Stress spectra of steel highway bridges under traffic loads

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Sresses in three steel highway bridges under usual traffic loads were recoreded and classified using the rain-flow counting method. The statistical evaluation of stress ranges provided an empirical formula where the number of heavy vehicles per day and the span of the investigated bridge element are the most important parameters. The formula presents the strees spectra, i.e. the tables of the number of stress ranges in various stress classes which may be applied to the design of steel bridges for fatigue.

1. INTRODUCTION

It is well known that the load of highway bridges according to the national standards (codes) is much greater than the usual traffic loads. The reason is the high life of bridges (about 100 years) in which the real loads may increase and the necessary safety and reliability.

Therefore, the axle loads of highway vehicles were recorded under usual everyday traffic, (ref. 1) and, later on, also their response on three steel highway bridges, (ref. 2).

2. EXPERIMENTS

Three steel highway bridges were chosen for experiments:

1. Plate girder, span 13.12 m,
2. Box girder with orthotropic roadway, span 45 m,
3. Truss girder, span 44.8 m.

The technical description of bridges may be found in ref. 2.

The stress-time histories were recorded in all important elements of bridges, i.e. in main girders, cross-girders, stringers, diagonals, etc.

Table 1. Number of vehicles

Bridge No.	Number of vehicles	
	recorded	per day, from the traffic statistics, 1980
1	304	387
2	518	693
3	119	421

The response of all heavy vehicles was measured during several days, however, the effect of light personal cars and motorcycles was neglected because they hardly contribute to the stress ranges.

The number of recorded vehicles is compared with the number of heavy vehicles according to the official traffic statistics (year 1980) in the Table 1.

The stress ranges $\Delta\sigma_s$ due to the standard loads according to the Czechoslovak National Code (ref. 5) was also calculated for all important bridge elements.

3. EVALUATION OF EXPERIMENTS

The evaluation of experimental results was automatized using the tape-recorder, osciloscope, sample analyzer, computer and plotter. The main results are given in the form of histograms of numbers of stress ranges an example of which is reproduced in Fig. 1.

The horizontal axis in Fig. 1 gives the stress ranges $\Delta\sigma_i$ in N/mm^2 (MPa) while the vertical axis represents the number of stress ranges n_i during experiments. The rain-flow counting method (ref. 3) was applied for the classification of stress-ranges into individual stress classes $\Delta\sigma_i$. This method is well suited for bridges as can be shown for the case of railway bridges, (ref. 4).

For the evaluation the following cases were distinguished:

- light lorry vehicles up to 5 t of total mass,
- lorry vehicles,
- buses,
- other heavy vehicles,
- all heavy vehicles together.

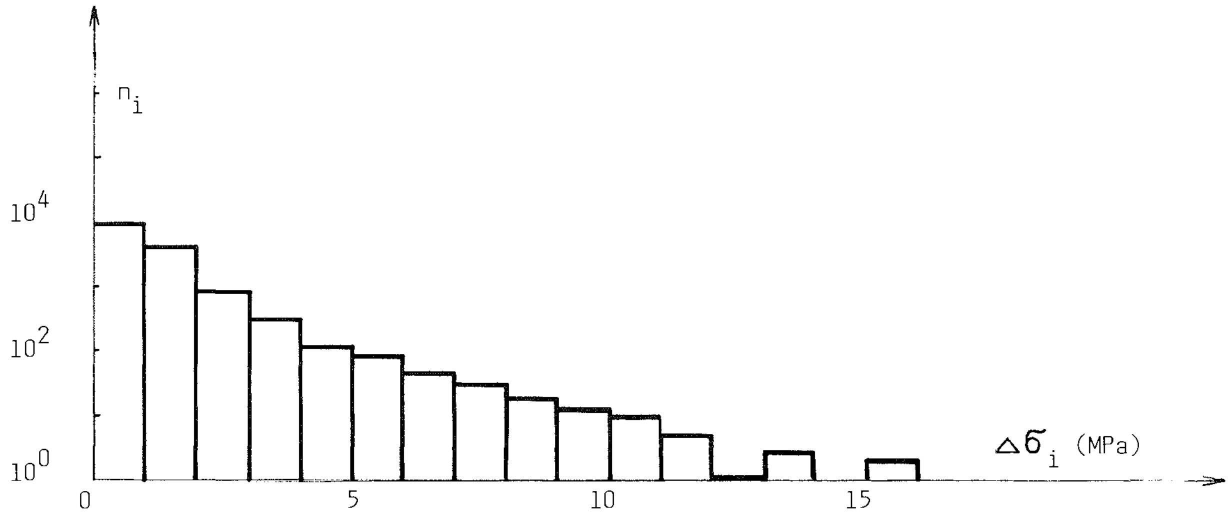

Fig. 1. Stress spectrum, bridge No 2, span 45 m, main girder, 518 vehicles (all together)

As it was not possible to carry out experiments during the whole year (financial reasons) the results were extrapolated for an annual traffic in the following way:

- the number of stress cycles was calculated for an average day,

- the ratio of the number of heavy vehicles from the official statistics to the number of that one recorded in an average day was expressed,

- the ratio of the number of heavy vehicles from the official statistics to the number 500 was calculated because the number of 500 heavy vehicles per day was taken as a basis,

- the daily stress spectrum was multiplied by 365 and in this way the annual spectrum was obtained.

The described extrapolation resulted in the annual spectra of stress ranges in all investigated bridge elements which were estimated for the traffic of 500 heavy vehicles in 24 hours.

4. STATISTICAL EVALUATION OF EXPERIMENTS

The set of experimental data represents the number of stress cycles n_i in stress classes $\Delta\sigma_i$. The multidimensional surface fitting gives the data that fit experiments with 50% reliability if the method of least squares is applied. However, the limit state design theory requires the loading data to be obtained with 95% reliability. Therefore, the data obtained by regression analysis should be enlarged on 1.65 s were s is the standard deviation. Assuming the normal distribution of experimental data around the regression surface the suggested approach assures after these operations the 95% reliability of results.

The number n_i of stress cycles in the i-th class is affected by the following parameters:

T - average number of heavy vehicles per day,

L - characteristic length of the investigated bridge element (usually the span),

$\lambda_i = \Delta\sigma_i / \Delta\sigma_s$ - dimensionless stress range where $\Delta\sigma_s$ is the maximum stress range due to the standard moving load multiplied by the dynamic impact factor.

As the average daily intensity of heavy vehicles counted according to the statistics around 500 for all investigated bridges it was assumed the regression surface only for two independent variables L and λ_i:

$$n_i = \frac{T}{500} f(L, \lambda_i) \qquad (1)$$

The optimum distribution was looked out for a multidimensional regression that could be transformed by logarithmisation to a linear regression. The exponential, power-exponential, power-power-exponential, linear-hyperbolic and power distribution was tested and the last one has shown as the optimum distribution:

$$n_i = \frac{T}{500} a L^b \lambda_i^c \qquad (2)$$

where a, b, c are the regression coefficients.

The assumed regression with the 95% reliability takes the form

$$n_i = \frac{T}{500} a L^b \lambda_i^c e^{ks} \qquad (3)$$

where s is the standard deviation, and

k = 1.65 assures the 95% reliability.

Table 2. Number and amplitude of stress cycles of highway bridges per year

Length L (m)	Average daily intensity of heavy vehicles	Amplitude of stress cycles λ_i									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
		Number of stress cycles n_i per year (in thousands)									
2		7 100	190	23	5.2	1.6	0.63	0.28	0.14	0.076	0.044
3		5 900	160	19	4.3	1.4	0.52	0.24	0.12	0.063	0.037
4		5 200	140	17	3.8	1.2	0.46	0.21	0.10	0.056	0.032
5		4 700	130	15	3.4	1.1	0.41	0.19	0.092	0.050	0.029
10	500	3 400	92	11	2.5	0.78	0.30	0.14	0.067	0.036	0.021
15		2 800	76	9.2	2.1	0.65	0.25	0.11	0.056	0.030	0.017
20		2 500	67	8.1	1.8	0.57	0.22	0.098	0.049	0.026	0.015
30		2 000	55	6.7	1.5	0.47	0.18	0.081	0.041	0.022	0.013
50		1 600	44	5.3	1.2	0.37	0.14	0.064	0.032	0.017	0.010
100		1 200	32	3.8	0.86	0.27	0.10	0.047	0.023	0.013	0.007

The statistical evaluation of all experimental results has provided the following coefficients valid for highway bridges (similar data for railway bridges may be found in ref. 4):

$$\begin{aligned} a &= 13.098\,79 \\ b &= -\ 0.460\,76 \\ c &= -\ 5.208\,54 \\ s &= 0.929\,62 \\ k &= 1.65 \end{aligned} \qquad (4)$$

Using these coefficients the Table 2 was calculated. The regression surface is limited by the class $\lambda_i = 1$ because the static strength of the element is exhausted for $\lambda_i \to 1$. The results are rounded by two first valid numbers and they are given in thousands per year.

The stress spectra have shown the following properties:

- they include both static and dynamic response of bridges,
- stress spectra include a great number of low cycles while the great stress ranges are rare,
- they depend on intensity and on composition of traffic. The direct proportionality with the average daily intensity of heavy vehicles is assumed in Tab. 2.,
- they depend on the characteristic length of the investigated bridge element (on the length and form of the pertinent influence line).

The Tab. 2 was taken over in the Czechoslovak standard, ref. 5, for loading of bridges. Its data serve for the calculation of the traffic load factor which may be applied to the estimation of fatigue strength and fatigue life of bridges, (ref. 4).

5. CLASSIFICATION OF HIGHWAY TRAFFIC

Fatigue of bridges is affected especially by the heavy vehicles while the effect of light vehicles is negligible. Therefore, the suggested classification in Tab. 3 reflects this fact.

Table 3. Classification of highway traffic with respect to the fatigue of bridges

Traffic classes T_i	Average daily intensity of heavy vehicles T	Length of network %	Approximate average daily intensity of all vehicles	Ratio T_i/T_4
T_1 very heavy	3501 to 10 000	2	30 000	20
T_2 heavy	1501 to 3 500	10	11 000	7
T_3 medium	501 to 1 500	37	4 500	3
T_4 light	to 500	51	1 500	1

6. CONCLUSIONS

The experiments carried out on 3 steel highway bridges presented the stress spectra, i.e. the tables of number of stress cycles in appropriate stress classes under usual traffic flow.

The stress spectra include both static and dynamic components of stresses and they depend on intensity and composition of traffic flow.
A great number of low cycles appears in stress spectra while the great stress ranges are rare.

It has appeared that only heavy vehicles should be counted while the effect of light vehicles is negligible with respect to the fatigue. The classification of highway traffic reflects this fact.

The statistical evaluation of stress ranges has resulted in an empirical formula for the calculation of stress cycles in each stress class where the number of heavy vehicles per day and the span of the investigated element are the most important parameters.

The stress spectra may be applied to the design of steel bridges for fatigue and to the estimation of their fatigue life.

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