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Strength of Longitudinal and Cross Girders of Steel Railway Bridges

Résistance des longerons et entretoises de ponts-rails métalliques

Festigkeit der Längs- und Querträger stählerner Eisenbahnbrücken

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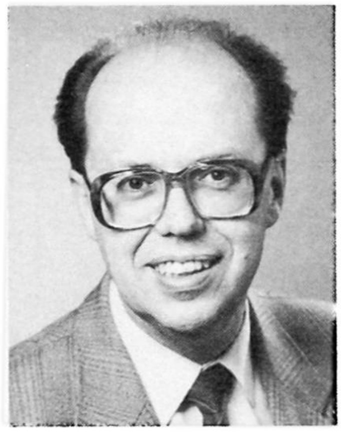


Marcel A. Tschumi, born 1938, obtained his civil engineering diploma at the Swiss Federal Institute of Technology in Zürich in 1962. Since then he has been involved in the design of structures and bridges.

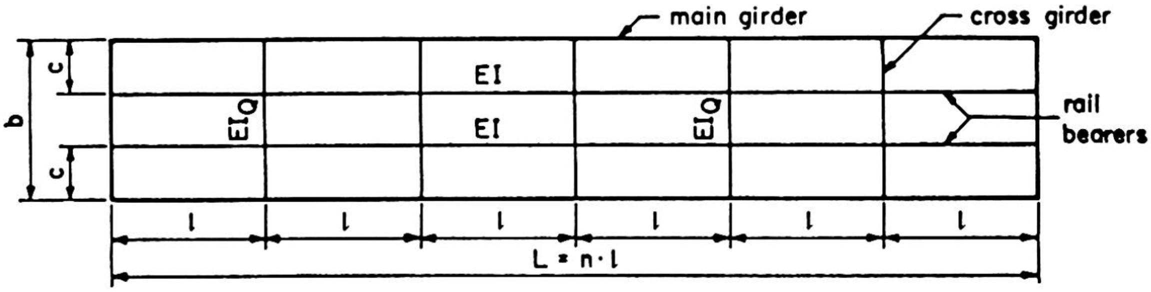
SUMMARY
The present paper gives details of the organisation and execution of strain gauge tests on longitudinal and cross girders on five different European single track steel railway bridges. The bridges were subjected to known static and dynamic loads (test locomotives) and to about 100 service trains the wheel loads of which were measured. The work is a joint effort of the Office for Research and Experiments of the International Union of Railways.

RESUME
L'article donne quelques détails sur l'organisation et l'exécution de mesures extensométriques sur les longerons et entretoises de ponts métalliques à voie unique, situés dans cinq pays européens. Les ponts ont été soumis à des charges statiques et dynamiques définies (locomotives test) ainsi qu'au passage d'environ 100 trains de service dont les charges par roue avaient été mesurées. Il s'agit d'un travail exécuté au sein de l'Office de Recherches et d'Essais de l'Union Internationale des Chemins de Fers.

ZUSAMMENFASSUNG
Der vorliegende Artikel gibt einige Angaben über die Organisation und die Durchführung von Dehnungsmessungen an Längs- und Querträgern von fünf einspurigen, stählernen Eisenbahnbrücken in Europa. Die Brücken wurden bekannten statischen und dynamischen Belastungen ausgesetzt (Versuchslokomotiven) sowie rund 100 Betriebszügen, von denen die Radlasten gemessen worden sind. Es handelt sich um eine Gemeinschaftsarbeit des Forschungs- und Versuchsamt des Internationalen Eisenbahnverbandes.

1. INTRODUCTION

Five steel single track truss bridges with rail bearers and cross girders were tested. These belong to the railways CFR (Rumania), PKP (Poland), NS (Netherlands), SBB (Switzerland) and JŽ (Jugoslavia). They were chosen to cover a wide range of cross girder spacings (3.875m to 9.55m). The most important data of the bridge decks are the following:



railway	main span L (m)	n	rail bearers l (m)	rail bearers I (m^4)	cross girders b (m)	cross girders c (m)	cross girders I_Q (m^4)
CFR	31.00	8	3.875	0.399×10^{-3}	5.00	1.60	2.26×10^{-3}
PKP	55.10	10	5.510	2.609×10^{-3}	5.10	1.65	6.77×10^{-3}
NS	59.64	12	4.970	0.842×10^{-3}	5.12	1.79	2.28×10^{-3}
SBB	65.80	10	6.580	2.122×10^{-3}	5.00	1.65	6.54×10^{-3}
JŽ	95.50	10	9.550	6.954×10^{-3}	5.80	2.00	9.31×10^{-3}

Fig. 1 Data of bridge deck

All five railways took their measurements on riveted bridges, and in all bridges, rail bearer continuity is achieved by means of continuity plates and fastenings.

The object of the measurements was to establish, for rail bearers and cross girders:

- a more realistic method of static design calculation
- better knowledge of the dynamic increment caused by railway loading
- the load spectra for fatigue calculations

To achieve this object it was necessary to measure:

- the wheel loads and axle spacing for the test train and service traffic
- the magnitude of the static forces on the rail bearers and cross girders produced by the test train
- the magnitude of the dynamic forces on the rail bearers and cross girders produced by the test train at different speeds
- the stresses in the rail bearers and cross girders produced by service traffic

The loading applied to the bridge by the wheels of the trains was measured using strain gauges on the web of the rails. In order to measure the speed of the trains it was necessary to have at least a second event gauge.

2. STATIC TESTS

2.1 General

For the static tests, at least two cross girders, the adjacent rail bearers and one end cross girder were measured for each bridge. The transducers were situated at the mid span of the elements. Sections with continuity plates were avoided by using immediately adjacent plain sections. The test train approached from each end of the bridge, and stopped at several positions. In order that the results on the different railways might be compared easily, a standard system for numbering the loading-positions and the strain gauges was chosen.

2.2 Conclusions from static tests

- The following two methods of distributing the axle loads between sleepers are recommended and give practically the same good results:

Fig. 2 Distribution of axle loads in length

- The local bending stresses calculated assuming that the rail bearer was continuous and elastically supported on the cross girders, and that the axle load was distributed between adjacent sleepers, produced the best comparison with those measured. However using this assumption means that the overall bridge bending stresses need to be calculated separately.
- Cross girder stresses were calculated assuming that it was part of a frame and the comparison between calculated and measured stresses was reasonable.
- End cross girders have practically built in ends (provided by the bearings of the main girders).

3. DYNAMIC TESTS

3.1 Purpose of the studies

The objects of the dynamic tests with the same test train as used in the static tests are:

- to determine the instantaneous wheel loads during the passage of the train at different speeds, once away and at least once on the bridge.
- to determine the variation in strain produced by the test train at different speeds for a reduced set of measuring points, so that the real dynamic increments, the ratios of the maximum stress which occurs at a given point when a train passes at a certain speed and the maximum static stress caused by the same train, can be deduced as a function of the speed v.

3.2 Dynamic increment $1+\varphi$

UIC leaflet 776-1 R [1] which is relevant to the calculation of railway bridges defines the dynamic factors Φ and $1+\varphi$. The factor Φ is used with the stresses obtained from the design load UIC 71 defined in the UIC leaflet 702-0 [2] ; it takes account of the dynamic effects of different service trains and is a function of the length of the influence line L_Φ and classified according to the state of maintenance of the track.

The coefficient $1+\varphi$ is applied to specific service trains, and its calculation involves not only knowledge of the length L_Φ but also of the speed v of the train and of the natural frequency n_o of the unloaded bridge.

The first task entailed in the theoretical studies of the Committee consisted of checking the formulae for Φ and $1+\varphi$ of UIC leaflet 776-1. These formulae were developed for simply supported beams and their applicability to rail bearers and cross girders were checked.

The dynamic increment φ consists of two components $\varphi' + \varphi''$, φ' depends on the parameter K as follows:

$$K = \frac{v}{2 n_o L_\Phi} \qquad \varphi' = \frac{K}{1-K+K^4}$$

where v = the speed of the train in m/sec
n_o = the natural frequency of the unloaded bridge
L_Φ = the length of the influence line for deflection, given in appendix 2 of the UIC leaflet 776-1.

φ' represents the component of the dynamic effect from perfectly horizontal track, whereas φ'' is the component caused by load variations from unsprung vehicle masses on vertical track irregularities.

The theoretical study of rail bearers and cross girders has proven to be much more complicated than that of the simply supported beam since they are components of a three-dimensional structure, and their dynamic behaviour is greatly influenced by the effect of unsprung vehicle masses. The study is not quite finished and the definitive conclusions will be given in the report ORE D 154 RP 4 which will be edited in 1985.

The following figure 3 shows as an example the maximum values of the measured dynamic increments φ of the PKP bridge against velocity.

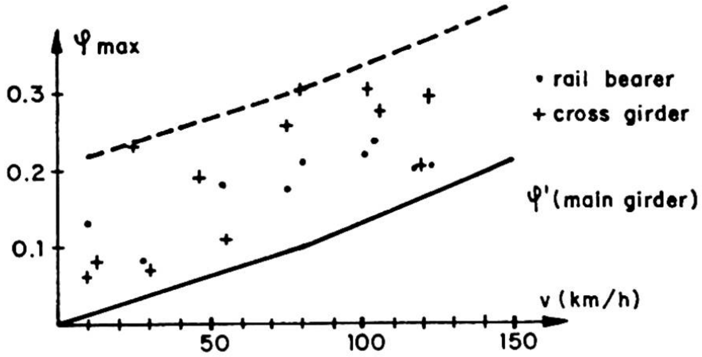


Fig. 3 Measured values of φ_{max} (PKP)

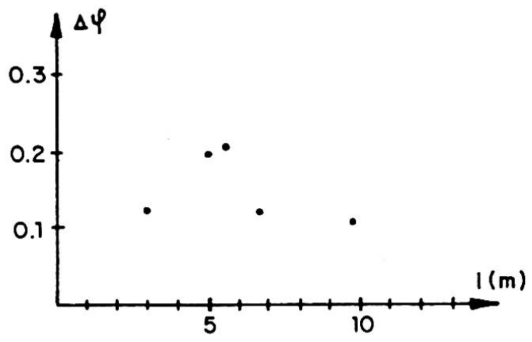


Fig. 4 $\Delta\varphi$ for the 5 bridges

The values for rail bearers and cross girders are drawn separately. Also shown is the curve of φ' for the main girder span L according to the UIC leaflet 776-1 formulae. All values are increasing with velocity and from the results of all five bridges it can be concluded, that φ for both rail bearers and cross girders is approximated by $\varphi' + \Delta\varphi$, where $\Delta\varphi$ may be a function of the cross girder spacing l (Fig. 4).

3.3 Dynamic increment for fatigue $1+\Psi$

The second task is complementary to the first and consists of determining the fatigue damage in the rail bearers and cross girders, expressing it by means of a suitable dynamic increment for fatigue $1+\Psi$, and indicating any relationship with the dynamic increment $1+\varphi$.

$1+\Psi$ will be determined as a function of the speed v and the slope k of the Wöhler line from measured strains due to the test train, in the following way:

- Step 1

  The stress-time history obtained from the passage of the test train at its lowest speed ($v \cong 5$ km/h) is known (Fig. 5).

  M for measurement

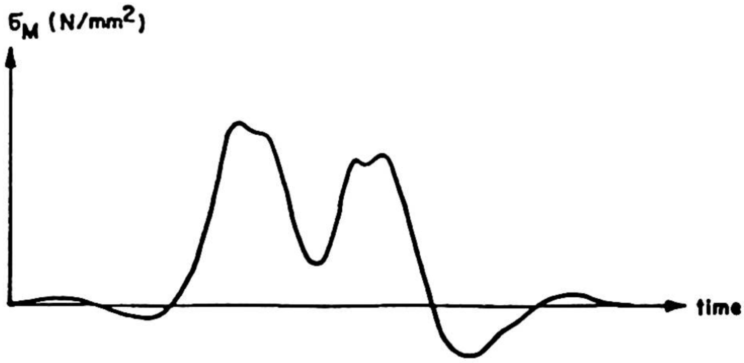


Fig. 5 Measured stress-time history

- Step 2

  From this the histogram of stress range $\Delta\sigma_{i,M}$ is obtained using the rainflow counting method and is presented as a multi-stage spectrum. This has to be carried out seperately for every speed of the test train (Fig. 6).

  N= number of load cycles

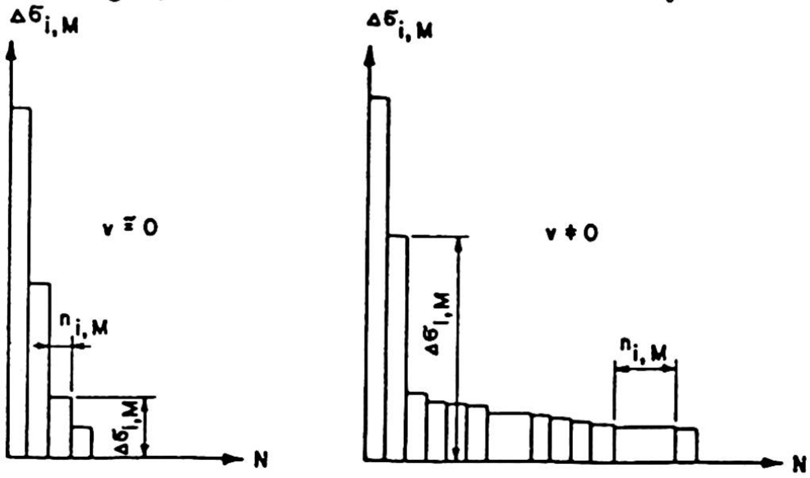


Fig. 6 Multi-stage spectrum

- Step 3

  The equal damage single-stage spectrum for every speed v of the test train (v_1, v_2, v_3, ...) are:

$$\Delta\sigma_{e,v,M} = \left[\frac{1}{N_{e,M}} \Sigma n_{i,M} \cdot \Delta\sigma_{i,M}^{k}\right]^{1/k} \qquad N_{e,M} = \sum_i n_{i,M}$$

  e for equivalent

- Step 4

  By assuming the Palmgren-Miner linear damage summation hypothesis, the single-stage spectra $\Delta\sigma_{e,v,M}$ are transformed into other damage equivalent single-stage spectra $\Delta\sigma_{T,e,v,M}$, with one load cycle per train. We obtain then for the different speeds v different values

$$\Delta\sigma_{T,e,v_1,M} \ , \ \Delta\sigma_{T,e,v_2,M} \ \ldots.$$

  T for transformed

- Step 5

  The dynamic increment for fatigue (Fig. 7) is therefore

$$\Psi = \frac{\Delta\sigma_{T,e,v,M}}{\Delta\sigma_{T,e,v=0,M}}$$

  where $v = v_1, v_2, \ldots.$

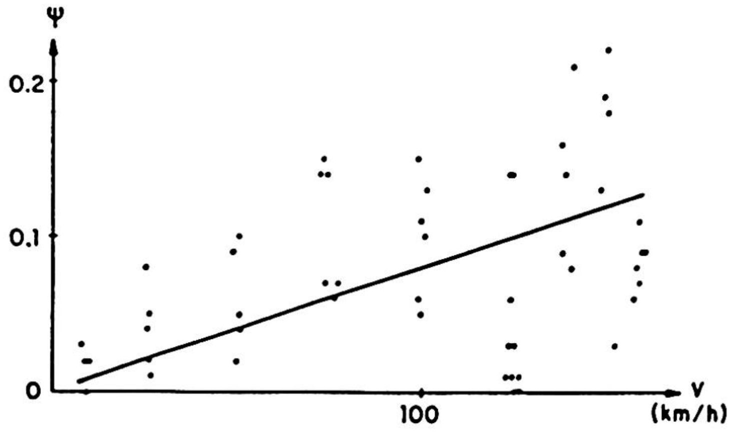


Fig. 7 Dynamic increment for fatigue

A test train (only a locomotive) does not produce many stress ranges, so the first results from the five measured bridges show that the equivalent stress range is about the same as the maximum stress and therefore the dynamic increment $1+\varphi$ is nearly equal to the dynamic increment for fatigue $1+\psi$.

4. MEASUREMENTS UNDER TRAFFIC

The object of these measurements is to determine the effective loads and resulting stresses in the elements of the bridge during the passage of actual trains in service. The number of trains recorded should be sufficient to permit statistical evaluation of the measured data. About 100 trains, which more or less corresponds to the daily traffic for one track, is considered to be a reasonable number.

It should be pointed out that the purpose of calculating the fatigue damage for an existing bridge differs to some extent from that for a new bridge; the method, however, remains the same.

- For new bridges the fatigue is determined using the loading diagram UIC 71. λ is a load factor by which the stresses taken from the UIC-loading diagram, including dynamic increment Φ, must be multiplied so as to obtain the same accumulated damage as would be caused by the service trains. The simulation of existing loads found in service is effected on the railways using defined, typical, i.e. idealised trains which may over a period of time cause the same type of damage as the trains in service. At the moment, European railways have different and individual typical trains for fatigue considerations.
- In the case of bridges already in use, the load spectrum needs to be determined with the greatest possible accuracy. It is then possible to calculate the damage already caused and also estimate the remaining life, using the same method as for new bridges.

For the purpose of comparison, a single slope Wöhler line, with gradient k= 5, and the linear damage theory of Palmgren-Miner were adopted. The determination of a better, statistically established slope of the Wöhler line, based on different fatigue results which can be found in the literature, is another objective of the Committee ORE D 154. The effect of a double slope Wöhler line will also be considered.

λ-values will be calculated using the different approaches:

$\lambda_{T,typ,M}$ experimental method, using strain measurements for about 100 service trains

$\lambda_{T,typ,C}$ experimental-theoretical method, using measured wheel loads from 100 service trains and the theoretical influence lines.

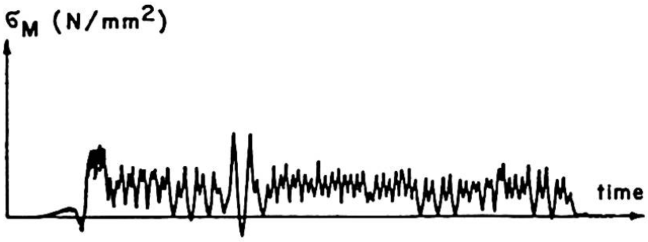
$\lambda_{T,typ,CC}$ theoretical method, using theoretical influence lines and the axle loads of typical, idealised trains.

By comparing these values λ it is possible to determine the accuracy of the theoretical and experimental-theoretical method by using the pure experimental method. In the ideal case all three values of λ are the same.

In the following, the detailed determination of the values λ is shown for the example of $\lambda_{T,typ,M}$, the others being derived similarly:

- Step 1

  For each service train the stress history σ_M is known from the crossing the bridge (Fig.8).



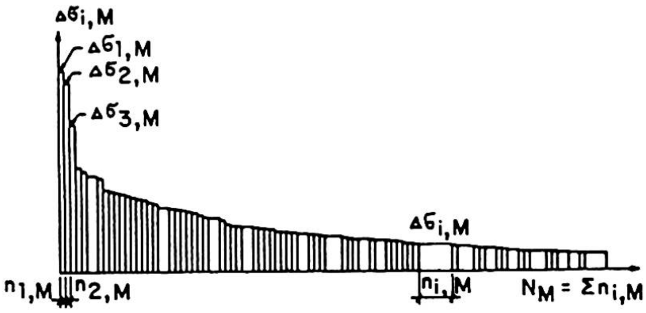


Fig. 8 Measured stress-time history

Fig. 9 Multi-stage spectrum

- Step 2

  The histograms of the stress range $\Delta\sigma_{i,M}$ are obtained for each train using the rainflow counting method and presented in the multi-stage spectrum (Fig. 9).

- Step 3

  Determination of the relative stresses $\lambda_{i,M}$ for each service train, using

  $\Delta\sigma_{UIC} = \Phi \cdot (\max \sigma_{UIC} - \min \sigma_{UIC})$ and $\Phi = \dfrac{1.44}{\sqrt{L_\Phi} - 0.2} + 0.82$

  we obtain (Fig. 10)

  $$\lambda_{i,M} = \frac{\Delta\sigma_{i,M}}{\Delta\sigma_{UIC}}$$

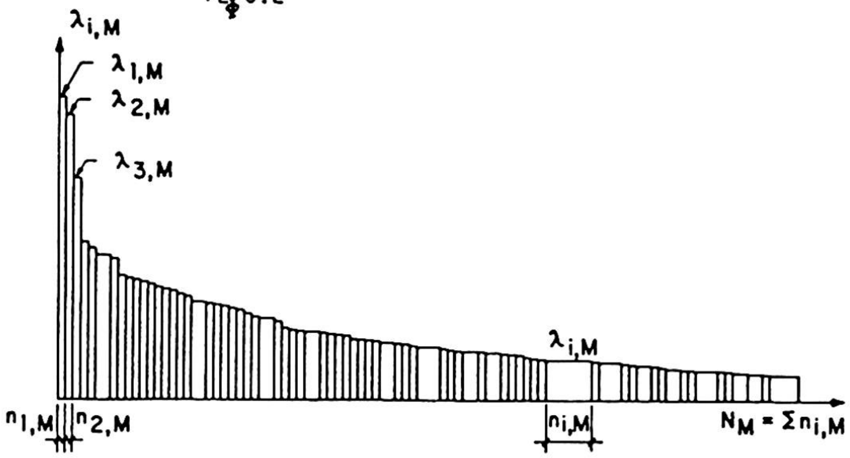


Fig. 10 Related multi-stage spectrum

- Step 4

  Determination of the equal damage single-stage spectrum for each train separately (Fig. 11)

  $$\lambda_{e,j,m} = \left[\frac{1}{N_{em}} \Sigma\, n_{i,m} \cdot \lambda_{i,m}{}^{k}\right]^{1/k}$$

  with $N_{em} = \sum_i n_{i,M}$

  and j as designation of the
  100 service trains
  1,2,3,..............100

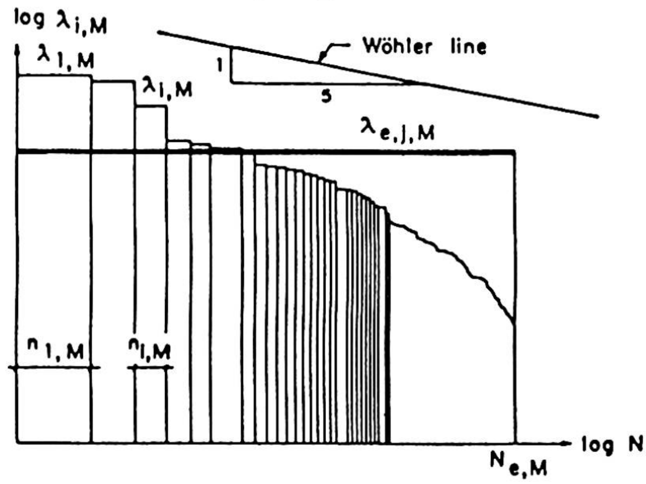


Fig. 11 Single-stage spectrum of instances where damage incurred is equal (heavy line)

- Step 5

  Transformation of the single-stage spectrum $\lambda_{e,j,M}$ into another damage-equivalent single-stress spectrum $\lambda_{T,j,M}$ with only one cycle:

$$\lambda_{T,j,M} = \left[\frac{1}{N_T} \cdot \sum_j n_{i,M} \cdot \lambda_{i,M}^k\right]^{1/k} \qquad \text{in which } N_T = 1$$

- Step 6

  Combination of all 100 measured transformed single-stage spectra $\lambda_{T,j,M}$

  Using: $n_{T,j,M} = 1$ on the assumption that all the 100 service trains differ from each other

  $N_{T,B,M} = \sum_j n_{T,j,M}$ = 100 service trains (B for service)

  $\lambda_{T,j,M}$ see above, transformed single-stage spectrum for one load cycle per service train j

  the transformed single-stage spectrum $\lambda_{T,M}$ for the 100 measured service trains is determined as follows:

$$\lambda_{T,M} = \left[\frac{1}{N_{T,B,M}} \sum_{j=1}^{N_{T,B,M}} n_{T,j,M} \cdot \lambda_{T,j,M}^k\right]^{1/k}$$

- Step 7

  Determination of $\lambda_{T,typ,M}$ related to the number of the characteristic, i.e. typical service trains specified by a railway ($N_{T,typ,M}$ not equal to the number of measured service trains $N_{T,B,M}$):

$$\lambda_{T,typ,M} = \lambda_{T,M} \left[\frac{N_{T,B,M}}{N_{T,typ,M}}\right]^{1/k}$$

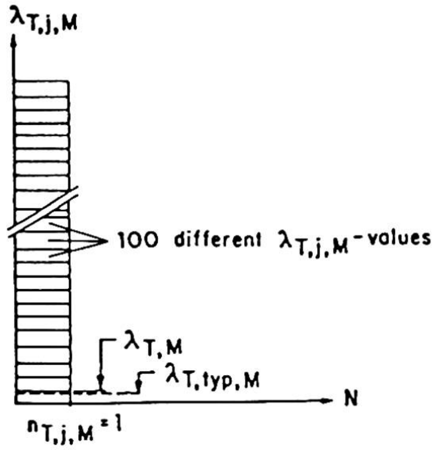


Fig. 12 Composition and transformation of single-stage spectrums

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- RP 1 Loading, design and construction, state of technology of different European railways, Sept. 1981
- RP 2 Details of strain gauge measurements, Sept. 1981
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- RP 5 Fatigue studies, to be published in 1985
- RP 6 Final report, to be published in 1986

[ORE D 154] is basing on earlier studies [ORE D 128] and [ORE D 130].