	> 1 000 000	792 792	1 581 539	65967	> 1 000 000	126 274	12.52
T20	> 1 000 000	938 720	1 630 948	124 209	87 016	102 338	15.95

The case study leads to several conclusions and recommendations.

a) First, the manufacturer was alerted to several critical locations in the vehicle structure and to the need for their re-design (reinforcement or substitution of material). These included all the structural details listed in Table 2. The crucial ones were those in the chassis frame (T31, T48 and T49) and in side wall (T3 and T10).
b) It was confirmed that driving a bus at a testing ground can accelerate its road testing for fatigue life assessment by an order of magnitude. In a rough approximation, this means that the design mileage L_{DL} = 1,000,000 km can be demonstrated by travelling approximately 100,000 km on a test track without failure. Half of this mileage should be travelled with an empty vehicle and the other half with a fully-loaded vehicle. Alternating the payload regularly (e.g. after each 10,000 km) is recommended.
c) In theory, an even more aggressive composition of the test track could be designed. It would involve a larger proportion of those sections of the testing ground which produce the most severe damage. However, suspension elements would have to be protected from degradation. The sequence of the test track sections should enable them to “relax”; particularly the shock absorbers would need to cool down, because they might overheat during riding on some types of road surface.
d) The test acceleration factor for accelerated fatigue tests on special testing grounds in this case was in the range $A_{empty/full=50/50} \approx 8 - 16$. Theoretically, an appropriate sequence of test road sections can be found to narrow this range down. For a majority of critical structural details, the specified fatigue life could be demonstrated by travelling an approximately equal distance.

4. Conclusions

1) The case study confirmed that it is feasible (and in large series production even advisable) to perform an accelerated fatigue test of a bus body structure at a testing ground. This project succeeded in early identification of several critical locations of a newly-developed vehicle structure.
2) Input for follow-up research was obtained, as described in detail in points c) and d) in the preceding section. It should be based on characterizing the severity of load spectra produced by driving on test course sections with various roughness profiles and on determining the test acceleration factors for such road sections.
3) In addition, the measured data should be representative of the future service of the vehicle.
4) Computational prediction of fatigue life also requires that correct S-N curves be available for all critical structural details of the vehicle. For this reason, systematic effort should be devoted to laboratory testing of such structural details and to their statistical evaluation.
5) Further inspiration could be obtained from evaluation of the transfer functions of stress responses in important structural nodes depending on the road aggressiveness (driving on various rough surfaces).

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