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Measurements on Railway Bridges to Determine Axle Loads and Stress Range Spectra

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Summary

The construction monitoring system presented in this article is designed for the construction of railway bridges. When monitoring bridge structures, it is the task to permanently record the type, intensity, position, duration and frequency of the impact loads as well as the resulting effects on the whole system like elongations, vibrations etc. and the condition of construction components such as supports, expansion joints etc. Moreover, the experimental determination of the stress-time history in an assessment point makes it possible to determine the exact traffic load factor for the fatigue assessment of the supporting structure.

1. Introduction

Environment, structure and function of a construction are too be understood as components of a system. All factors within this system undergo changes over the time thus mainly causing the ageing process of the construction. One of the problems even the first bridges were confronted with is the constant growth of heavy traffic. In practice, railway bridge dimensioning is based on the simple Load Model UIC-71 according to UIC leaflet 702 V [1] which covers the impact of usual traffic and on the basis of the Load Model SW which is equivalent to the unitised train of the load class SW/2 according to UIC leaflet 776-1E [2].
Many tests showed that stresses in various bridge components under traffic load were usually smaller than stresses due to loading assumptions. Thus, it is not economical to base the calculations of the fatigue limit on the extremely large stresses under the design load of 2×10^6 load cycles for example.
For the fatigue assessment the vertical traffic load of rail vehicles is represented by a combination of various types of trains. The fatigue assessment for „usual traffic" is carried out with mixed traffic, the fatigue assessment for „traffic with 250 kN-axles" is carried out with heavy goods traffic. Each type of „combined traffic" is based on the annual traffic load of 25×10^6 tons transported per track. The fatigue assessment is to be based on a life span of 100 years.

In „DRAFT ENV 1993-2 [3]: Chapter 9, April 1996", it is proposed to use a simplified method of fatigue assessment. In the following only the assessment of the uniaxial stress will be discussed, the superimposed stress resulting from the principal- and secondary load-act will not be taken into account, either.
The assessment is defined as follows:

$$\gamma_{Ff}\,\Delta\,\sigma_{E2} \leq \Delta\sigma_c\,/\,\gamma_{Mf}$$

Notation:
γ_{Ff}..... is the partial safety factor for the fatigue loads, in case no other detail is given γ_{Ff} is assumed to be 1,0.
γ_{Mf}...... is the partial safety factor for the fatigue strength.

$\Delta\sigma_c$.... is the reference value of the fatigue strength at 2 million stress cycles (for longitudinal stresses).

$\Delta\sigma_{E2}$.. is the equivalent constant amplitude stress range (for longitudinal stresses) for 2 million stress cycles.

$$\Delta\sigma_{E2} = \lambda\Phi_2\Delta\sigma_{71}$$

λ........ is the damage equivalence factor for railway bridges.

$$\lambda = \lambda_1 \cdot \lambda_2 \cdot \lambda_3 \cdot \lambda_4$$

λ_1....... is the "real" traffic load factor, it takes into account the length of the influence area for various types of girders. The calculation is based upon the reference construction, i.e. the moment stress of a single-span girder (σ) in the mid-span for various lengths L due to UIC mixed traffic on a single-track structure. The line load is 25 million tons per year with a fatigue life of 100 years.

λ_2....... is the factor taking into account the deviation from the traffic volume.

λ_3 ...... is the factor taking into account the deviation from the design life.

λ_4....... is the factor, which is used, if a structural element is stressed by more than one loaded track. In order to calculate the maximum stress range, two tracks are to be loaded unfavourably with the norm load train.

Φ_2...... is the dynamic factor (as explained in ENV 1991-3, paragraph 6.4).

$\Delta\sigma_{71}$...$|\max\sigma_{71} - \min\sigma_{71}|$ $\rightarrow$ The reference stress range $\Delta\sigma_{71}$ of the vertical traffic load due to Load Model UIC-71 (UIC-leaflet 702V). In order to obtain the highest and the lowest values of the stress range in a stress cycle, the load train has to be put into the position which is most unfavourable for the monitored structural element.

In accordance with "ENV 1991-3"[4] the following traffic parameters are to be considered for the assessment of the service load:

- uniform trains with standard axle loads, axle distances, a defined number and succession of railway cars and locomotive,
- standard traffic mix.

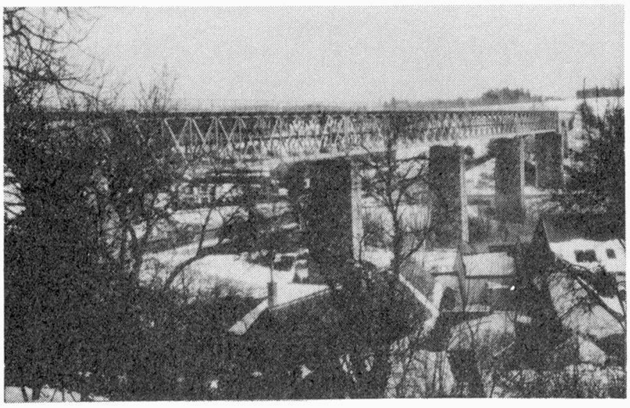

Fig. 1 Kampviadukt near Zwettl

The idealised mechanic model deviates from the real structural system, as it does not consider the space load-action, effective slab-width etc. accurately. Therefore the results of the statically calculated stresses for the main load-bearing construction are too large, the stresses calculated for the bracings are too small. An error of a mere 10 % due to the load-bearing model leads to an inaccuracy in the prediction of the life span of more than 30 %.

In order to obtain a realistic assessment of the stress induced on the Kamp-viaduct (Fig. 1), the "Austrian Railways" commissioned the "Department for the Experimental Research in the Fields of Steel Engineering, E 213.1", at the Technical University of Vienna to determine the real axle loads of the local railway between Zwettl and Martinsberg.

2. Objectives

The "Department for Planning, Engineering-Energy" (Abt. PE-E) of the "Austrian Railways" wanted to obtain the actual wheel pressures of all goods trains and passenger trains crossing the Kamp-viaduct in Zwettl, km 21,787 (Fig. 1) over a period of two months. Further, it was the task to determine the stresses in the upper and bottom chord of the steel load-bearing structure in the first section of the bridge (Zwettl-abutment). The bridge structure consists of four discontinuous truss girders, each having an effective span of 46,64 m (Fig. 1). The system of a truss girder is 5 m high and 3,2 m wide and consists of 11 fields of the framework, each field having a web of two diagonal members.

3. Planning of the project

Two measuring areas were selected on the bridge (Fig. 2):

•) "Measuring area a" for measurings of wheel pressures and temperatures at a rail.

•) "Measuring area b", for measurings of strains and temperature at the top chord and strains at the bottom chord of a main girder.

The measuring system was designed to automatically acquire and analyse all axial stresses, strains in the chord members in the mid-span of the bridge due to traffic loads and temperatures affecting the bridge girder system over a period of two months.

The main components of such a measuring system are:
- triggering function
- acquisition of measurings provided by sensors, such as:
  strain gauges
  electrical resistance thermometer
  trigger signals
- signal amplifiers
- analogue-digital converter
- an industrial computer equipped with software for acquiring, storing and analysing the measured values
- display

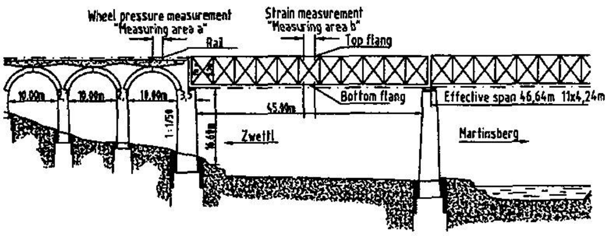

Fig.2 The two measuring areas on the bridge structure

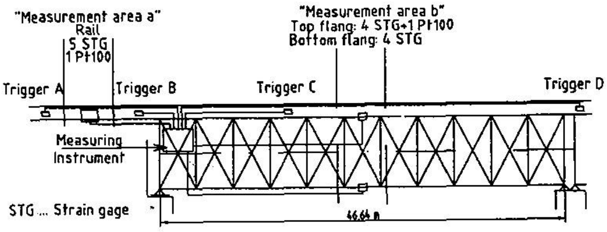

Fig. 3 Survey of the measuring points

Four triggers were located on the bridge (Fig. 3). The acquisition of measuring data was started as soon as a trigger was passed. "Measuring areas a and b" are designed to acquire data continuously during the train passage of the bridge at the speed of v>5km/h.

The measuring system was installed on a platform between the two inspection runways in the first steel supporting structure next to the Zwettl abutment (Fig. 3). The local power supply for the measuring system was provided by the "Austrian Railways".

4. The measuring system

The measuring system was designed to monitor both
a) the loads imposed on the supporting structure and
b) the strains in the structural elements.
The measuring system determines the following parameters of the rail vehicles (traffic load):
- wheel pressures
- wheel distances
- speed of trains
- direction of traffic
- lateral impact
- dynamic stress
- time and date

Due to continuous strain measurings on the surface of structural members during the train passage, it is possible to calculate the
- linear states of stress (tensile, compressive and shear stresses)
- plane states of stress (principal stresses and the position of the stress ellipse).

A schematic drawing of the installed measuring system can be seen in Fig. 4.

The industrial computer controls the whole data-acquiring process. The readings are transfered on line to the hard disk and subsequently stored on a digital-audio-tape. The acquired readings are analysed and assessed either on the measuring computer or on a HP-workstation 735/125. Standard evaluations within the evaluation programme are automised to a large extent by macros. The complete measuring equipment is installed in a 19-inch-cabinet. The power supply is secured by a 750-Watt-UPS. Fig. 3 shows the sensor locations.

A sleeper was removed in **"measuring area a"** for wheel-pressure measurements, the rail was instrumented with 5 strain gauges. The bending strains of the rail are used to determine the wheel load. The temperature is measured with an electrical resistance thermometer Pt 100.

"Measuring area b" was located in the mid-span of the bridge. The outer and interior upper chord of the main girder were each instrumented with two strain gauges and one electrical resistance

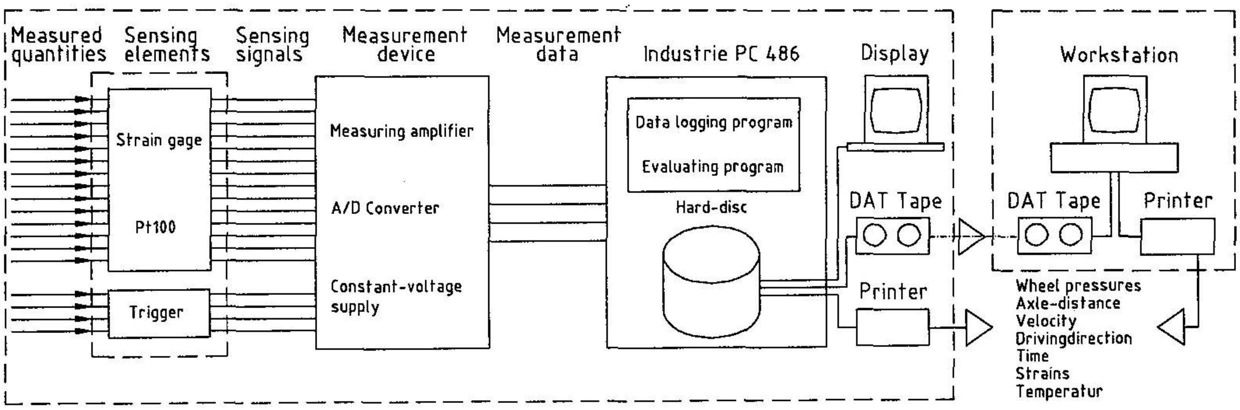

Fig. 4 Scheme of the measuring system

thermometer Pt 100. The outer and interior bottom chord of the main girder were each instrumented with two strain gauges (Fig. 7).

The measuring system is started via one of the four triggers (A, B, C or D). Trigger A and B mark the boundary of "measuring area a" and are also used for velocity measuring.
Trigger D is mounted on the rail over the first pier. As soon as a train coming from Martinsberg has arrived at the first section of the bridge, the measuring system is started by trigger D.

Trigger C registers any shunting traffic on the bridge (Fig. 3).

5. Measuring Results

The installation of the measuring system on the Kamp viaduct was started on November 30th, 1995. All measuring data of rail vehicles crossing the Kamp viaduct from December 19th, 1995 to March 23rd, 1996 were evaluated.

5.1 Measurings in „measuring area a"

Each load train is characterised by several parameters in the evaluation protocol (Fig. 5).

JUL 2 1996 12:39:44		zug00189	Page 1
1 I	Zug-Name	: zug00189	
2 I			
3 I	Anzahl Meßwerte	: 56484	
4 I	Datum	: 12-21-1995	
5 I	Uhrzeit	: 08:57:21	
6 I	------------------------------	------------------------------	------------------------------
7 I	Rad-Druck [t]	Rad-Abstand [m]	Geschwindigk. [m/s]
8 I			
9 I	8.707	5.835	5.030
10 I	9.088	2.566	
11 I	9.023	5.659	
12 I	7.446	2.591	
13 I	11.918	4.653	
14 I	10.536	6.263	
15 I	11.777	3.848	
16 I	10.548	6.363	
17 I	9.775	3.899	
18 I	11.364	6.414	
19 I	10.896	5.232	
20 I	10.112	8.728	

Fig. 5 Evaluating protocol

Each train is characterised by the:
- name of the train
- number of readings
- date of measuring
- time of measuring

The railway vehicles are characterised by their:
- wheel pressures
- axle distances
- velocity

If the speed of a train is not constant during the passage of „measuring area a", the readings of the axle distances will be inaccurate. In order to give an example for the passage of „measuring area a" by train 189, Fig. 6 shows a worksheet stating the strain-time histories and trigger signals for determining the wheel pressures and velocity. In order to examine the accuracy of the wheel-pressure measuring, „measuring area a" was passed 12 times with a diesel-hydraulic locomotive 2043 (70,320 t).

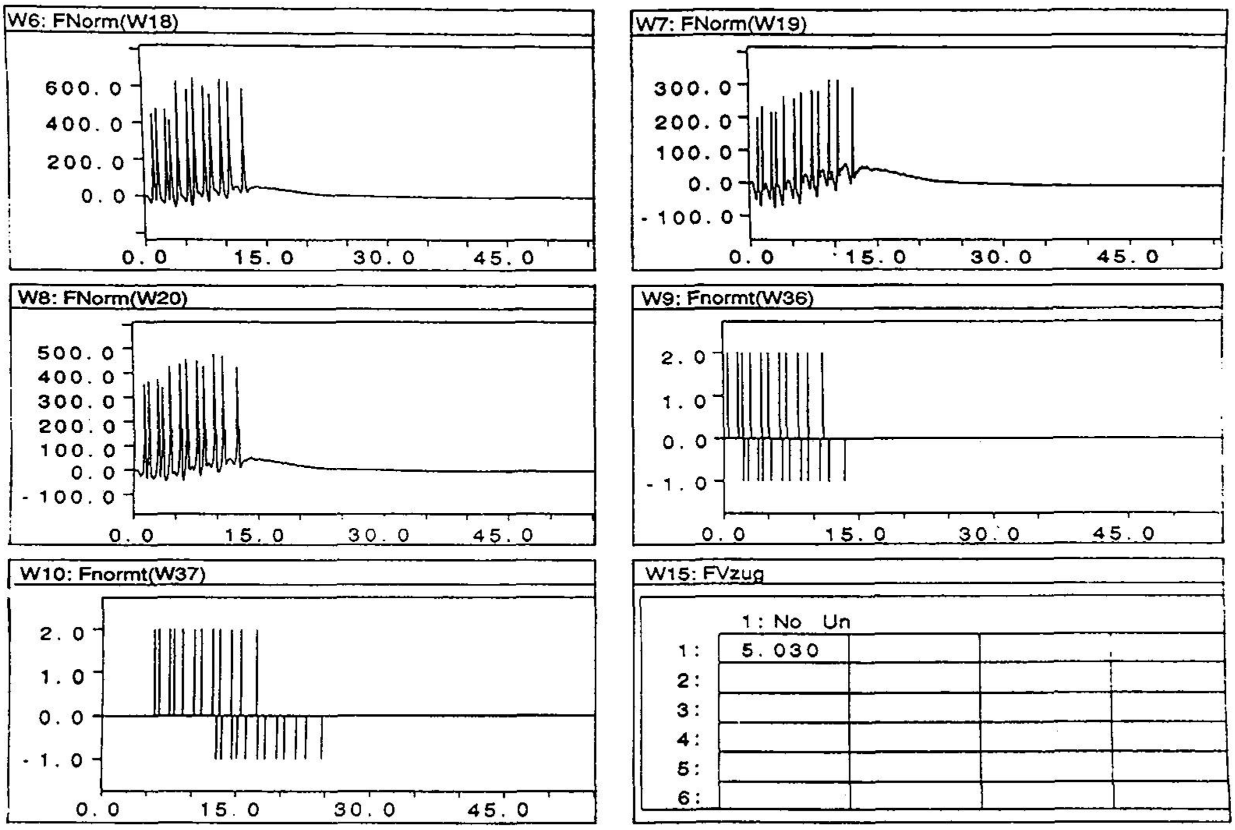

Fig. 6 Worksheet of strain-time histories and trigger-signals and velocity for the train 189 in the „measuring area a"

The evaluation of the measuring results of half of the locomotive weight (sum of four consecutive wheel loads) with regard to its accuracy shows that
the mean of the 12 times measured half of the total weight X_n is:

$X_{12} = 35{,}191$ t

the maximum deviation of the measuring value from the mean is:

$\max \delta_i = +0{,}404 \text{ t} \rightarrow 1{,}148\ \%$

the "corrected" standard error $S_n(x)$ is: $S_{12} = \frac{s_{12}}{\sqrt{12}} = 0{,}071 \text{ t}$ whereby $s_{12} = 0{,}245 \text{ t}$

final result: $X_{12} \pm S_{12} = 35{,}191 \pm 0{,}071$ t

the total weight of the locomotive is defined as

$\approx 70{,}240 \text{ t} < X < 70{,}524 \text{ t}$

5.2 Measurings in „measuring area b"

„Measuring area b" is designed for recording the stress history of a load train which is characterised by its wheel pressures and axle distances at the upper and bottom chord (midspan of the bridge). The strain-time history at four measuring points during the passage of train 189 (time: 21.12.1995/8:57:21 h) is given as an example for the measurings at the bottom chord of the main girder. Fig. 7 gives the positions of the four strain-gauge-measuring points, Fig. 8 shows the strain-time histories on the measuring channels 9, 10, 11 and 12, respectively.

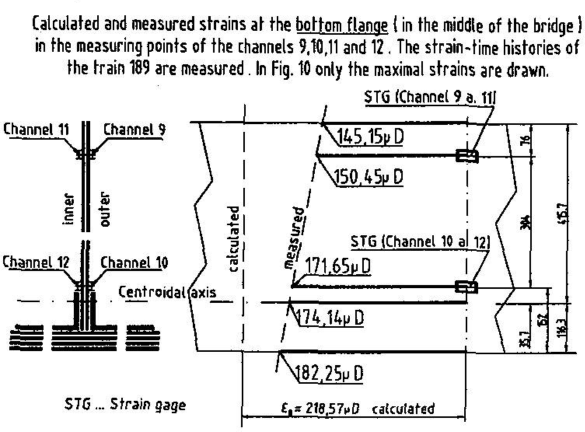

Fig. 7 Position of the four strain gauge-measuring points at the bottom flange of the main the girder

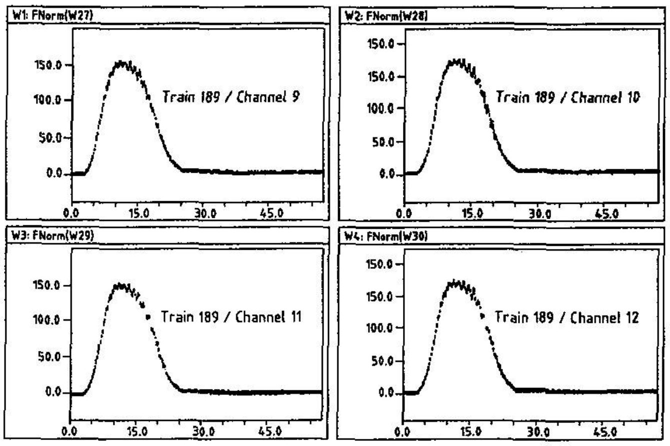

Fig. 8 Worksheet of the strain-time histories at the four strain gauge measuring points at the bottom flange during the running of the train 189

5.3 Assessment of the force imposed on the bottom chord during the passage of train 189

The measured passing time between triggers A and D indicates that the speed of the train must have diminished between both triggers thus distorting the recordings of the wheel distances (Fig. 5). In order to approximately determine the real wheel distances, a linear velocity function between trigger A and D, as shown in Fig. 9, will be assumed in the following evaluation.

V_A is the velocity of the train, measured when the head of the train comes into trigger section A-D.
V_D is the velocity of the train, measured when the last wheel of the train leaves trigger section A-D.

This assumption allows the approximate calculation of the missing boundary condition V_D. Thus, the velocity function during the passage of section $\overline{AD} + \sum_{i=1}^{11} a_i$ (a_i is axle distance according to Fig. 5) is:

$$v(t) = V_A + \frac{V_D - V_A}{T_D - T_A} t$$

Fig. 10 explains the calculation of the corrected axle distances $\bar{a}_i$ with the known velocity function v(t).

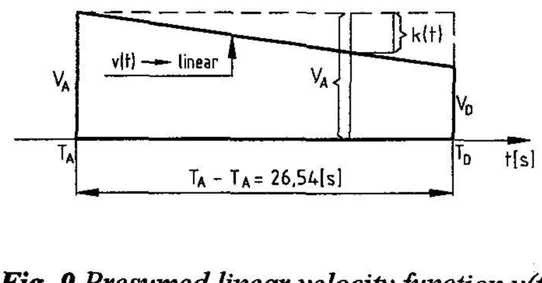

Fig. 9 Presumed linear velocity function v(t) for the correction of the axle-distances a_i of train 189

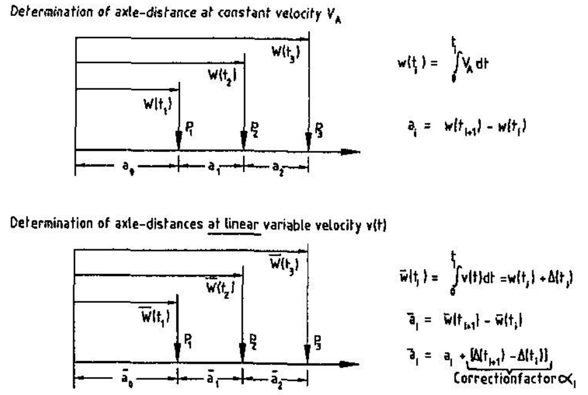

Fig. 10 Calculation of the corrected axle-distances $\bar{a}_i$

In Fig. 11 the goods waggon dimensions according to catalogue „Güterwagen, Daten und Details, DB 520; Ausgabe 1995" are compared to the measured axle distances. Fig. 12 shows the determination of the maximal moment in the bridge main girder due to the wheel pressures as stated in Fig. 5 but with the corrected axle distances $\bar{a}_i$.

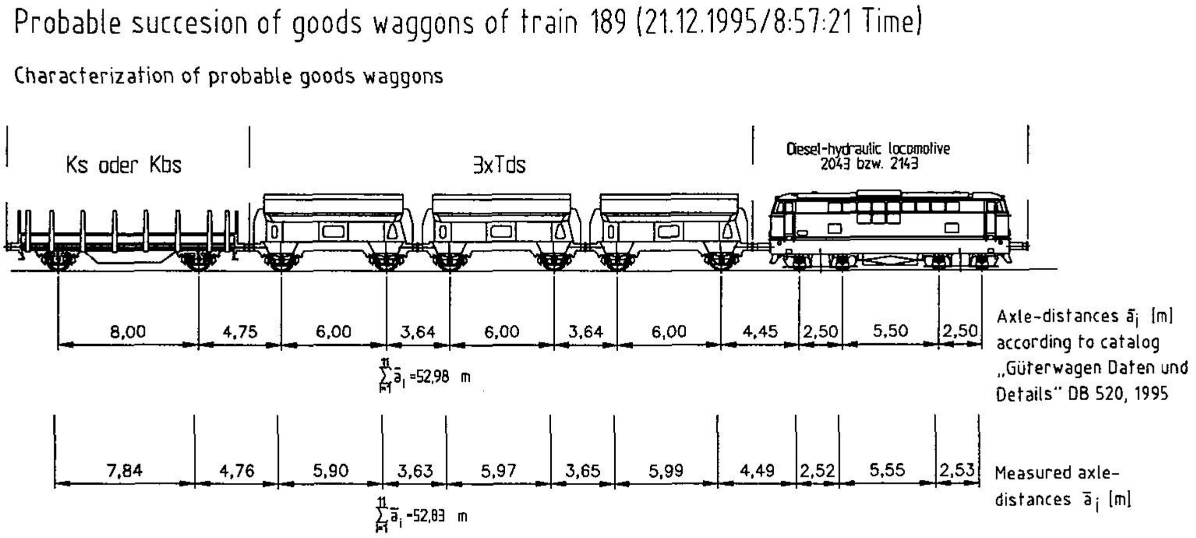

Fig.11 Checking of measured axle-distances for train 189

Fig. 12 shows the load train position causing the maximal bending moment on the mid-span of the bridge.

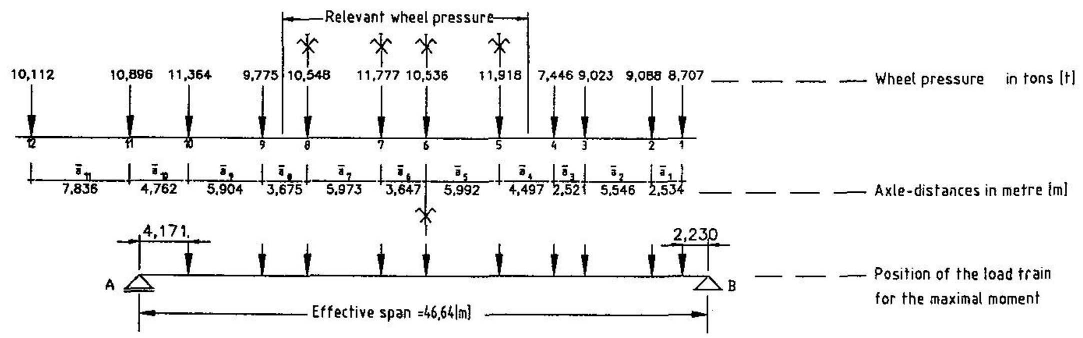

Fig.12 The position of the train 189 for maximal bending moment in the middle of the bridge

The maximum measured strains which occured in the strain-time history during the passage of train 189 on channels 9, 10, 11 and 12, respectively, can be seen in Fig. 7. According to Fig. 7 the maximum strain in the centroidal axis of the bottom chord is ε_{Sch} = 174,13 μD. This results in a normal stress of:

$$\sigma_{Sch} = 0,000174 \cdot 21000 \frac{kN}{cm^2} = 3,654 \frac{kN}{cm^2}$$

The measured normal stresses are smaller than the calculated normal stresses:

Gross sectional area:

$$\text{calculated } \sigma_G = 4,59 \frac{kN}{cm^2} > \text{measured } \sigma_{Sch} = 3,654 \frac{kN}{cm^2} \rightarrow 20,4\% \text{ smaller}$$

Net sectional area:

$$\text{calculated } \sigma_N = 5,04 \frac{kN}{cm^2} > \text{measured } \sigma_{Sch} = 3,654 \frac{kN}{cm^2} \rightarrow 27,5\% \text{ smaller}$$

The assessment of the force induced on the bottom chord during a train passage shows a difference between measured and calculated bottom chord stresses. The calculation indicates too large stresses since the mathematical model of the main girder calculation does not consider the spartial capacity of structural components like lateral bracings or roadway construction. However, due to the simplified model described above, moving loads are not taken into account when calculating bracings.

6. Comments on further data evaluation

In fatigue assessments of railway-bridges the service load is covered only by the traffic load factor λ_T. The stress in a cross-section point induced by railway vehicles is dependent on the structural system and on the position of the cross-section point in the supporting structure. For this reason, the traffic load factor is also dependent on the supporting structure and the effective span length. However, the traffic load factor λ_T is also influenced by the stress range spectrum and thus by the traffic density; fatigue life, existence of multi-track lines, combination of train types and the type of stress induced (normal or shear stress).
It is possible to determine the actual stress in an assessment point of an existing bridge with the measuring system described in chapter 4.
The further steps of the fatigue assessement are based on the hypothesis of the linear cumultative damage calculation by Palmgren-Miner.
Fatigue assessment using the damage sum:

$$D_d \leq 1 \text{ whereby } D_d = \Sigma \frac{n_i}{N_i}$$

n_i is the number of cycles of stress range $\Delta\sigma_i$; during the required design life.
N_i is the number of cycles of stress range $\Delta\sigma_i$ to cause failure ($\Delta\sigma_i$ = constant).

Below, only the basic principles leading to the determination of traffic load factor λ_T are presented:

1. A given record of the stress-time history in one point of the supporting structure (Fig. 13 shows the stress or strain-time history in one gauge measuring point at the bottom chord).

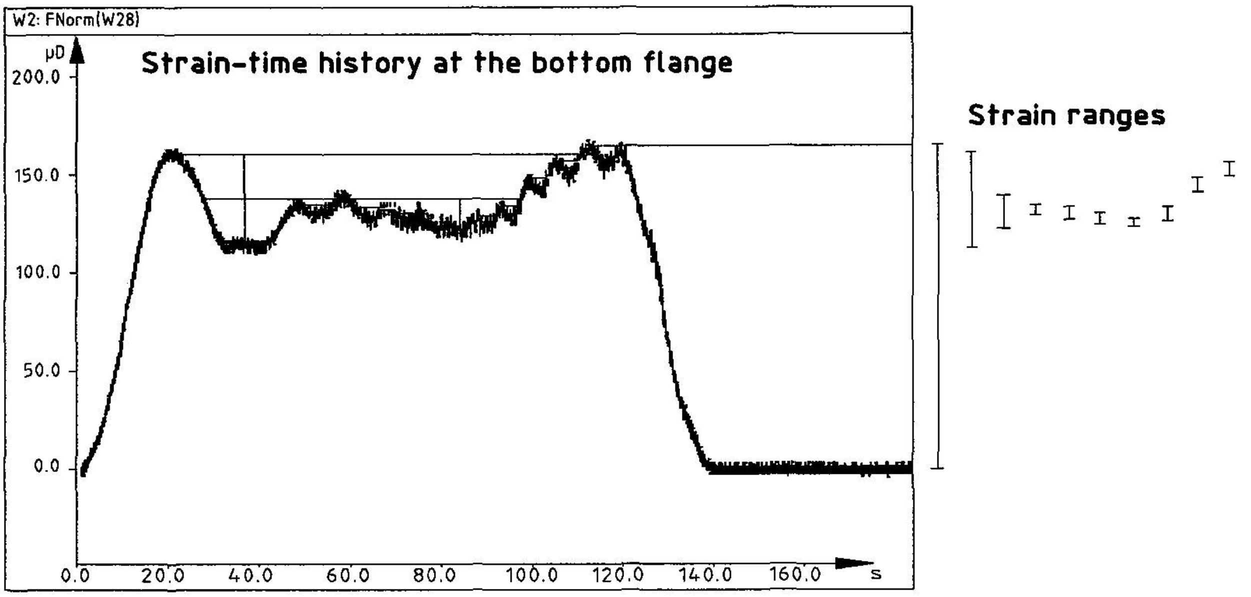

Fig. 13 Strain-time history in the measuring point at the bottom flange during the running of the train 278.

2. Stress ranges of the stress-time history are arranged in stress classes.
3. Stress ranges from the given stress-time history in the asssessment point are counted-out using the "rainflow" method or "reservoir" method. The stress ranges which were recorded during the train passage are summed and arranged according to their magnitudes. They form the stress-range spectrum of the monitored train.
4. The total stress range spectrum of the train traffic is determined. The stress-range spectra of the single trains are used to determine a train total stress range spectrum related to a certain time-unit (one day in most cases).
5. Calculation of traffic load factor λ_T:

   Determination of the equivalent constant amplitude stress range (for normal stresses) $\Delta\sigma_{\ddot{a}}$:

   $\Delta\sigma_{\ddot{a}}$ (for a fatigue strength curve with two slopes $m_1 > m_2$) can be determined as follows:

$$\Delta\sigma_{\ddot{a}} = \left[\frac{1}{n_T} \left(\Sigma n_i \Delta\sigma_i^{m_1} + \Delta\sigma_D^{(m_1 - m_2)} \Sigma n_j \Delta\sigma_j^{m_2} \right) \right]^{\frac{1}{m_1}}$$

Notation:

$\Delta\sigma_i$, $\Delta\sigma_j$..... The stress ranges
$\Delta\sigma_D$ .... Constant amplitude fatigue limit
m_1, m_2 ...... Constant slopes of a fatigue strength curve
n_i, n_j .... Number of cycles of stress range $\Delta\sigma_i$, resp. $\Delta\sigma_j$

The equation for the traffic load factor is:

$$\lambda_T = \frac{\Delta\sigma_ä}{\overline{\Delta\sigma}_{UIC}}$$

$\overline{\Delta\sigma}_{UIC} = \Phi \; \Delta\sigma_{UIC}$ ...... Maximum stress range due to the UIC load model, multiplied by the dynamic factor Φ.

The fatigue assessment with equivalent constant amplitude stress range (normal stress) is indicated as follows:

$$\lambda_T\left(\gamma_{Ff}\,\overline{\Delta\sigma}_{UIC}\right) \le \frac{\Delta\sigma_R}{\gamma_{Mf}}$$

$\Delta\sigma_R$.... Fatigue strength (normal stress) values on the fatigue strength curve for the relevant detail category, determined for the same number of stress cycles as used to calculate $\Delta\sigma_ä$
γ_{Ff}...... Partial safety factor for fatigue loading
γ_{Mf}..... Partial safety factor for fatigue strength

7. Conclusions

The measuring system described in chapter 4 makes it possible to determine the service condition of a structural system. This monitoring concept differentiates between monitoring the load and the condition of the supporting structure. It permanently registers the position, intensity, duration, velocity and frequency of the external loads. It also records the deflections, deformations, strains, vibrations, construction settlements and changes in crack widths and temperature, it shows the condition of the supporting structure under external loads. The standard deviations of the starting parameters and the uncertainty in the caluculation method according to "ENV 1993-2 DRAFT, April 1996" leads to an inexact traffic load factor λ_T. This fact speaks for the experimental determination of the stress range spectrum.

It is recommendable to solve the following tasks experimentally:

- the experimental determination of the stress-time history (stress range spectrum) in an assessment point of the supporting structure as this will lead to a more economical traffic load factor
- the determination of structural components for which the assessement of fatigue is relevant
- the determination of the plane state of stress during the train passage (temporal inconstant principle stresses and their position) in supporting structural components (gusset plate, deck plate of orthotropic plate etc.).

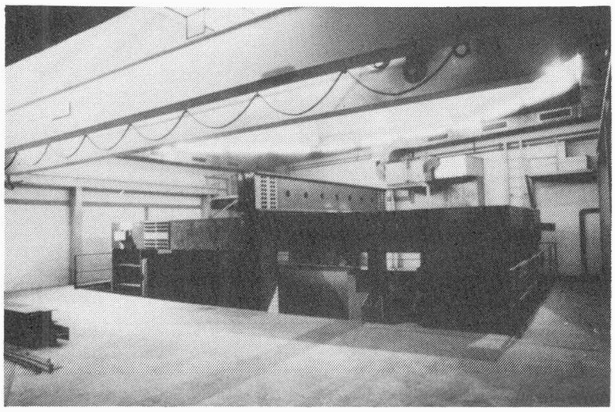

Fig. 14 Frame designed for inducing forces

The stress-time histories are also essential for the performance of service load experiments in the laboratory. By means of these tests it is possible to assess the service lives and compare the service lives of design variants. The stress-time histories, which were measured on the bridge structure and recorded on digital-audio tape, are used for the control of the testing machines. In order to conduct such experiments assessing the service loads, the author developed a frame designed for inducing forces which can be seen in Fig. 14.

8. Acknowledgements

The described measuring system was developed by the author in order to obtain accurate data of the traffic load imposed on a 90-year-old-railway bridge. The author would like to express sincere thanks to Dipl.-Ing. G. Schoitsch, head of the Dept. PE-E, Dipl.-Ing. R. Fila and Dipl.-Ing. H. Holzinger, all members of the „Austrian Railways" head office, for their good cooperation. The author would also like to thank his collaborator Ing. P. Krajiczek, especially for the time-consuming sample runs of the measuring system in order to examine the hardware and software components.

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